TIGHT BANDING BOOK

DAMAGE BOOK

UNIVERSAL
LIBRARY

OU_162635

UNIVERSAL
LIBRARY

CONTENTS

CHAP. PAGE

I NON-FERROUS METALS 1

Copper. Joining of Copper. Welding of Copper. Alloys of Copper. Copper-Silicon Alloys. Nickel. Nickel-Clad Steel. Nickel-Molybdenum Alloys. Monel Metal. Other Alloys of Nickel. Nickel-Iron Alloys. Nickel-Chromium Alloys. Inconel. Aluminium. Joining Methods for Aluminium. Welding of Aluminium. Use of Aluminium in Chemical Engineering. Tantalum. Lead. Sheet Lead. Lead in Chemical Plant. Silver. Platinum and Allied Metals. Uses of Platinum Metals with Special Emphasis on Uses in Chemical Industry.

II CAST IRON AND ALLOYS 74

Cast Iron. Special Structural Cast Irons. (1) Low-Alloy Cast Iron. (2) Austenitic Cast Irons. Composition Required to Produce the Austenitic Structure in Cast Iron. Corrosion-Resistance, Erosion-Resistance, Heat-Resistance of Austenitic Cast Irons. Non-Magnetic and Electrical Properties of Austenitic Cast Irons. Austenitic Cast Irons of High Expansion. Iron Castings for Vitreous Enamelling. High-Silicon Acid-resisting Cast Irons.

III STEELS AND ALLOY STEELS 91

Plain Carbon Steels. Heat Treatment of Steels. The Effect of Various Elements on Mechanical Properties of Structural Steels. Temper-Brittleness. Low-Carbon Nickel Steel to Replace Wrought Iron (DuNic). Nitrogen Hardened Steels. Corrosion-Resisting Steels. Application of the Corrosion-Resisting Steels in many Industries including: Fertilisers; Nitrates; Superphosphates; Fuel Production; Cellulose and Cellulose Products; Paint, Lacquer and Varnish; Rubber; Tanning; Soap Industry; Foodstuffs. Welding of Corrosion-Resisting Steels. Heat-Treatment of Corrosion-Resisting Steels. Soft and Hard Soldering and Brazing of Corrosion-Resisting Steels. Stainless Clad Steel.

IV PROPERTIES OF METALS AT HIGH AND LOW TEMPERATURES . 117

Influence of Composition of Steels upon Creep. Steels Resistant to Creep at Moderate Temperature, and the Use of Creep Data in Design of Pressure Vessels. Heat-Resisting Steels of the Highly Alloyed Type. Heat Treatment of Heat-Resisting Steels. The Properties of Non-Ferrous Materials at Elevated Temperatures. Hydrogen Attack of Non-Ferrous Metals. The Properties of Metals at Low Temperatures.

V NON-METALLIC MATERIALS OF CONSTRUCTION 149

Chemical Stoneware. Fused Quartz or Silica Equipment. Rubber for Chemical Equipment. Use of Rubber in Chemical Engineering. Rubber Paints, Cements, etc. Rubber Varnishes. Rubber Cements. Sulphonated Rubber. Chlorinated Rubber. Latex. Use of Rubber for Handling of Corrosive Liquors and Gases. Rubber-Like Materials. Asphalt as a Chemical Engineering Material. Plastics in Chemical Plant Construction. General Notes on the Properties of Plastics. Wood. Acid-resisting Cements.

CHAP. PAGE

VI THE DESIGN AND CONSTRUCTION OF PRESSURE VESSELS FOR THE CHEMICAL INDUSTRY 178

Shells of Vessels designed on "Thin Cylinder" Theory. Shells of Vessels for Service over 1000 lbs. per sq. in. The Design of End Plates or "Heads" of Pressure Vessels. Openings in Shell and End Plates. Cast Pressure Vessels. Riveted Construction of Pressure Vessels. Rules for Welded Construction of Pressure Vessels. The Fabrication of Pressure Vessels and Accessories by Welding. Design of Pressure Vessels in Copper, Aluminium, etc. The Protection of Steam-Heated Pressure Vessels against Overpressure.

VII PIPES AND PIPEWORK 242

Steam-Pipes. Bends, Expansion Bends and Joints. Expansion of Steam-Pipes. Branches and Connections to Mains. Steam Separators and Receivers. Steam-Piping Supports. Drainage of Steam Mains. Steam Traps. Steam-Reducing Valves. Flow of Steam in Pipes. Pipes and Pipework for other than Steam Services. Graphical Method of determining Pressure Drop and Heat Transfer in Pipes.

VIII HEAT INSULATION 273

Thermal Conductivity. General Considerations of Heat Transmission from Hot Surfaces. Practical Insulation Data.

IX STEAM PLANT FOR CHEMICAL WORKS 294

Combined Plants for the Generation of Power and Process Steam. Pass-Out Engines. Methods of Low-Pressure Steam Control. High-Pressure Steam Control. Use of the Mollier Diagram in the Evaluation of Combined Power and Process Plants. Power Available from Process Steam. Allocation of Fuel Costs in Combined Power and Process Plants. Double Pass-Out Systems. Relative Fuel Costs.

X EVAPORATORS: FLOW OF FLUIDS—HEAT TRANSFER—EVAPORATORS 328

Flow of Fluids in Tubes. Fluids inside Circular Pipes and Turbulent Flow. Fluids outside of Pipes. Liquids outside Pipes. Fluids in Natural Convection. Condensing Vapours. Total Heat Transferred. Evaporators and Evaporation. Heat Transfer Coefficients in Evaporators. Evaporator Steam Economy. Economy of Multiple-Effect Evaporation. Capacity of Multiple-Effect Evaporation. Temperature Distribution in Multiple-Effect Evaporators. Effects of Boiling-Point Elevation and Hydrostatic Head. Evaporation in Evaporators using the Vapour Recompression Method. Description of Typical Commercial Evaporators. Accessories for Evaporators. Heating by Circulation of Hot Fluids.

XI DRYING 402

Rate of Drying under Constant Drying Conditions. Drying during the Constant Rate Period. Drying during the Falling Rate Periods. Effect of Humidity and Velocity of Air across the Material. The Direction of the Air Stream. Temperature of the Material. Skin Effects. Obtaining Maximum Surface exposed to Drying Medium. Notes on Considerations Affecting the Choice of Suitable Industrial Drying Equipment. Rotary Driers for Granular or Loose Material. Fuel Requirements of Rotary Dryers. Vertical Continuous Dryers for Granular Loose Materials. Spray Dryers. Spray Drying Chamber. Agitator Batch Dryers. Drum Dryers. Vacuum Shelf or Compartment Dryers.

XII ADSORPTION 422

Mechanism of Adsorption. Operation of Industrial Vapour Phase Adsorption Plants using Activated Carbon. Silica Gel and Activated Alumina.

CHAP. PAGE

XIII DISTILLATION 431

Calculation of the number of Theoretical Plates in a Fractionating Column. Batch Distillation. Steam Distillation. Practical Distillation Plant. Azeotropic Distillation. Manufacture of Absolute Alcohol. Manufacture of Ethyl Acetate. Sublimation.

XIV FILTRATION 481

(1) Filter Presses. (2) Pressure or Vacuum Filters. (3) Leaf Filters. (4) Rotary Continuous Filters. (5) Pulp Filters.

XV CRUSHING AND GRINDING EQUIPMENT 512

Kick's Law and Rittinger's Law. Choice of Methods of Comparison of Crushing and Grinding Operations. Description of all Classes of Commercial Grinding and Crushing Plant.

XVI CHEMICAL WORKS PUMPING 538

APPENDIX. THE DESIGN AND OPERATION OF CHEMICAL PLANT FROM THE SAFETY ASPECT 541

AUTHOR INDEX 545

SUBJECT INDEX 549

CHAPTER I.

NON-FERROUS METALS.

Copper.

COPPER is one of the most useful of the non-ferrous metals in chemical plant construction. It has a high degree of corrosion resistance over a wide range of conditions, and it has good strength which is maintained at moderate temperatures.

Copper is very ductile in the annealed condition, and it can be worked into complex shapes. It also lends itself to a variety of joining methods such as welding, soldering, brazing, silver soldering, riveting, etc. It has high heat conductivity second only to that of silver, and six times that of steel.

Physical Properties of Copper.

Sp. gravity	8·93
Melting point	1083° C.
Thermal conductivity	0·92 cal./cm.²/cm./° C./sec. 0·74 B.Th.U./sq. ft./in./° F./sec. 222 B.Th.U./sq. ft./ft./° F./hr. 2670 B.Th.U./sq. ft./in./° F./hr.
Specific heat	0·092
Coeff. of thermal expansion	16·6 × 10^{-6} per ° C. 9·22 × 10^{-6} per ° F.
Electrical resistivity	1·7241 microhms/cm.³ at 20° C.

Mechanical Properties of Copper.

	Annealed.	Cold Worked.
Tensile strength, tons/sq. in.	14–15	20–30
Hardness, Brinell	45–55	80–100
Elongation per cent. on 2 ins.	50–60	5–20
Modulus of elasticity	14–18 × 10^6 lbs./sq. ins.	

The foregoing figures represent average values for pure commercial copper, and they can be used for practical purposes.

In the following notes on copper I am indebted for assistance to The Copper Development Association, the Deutsches Kupfer Institut, and Dr.-Ing. H. Holler of Frankfurt.

The following are the principal types of copper in commercial use :—

High Conductivity (H.C.) Copper.—This is copper of high purity

usually containing 99·9 per cent. or more copper. It is extensively used for electrical purposes.

Best Select (B.S.) Copper.—This is refined copper containing small amounts of various impurities usually sufficient to prevent it from quite conforming to the conductivity standard for H.C. copper. It is suitable for a wide range of applications.

Arsenical Copper.—This is copper containing up to about 0·5 per cent. arsenic. In comparison with most other metals, the conductivity of arsenical copper is high, although appreciably lower than for H.C. copper. The arsenic confers slightly increased strength at ordinary and moderate temperatures, and raises by about 100° C., the temperature at which softening first occurs upon annealing. Arsenical copper has also a somewhat better resistance to oxidation at moderate temperatures than copper. For these reasons arsenical copper is widely used for general purposes.

Deoxidised Copper.

The above types of copper usually contain a small percentage of oxygen, and are then known as " tough pitch " H.C., B.S., or arsenical copper. Deoxidised copper—arsenical or otherwise—is also available, and is made by removing oxygen from tough-pitch varieties by the addition of deoxidants (of which phosphorus is the most common) to the molten copper.

In the construction of chemical and other plant, deoxidised varieties have been increasingly used in recent years, very largely because unless a special technique is used, successful welding is only practicable with such types. Even the small amount of oxygen present in tough-pitch copper causes difficulty in welding owing to its interaction with the hydrogen of the welding gases, liberating steam which is liable to cause unsoundness in the weld. (See pp. 5 to 20.)

It is to be noted, however, that tough pitch copper is being quite successfully welded in Germany as a result of the development of a special technique.

Annealing of Copper.

For practical purposes a temperature of about 200° C. may be regarded as the minimum annealing temperature for pure commercial copper, though the presence of small amounts of certain other elements such as silver, arsenic and nickel necessitates raising this temperature considerably.

Annealing at 200° C. is, however, inconveniently slow, and it is therefore more general to anneal for a short time at a temperature of 500°–600° C. Too prolonged heating or the use of a higher temperature than this should be avoided, particularly if tough-pitch copper is being annealed on a forge, as the reducing gases of the flame may

react with the cuprous oxide in the copper, thereby adversely affecting the mechanical and working properties. The method of quenching is immaterial so far as hardness is concerned.

General Corrosion Resistance of Copper.

In considering the corrosion or attack of metals by various media it is difficult to generalise owing to the large number of variable factors usually present. For example, it is accepted that copper is practically immune to the attack of dilute sulphuric and acetic acids in the complete absence of oxygen or air—and copper is therefore widely used in acetic acid plant—whereas in the presence of air, corrosion may result.

In general, copper can be used with dilute acids, caustic alkalis, sea and other waters. In some instances, certain of the copper alloys, instead of copper itself, may be used with advantage. (See pp. 23 to 33.)

Copper can be expected to offer good resistance to such corroding agents as the following, but, as previously noted, much depends on the concentration and on the conditions of exposure.

Acids.

Acetic acid, vinegar, acetates ; carbolic acid ; citric acid ; formic acid ; oxalic acid ; tartaric acid ; fatty acids ; sulphur dioxide, sulphite solutions—as used in pulp mills.

Alkalis.

Potassium hydroxide and sodium hydroxide.

Solutions of Various Salts.

Aluminium chloride, aluminium sulphate, calcium chloride, copper sulphate, ferrous sulphate, sodium carbonate, sodium nitrate, sodium sulphate, zinc chloride, zinc sulphate.

Waters.

Domestic water supplies, industrial and mine waters, etc., sea and harbour waters.

Copper is not recommended for use with :—ammonia, nitric acid, acid chromate solutions, ferric chloride, mercury salts, perchlorates, persulphates.

Resistance to Oxidation and Properties at Elevated Temperatures.

The amount of oxidation which occurs when copper is heated in air is largely a function of temperature, and while oxidation is slight at low temperatures, there may be rather serious scaling at high temperatures. On the other hand, under certain working conditions the

oxides formed are adherent and so result in a diminished rate of attack —as for instance in locomotive fireboxes, and on copper singe plates which are maintained at red heat to singe the hairs from textile materials.

Two principal types of oxides are formed upon copper during heating; the black scale is cupric oxide (CuO), and the underlying adherent oxide, which has a characteristic red colour, is cuprous oxide (Cu_2O). The types of oxides formed and the rate of oxidation of copper may be modified appreciably by the addition of other elements, which also generally result in the better retention of strength at elevated temperatures. On account of these properties various copper alloys are widely employed, amongst which may be mentioned the copper-nickel and copper-aluminium groups. (See Fig. 2A, Table 1A, and Chap. IV, p. 136, for properties of copper and alloys at elevated temperatures.)

Joining of Copper.

Soldering.

Soft soldering is a somewhat similar process to that of tinning, but tin-lead alloys are generally used. The success of joining by soldering operations depends upon the natural ability and readiness with which copper and tin form intermetallic compounds and solid solutions, since it is the tin content of solder which is the active element.

Joining by soft soldering may be performed by dipping the work after cleaning and fluxing in a bath of molten solder, or by the application of a stick or piece of solder direct to the heated work, or by flowing off molten solder from a hot copper soldering "bit."

Ammonium chloride and zinc chloride (killed spirits) are widely employed as fluxes and to assist in cleaning the metal, but care must be taken to remove these after completion of soldering, as they are very corrosive. In certain applications, particularly in the electrical industry, it is preferable to use fluxes of the resin type to minimise the possibility of corrosion.

A wide variety of solders are in general use, and of those covered by B.S.S. 219, Grade A contains nominally 65 per cent. tin, 34 per cent. lead and antimony 1 per cent. maximum; it is a fluid solder with a low melting point and approximates closely to the tin-lead eutectic composition (63/37—melting point 181° C.). Grade B contains nominally 50 per cent. tin, 47 per cent. lead and $2\frac{3}{4}$ per cent. antimony and is a cheaper type than Grade A; the melting point is rather indefinite as solidification occurs over a temperature range of about 180° C. to 220° C.

When a higher strength than can be obtained by the above-mentioned solders is required, particularly at temperatures above the boiling point of water, and where some shear strain is encountered,

a solder containing 95 per cent. tin and 5 per cent. antimony is often used.

Brazing and Hard Soldering.

These processes are carried out at much higher temperatures than those used for soft soldering, and require the aid of a borax type of flux, for the alloys used have melting points which generally range from 750° C. to about 900° C.

A wide variety of brazing solders is in use, of which B.S.S. 263 is concerned with the three following compositions :—Grade AA has a nominal composition of 60 per cent. copper, 40 per cent. zinc, and possesses a melting point of approximately 900° C. Grade A has a nominal composition of 54 per cent. copper and 46 per cent. zinc, while Grade B consists of 50 per cent. copper and 50 per cent. zinc and possesses a melting point of 860° C. approximately. The melting points of such alloys are lowered and the fluidity improved by additions of silver in amounts of 10 per cent. upwards, thus giving the various rather expensive types of silver solders.

Brazed joints are much stronger than those made by the average soft-soldering process, and in some cases with good workmanship the strength is but little inferior to that resulting from welding. One disadvantage of brazed joints, as compared with welded joints, is associated with the contact of materials of essentially different composition, tending to preferential attack in the presence of certain corrosive liquids.

Welding of Copper.

Welding copper autogenously (i.e. with the use of a copper filler rod) was at one time considered a difficult process, but is now widely used.

The very high thermal conductivity of copper (several times that of steel), which for most purposes is one of its advantages, is from the point of view of welding a disadvantage, since heat is conducted away from the parts to be welded so quickly that it is more difficult than in the case of steel or iron to raise the temperature of the metal to melting point. It is for this reason copper cannot be cut neatly by the oxy-acetylene flame.

Forge welding can only be performed with difficulty owing to the absorption of oxygen during heating.

Electric resistance butt welding is regularly employed for the joining of copper rods, bars and wires, especially in the production of copper wire, but tubes cannot at present be joined satisfactorily by this method. The electrical energy required for butt welding copper is greater than that required for steel and the maximum sectional area which can be welded is smaller, being about 3 sq. ins.

Electric arc welding processes, using either deoxidised copper or carbon electrodes, are not widely applied to copper at present, for the welds are generally more porous than those obtained by the oxy-acetylene welding process. Electric arc welding processes are, however, more applicable when using alloy filler rods (generally suitably coated with flux) and the process can then be regarded as similar to bronze welding. (See p. 20.)

Electric spot welding can only be satisfactorily carried out on copper when in the form of very thin sheet or strip up to about 0·03 in. thickness.

The Welding of Copper by Oxy-Acetylene Process.

Experience gained in the autogenous welding of steel is not by itself sufficient to ensure success in copper welding, but must be supplemented by some knowledge of the metallurgical and mechanical changes which take place in copper during welding.

Generally speaking, the oxy-acetylene flame is the only one which need be considered for copper welding. The blowpipe must be robust and, even when working at a high rate, the flame should only be permitted to "sputter" slightly, as this disturbs the progress of the work. The mixing tube should be as long as possible in order to protect the hand of the welder from the heat, but at the same time it should not be too heavy or cumbersome to manipulate. It is very important that good welding rods and fluxes should be used, and these will be considered in more detail later.

The principles adopted in the welding of copper apply generally to the welding of the majority of the non-ferrous metals. Hence this subject is dealt with in some detail.

Leftward and Rightward Welding.

There are two well-recognised methods suitable for gas welding of copper—leftward and rightward welding. Fig. 1 illustrates leftward welding, which is specially suitable for thin sheets (0·160 in.). In this method the welding rod is melted into the joint by a semi-circular movement of the welding flame, the bevelled edges of the sheet being also well melted so as to avoid the production of a "cold weld." Though leftward welding can be used for all thicknesses of metal, particular care must be taken when welding sheet over 0·8 in. thick from one side only (I- and V-seams) to avoid dangerous cavities at the bottom of the seam. In practice, however, examples exist of all types of seam welded by this method.

For rightward welding, which is also applicable to all types of seams, the position of the blowpipe and the direction of welding are as shown in Fig. 2. The blowpipe is moved along as steadily as possible between the bevelled edges without sideways movement, while the

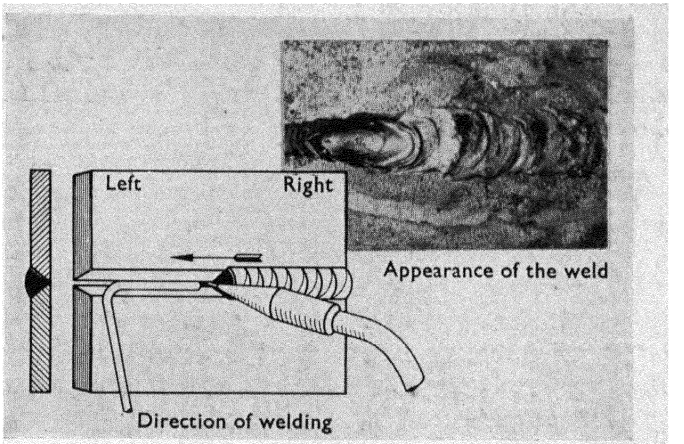


FIG. 1.—Leftward welding.

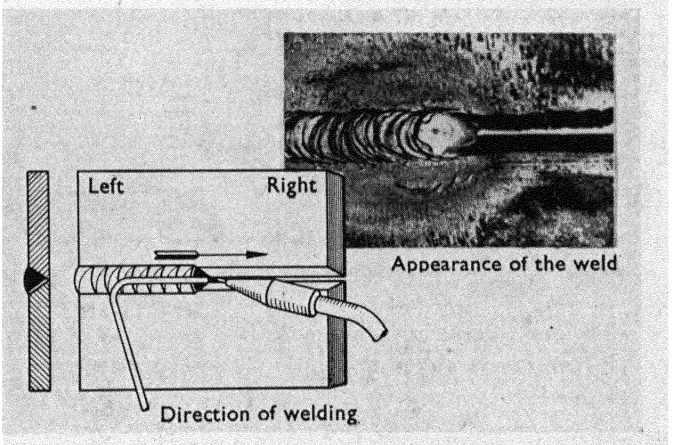
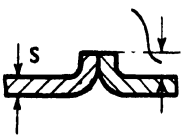
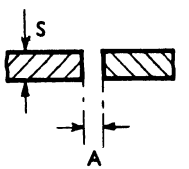
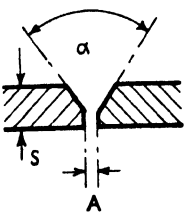
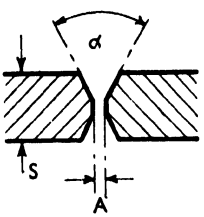


FIG. 2.—Rightward welding.

[*To face page* 6.

TABLE 1.

CHARACTERISTICS AND USES OF THE TYPES OF JOINT.

	Type of Joint.	Formation of Joint.	Thickness of Sheet S (ins.).	Gap A (ins.).	Angle α°.	Remarks.
1	Flange or flash joint		0·04″–0·08″ 0·012″–0·12″ {10–30 S.W.G.}	0	—	Usual only for thin sheets
2	Butt joint I-joint		0·02″–0·16″ {8–25 S.W.G.}	$\frac{1}{32}$″–$\frac{3}{32}$″	—	—
3	V-joint		$\frac{5}{32}$″–$\frac{3}{4}$″	$\frac{1}{16}$″–$\frac{1}{4}$″	60	Generally used if seam accessible from one side only
4	X-joint		$\frac{1}{4}$″–1$\frac{1}{4}$″	$\frac{1}{16}$″–$\frac{5}{16}$″	60	Useful if seam accessible from both sides. Best joint for thick sheets
5	Bell or cup joint		0·04″–0·40″ {4/0–19 S.W.G.}	—	—	For tubes. Occasionally for circular seams in tanks, etc.

welding rod is melted by a semicircular stirring movement in the molten metal.

Which of these methods will yield the best results depends very largely upon the skill of the welder and on the fluidity of the welding rod. For easily fusible rods leftward welding is better, whereas the rightward method is more suitable when a less fluid filler rod is used,

as in this case the metal is applied in thinner layers, and does not flow along the weld cavity.

The Preparation of Seams for Welding.

The preparation of the edges of the sheets for welding differs but little from that customary with steel. Joints are classified as Flange, Butt and Bell joints (overlap joints are rarely used with copper), while the Butt joint is further subdivided into I-, V- and X-joints, the sheet thickness determining which of these is most suitable.

The relationships between sheet thickness, welding gap and bevel angle for the various types of seam are tabulated in Table 1, the data for each method being intended to apply only to straightforward welds.

Another important part of the work prior to the actual welding is the method adopted for keeping the sheet edges in the proper position relative to one another. The large expansion of copper on heating has already been referred to, and this prohibits the tacking together of long copper seams, as the heat would open up the seam. The means adopted to overcome this will be considered later.

Figs. 3-6 illustrate some of the devices which are used to maintain the welding gap at the desired width and to prevent the edges of the sheet closing up along the seam. Fig. 3 shows the simplest method, in which the gap is maintained by means of the wedge, which is moved forward in the direction of welding so as to prevent the edges of the sheet overlapping. This method is particularly useful for sheet thicknesses up to 0·2 in. For thicker sheets the devices illustrated in Figs. 4, 5, 6 have proved to be satisfactory. Fig. 4 illustrates an arrangement of fishplates clamped together by means of screw bolts, the distance between the two gap holders being adjusted according to the thickness of sheet. In the method illustrated in Fig. 5 the screw bolts are replaced by wedge bolts. Since the diameter of the bolt is generally greater than the width of the required welding gap, slots may be cut on each side of the joint so as to accommodate the bolt. Fig. 6 illustrates a gap holder with wedges on both sides. As the welding of the seam proceeds these fastenings are removed when the flame approaches to within 1 or 2 ft.—depending upon the sheet thickness—so as to prevent the building up of stresses. Straps fastened by flanges and bolts (Fig. 11) are often used for long seams on cylindrical units on account of the greater ease of regulation of the welding gap and the lighter grip on the sheet edges.

The Welding Flame.

The heat supplied by the blowpipe flame is not immediately available for melting the copper work, as rather a large proportion of the heat is lost from the actual welding area by radiation to the air

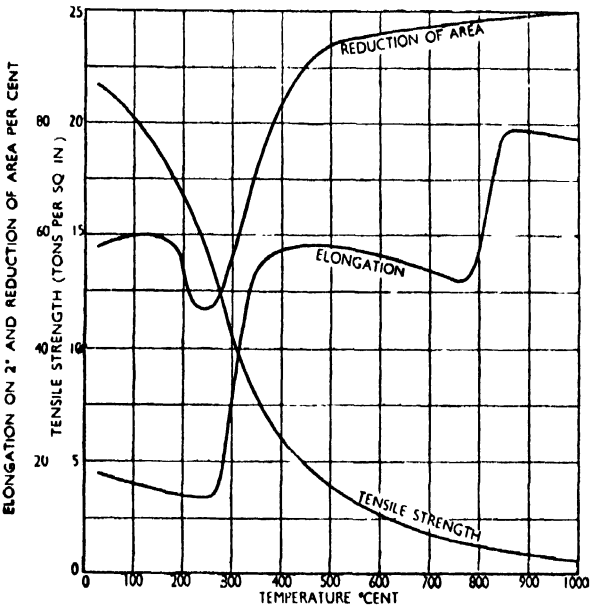


FIG. 2A.—Mechanical properties of copper at elevated temperature. Tests on H.C. copper-colled rolled (A.S.M.E. Symposium on Effect of Temperature upon Metals, 1931).

TABLE 1A.

STRENGTH OF COPPER AT ELEVATED TEMPERATURES.

Temperature (° C.).	Ult. Tensile Strength (tons/sq. in.).
20	14·5
160	11·7
300	8·4
410	5·4
555	3·1
650	2·1

Heyn and Bauer (*Das Schweissen von Kupfer und Messing*, Deutsches Kupfer Institut, Berlin.)

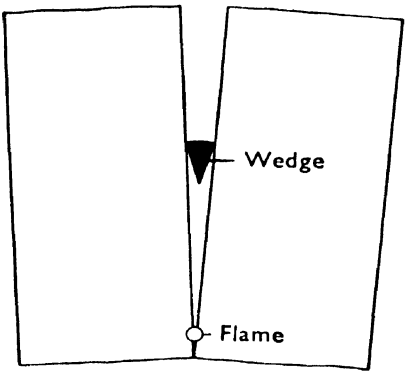


FIG. 3.—Wedge used to maintain the gap.

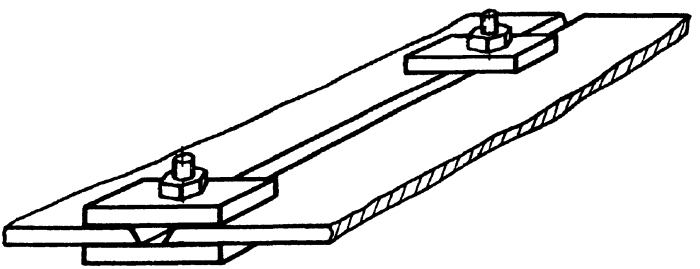


FIG. 4.—Maintaining the gap with clamps.

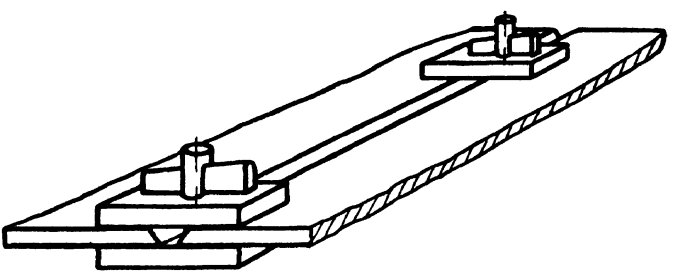


FIG. 5.—Maintaining the gap with wedges on one side.

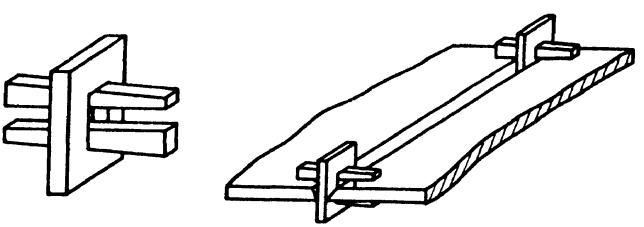


FIG. 6.—Maintaining the gap with wedges on both sides.

and by dissipation in the adjacent metal owing to its high conductivity. Thorough pre-heating of the copper work is always necessary, and welding can often only commence after a large part of the copper, and not merely the joint, has been pre-heated to 500° to 600° C. This is particularly the case if (for special reasons) ordinary copper wire is used as a filler rod. After the pre-heating is finished, a portion of the heat of the flame is utilised for the actual welding, while the remainder is used to replace heat lost in the rest of the copper.

As a general rule for copper sheet up to 0·20 in. thick, a welding nozzle is chosen which is one number higher than is used for welding steel of equal thickness; while for copper sheet over 0·20 in. thick a nozzle one or two numbers higher is used. The size of the sheets must be taken into account as well as the thickness, since the heat loss for large work is greater than for small. The use of two flames is an advantage in overcoming such loss, as by this means simultaneous heating of both sides (Fig. 11 illustrates this, a second welder being inside the cylinder) can be carried out either intermittently or continuously. The larger flame serves for pre-heating and later for regulating the heat of the molten metal, while the smaller flame is used exclusively for the welding proper. The pre-heating flame is moved forward with a semicircular motion in front of the welding flame, and its distance from the copper varied when necessary so as to maintain the required temperature.

Furthermore, it is of great importance for the success of copper welding that the flame should not only be of correct size, but also that it should be of the correct character. Throughout the welding operation, the flame must be neutral; that is to say, it must have a sharp-edged cone containing no excess of either oxygen or acetylene. An excess of acetylene should always be avoided as it tends to cause "boiling" of the copper which leads to porosity in the seam.

Care must be taken when welding copper that the tip of the flame cone is held at a greater distance from the molten surface than is the case with other metals such as steel, in order to prevent the absorption of unburnt gas from the welding flame. For thin sheets up to 0·12 in. thick, the distance should be about $\frac{1}{8}$-in.; for thicknesses of 0·40 to 0·80 in., at least $\frac{1}{4}$ in.; and for greater thicknesses at least $\frac{3}{8}$ to $\frac{1}{2}$ in. At the commencement of welding the flame is held as perpendicular as possible to the weld, and changed to the usual angle when the work is hot enough. If the heat becomes excessive on the edges of the sheet in the later stages of welding, the flame is inclined at a very acute angle to the work, so as to avoid the running away of the molten copper and the "burning" of the seam weld. This applies particularly to thin sheets.

The formation of cuprous oxide by the action of oxygen from the air on the molten metal is greatly reduced by the sheath of burnt gas,

consisting mainly of carbon dioxide, and when welding thick sheets the flame is always held perpendicular to the weld surface, as by this means the uniform spreading of the flame round the weld affords additional protection. For this reason, as well as on economic grounds, the flame should not be withdrawn during welding. The action of the flame sheath in reducing the formation of copper oxide also depends upon the property which carbon oxides possess of preventing the absorption of other gases, especially oxygen, by liquid copper; a property of which use is also made in casting copper.

Copper Welding Rods.

Pure electrolytic copper filler rod is only suitable for thin sheets and for short weld seams which do not have to undergo any working operations; its use is therefore restricted. As a rule special rods having somewhat lower melting points are used, to which alloy additions have been made in order to produce greater fluidity and to counteract oxide formation and gas absorption. The so-called copper welding rods almost always contain phosphorus, as well as one or more of the elements, silver, nickel, manganese, titanium, vanadium, etc. Apart from the improvements in mechanical properties brought about by the addition of such substances, the lowering of the melting point is beneficial, even though it is only slight (usually up to 15° C.). The rod must melt uniformly, even when it has been subjected for a long time to the action of the flame.

Flux.

The flux must be adapted to the peculiarities of the various metals —there is no universal flux. Borax, however, though generally used for brazing, is not suitable for copper welding since it swells up, has no oxide-solvent properties, and forms a particularly tough coating on the surface of the weld after cooling, which is very difficult to remove. The usual commercial copper welding fluxes— whether in powder or paste form—are suitable for both copper and brass, and consist essentially of boron compounds with the addition of various good oxide-solvent metal salts, but their precise composition is not disclosed by the makers, who as a rule also supply the filler rods.

Although thin sheets and short seams can be welded without the addition of flux, it is generally used in practice as it facilitates the operation and improves the finished weld. With sheet over 0·2 in. thick, however, it is as a rule impossible to obtain satisfactory copper welds without flux.

The Welding Process.

The welding of the longitudinal seam of a cylinder may be taken as a typical example of the work, since this is a regular operation

which, although apparently very simple, still presents many features which demand careful attention if difficulties are to be avoided.

Such a cylindrical shell is illustrated in Fig. 10. It is always preferable, at any rate with thin sheets, to use a backing plate such as a thick walled tube or, better still, a piece of steel rail (Fig. 7). Strips of asbestos board are often laid on the backing (Fig. 8) so as to prevent unnecessary dissipation of heat, though other insulating materials may also be used. The asbestos should be heated in the flame before being used for the first time so as to drive out absorbed moisture from the fibres. When a backing plate is used in welding thick sheets from one side (V-seam), then two independent asbestos strips are used, separated a somewhat greater distance than the sheet edges themselves, as illustrated in Fig. 9, and thus avoiding any obstruction to the flow of the molten rod. The simple gap holders (mentioned on page 10) serve to maintain the welding gap open, a wedge being quite adequate for thin sheets and seams of medium length. The edges of the sheet and the copper filler rod are first of all coated with paste, as already described on page 12, and are then heated till the sheet edges are thoroughly welded together. Special precautions are necessary since, as has already been mentioned, copper loses strength when heated,

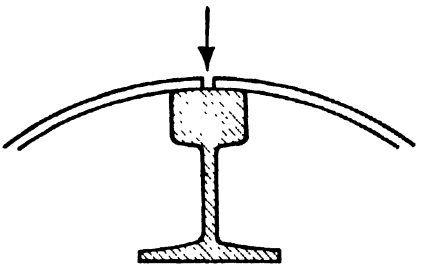


FIG. 7. –Backing for copper seam.

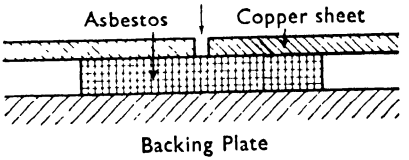


FIG. 8.—Use of asbestos for heat insulation.

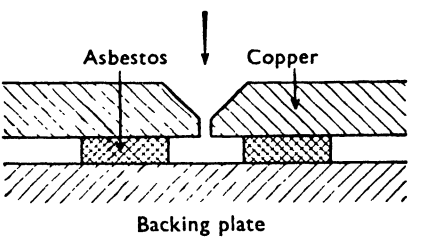


FIG. 9.—Use of asbestos for heat insulation.

and this loss is at its maximum in the hot weld because the copper itself is then in a coarsely crystalline cast state, which has a strength much inferior to that of the rolled metal.

Immediately the fused metal commences to cool, a contraction or shrinkage of the metal takes place across the seam (lengthways shrinkage is here of little importance), and this sets up stresses which are stronger than the heated copper, so that consequently shrinkage fissures are formed. This phenomenon also takes place parallel to

the weld with long seams, particularly if cooling begins in a circular or other direction in closed welded seams. Various measures, depending on the size of the unit, are taken to avoid the risk of strain fissures such as, for example, (i) the proper arrangement of the sheet edges in relation to each other ; (ii) the direction of welding ; (iii) the heating of the whole or part of the work as uniformly as possible and maintaining this heat during the actual welding ; (iv) the additional heating of the parts adjacent to the welding seam ; (v) hammering hot, etc.

Returning now to the actual welding process, the stresses in the finished weld are intimately related to the type of weld adopted and to the exact place at which welding is commenced. The starting point of the weld and the direction in which welding is carried out are of importance, irrespective of whether welding is carried out by leftward or rightward procedure. This does not apply when welding very short seams in small sheets, which can be wholly maintained at a uniform heat during the operation so that the transverse and longitudinal shrinkage of the seam occur almost simultaneously. With long seams having a welding gap appropriate to the sheet thickness (the absence of a gap between parallel sheet edges will inevitably cause fissures in the seam) welding should never commence at the end A of the sheet (Fig. 10) but at a point B. The flame is moved in the direction of the arrow 1 and the weld carried to the end of the sheet without interruption if possible. Then, beginning again at B, the remaining section is welded in the reverse direction towards A, as indicated by the arrow 2. The distance C, which indicates the point at which welding commences, varies from 4 to 12 ins. As has already been mentioned, the seams should not be tacked when welding copper as they will break open again.

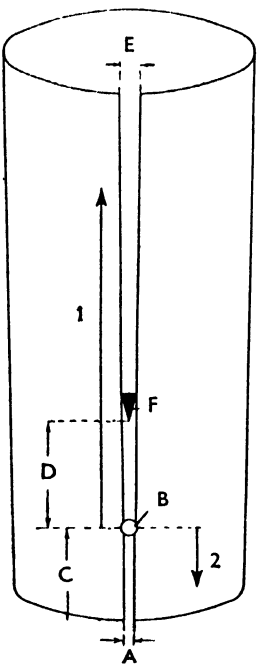


FIG. 10.—Procedure for sheet welding.

This procedure is necessary since, if welding is commenced at A and continued in the one direction only, as would generally be done with steel, then, after a short section of the seam has been completed, a contraction will gradually take place in that section, while in the neighbourhood of the flame an expansion would be taking place with the result that the leverage action so caused would be stronger than the short distance of seam already completed, which would therefore fracture. This fault would happen each time welding commenced at

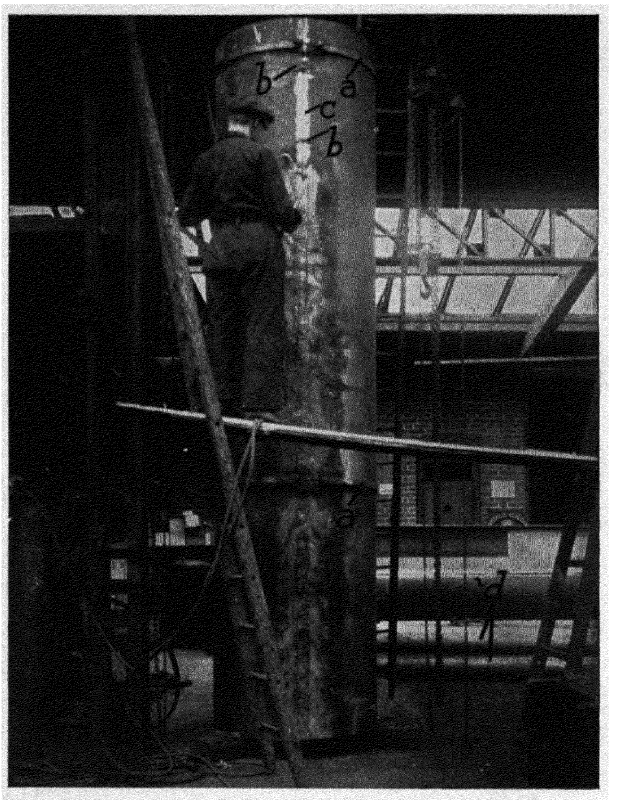


FIG. 11.—Welding a long vertical seam.

[*To face page* 15.

A, and the seam would have to be repeatedly trimmed, while the re-welding in the same place would result in greatly overheated or burnt welds. If welding is begun at B, however, then the edges of the sheets can move freely in the length C and accommodate the contraction of the weld, and then after the much longer section has been welded, the seam is sufficiently strong for the remaining piece C to be welded without trouble and without the risk of fracture.

The necessary width of gap is maintained by the wedge F, which is forced into the space in front of the flame at a distance D, which depends on the seam length and sheet thickness. In this way the edges of the sheet are prevented from touching during the actual welding, which, as has already been pointed out, would lead to the formation of fissures. The end E of the seam should remain open throughout, since the gradual expansion which takes place in the course of the welding brings the sheets together. When the wedge alone is not sufficient for regulating the width of the gap, a strap (Fig. 11) or chain can be put round at E when necessary, and the gap closed up by means of a clamp. The displacement of the sheet edges out of plane can be counterbalanced at the same time by fitting a second clamp on the joint, and this would also serve to prevent the sheet edges from being forced one over the other. Should the sheet lift off the support at the moment of welding, then it must be held down by an assistant.

In the welding of copper it is essential that the welding be carried out in a continuous operation, i.e. the joint must be completed throughout its whole length without a break, irrespective of the thickness of the sheet, otherwise oxide inclusions and the formation of fissures are unavoidable. Right-hand welding is generally preferable for thick sheets, as this tends to ensure a very gradual solidification of the weld, and prevents gases from being absorbed. In order to utilise the heat most efficiently and therefore to make the work more economical—apart from the technical advantages—it is often advisable to weld sheets over $\frac{1}{4}$ in. thick simultaneously on both sides and to use the pre-heating flame as a second welding flame ; in this way the working speed is approximately doubled for the same gas consumption, but welding must then be vertical and supports, of course, cannot be used.

Fig. 11 shows an example of such work. It illustrates a shell—13 ft. long by 2 ft. diameter, made of $\frac{3}{8}$-in. sheet—which must be quite smooth and free from surface irregularities on both sides. The welding gap is maintained by plates and bolts (Fig. 4) and by two circular straps which are clearly shown on the photograph. The seam has been finished as high as the shoulder of the welder, and after reversing the cylinder the remainder of the weld will be carried out in the opposite direction. The cylinder stands on wooden planks in order to ensure adequate air circulation for the second welder, who is standing

inside at the same height as the man shown. The white colour at the top of the seam is due to dried welding paste.

Figs. 12 and 13 represent diagrammatically the procedure adopted in vertical welding—which is always carried out in an upward direction. The welding of vertical thick sheets is shown both for V-seams which are welded on one side, and for X-seams which are welded on both sides. The V-seam is filled up starting at the apex of the V (the left-hand illustration) and is hammered while still hot in lengths of $1\frac{1}{2}$ to 3 ins., depending on the thickness of the sheet, using a heavier

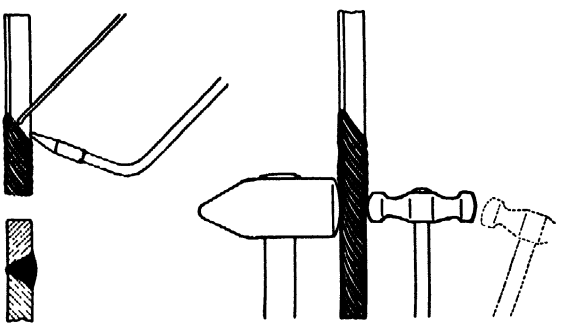


FIG. 12.—Welding a vertical V-joint.

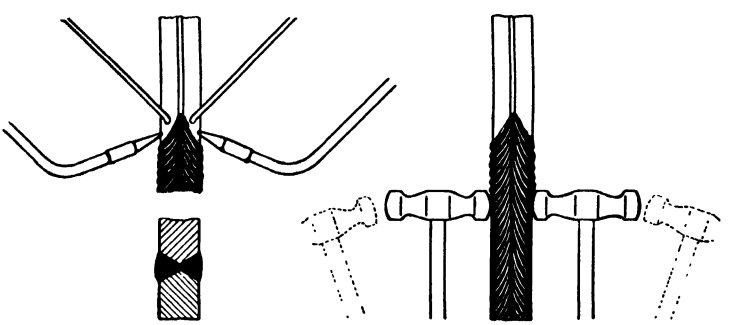


FIG. 13.—Simultaneous double-sided welding of an X-joint.

hammer on the inner side as a backing. The hammering is carried out with as long handled a hammer as possible, about $1\frac{1}{2}$ lb. weight, with one face flat and the other rounded. The hammering is effected with short, not too heavy, blows and can be continued until the metal is below red heat ; the actual welding is then immediately continued, and the heat from this anneals and improves the hard hammered weld.

When simultaneous double-sided or X-welding is employed, such as is shown in Fig. 13 (which is also analogous to Fig. 11), then both burners are worked at the same height. The melting is commenced

at the centre of the X, i.e. at the apex of the bevel, and the sections of the seam are hammered hot on both sides simultaneously.

Overwelding of copper, i.e. the repeated welding in the same place, should be entirely avoided wherever possible, since the uneven heating of the seam produces new stresses in the sheet, which often cause long fissures and cracks. If re-welding cannot be avoided, then the various preparatory measures which have already been detailed must

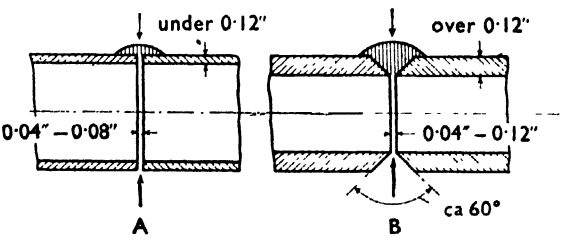


FIG. 14.—Copper tube welds.

be repeated, and, in particular, fresh welding rod and flux must be used.

The procedure adopted for welding copper tubes differs only slightly from that for steel tubes. Fig. 14 shows how the ends of the tubes are arranged for butt welding; at A for tubes under, and at B for tubes over, $\frac{1}{8}$-in. wall thickness. With thin-walled tubing the butts are placed a distance of 0·04 to 0·08 in. apart, while with thicker tubes

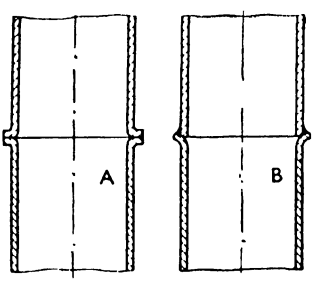


FIG. 15.—Vertical welds in thin-walled copper tubes.

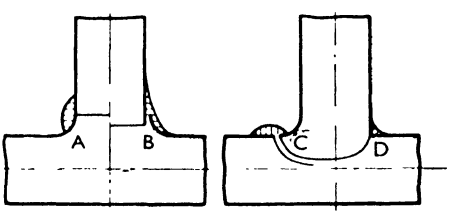


FIG. 16.—Attachment of branch tubes.

both the joint edges are bevelled to about 30° so that a welding trough of 60° is formed. If one of the edges is unbevelled for any reason, then it is good practice to cut away the other to about 45°. An increased thickness of weld metal may be used to strengthen the joint, particularly if it is to be subjected to high stresses. Flanged (Fig. 15A) or bell joints (Fig. 15B) can also be used for joining thin vertical tubes under 16 gauge wall thickness.

The hammering of tube welds in order to improve their mechanical

properties is only practicable when the diameter of the tube is large enough to allow of a good support for a mandrel inside. In most cases, the bore of the tube is inaccessible, and therefore the molten metal should be prevented from running inside the tube to any appreciable extent, as this diminishes the bore.

Branch tubes are attached by one of the four methods shown in Fig. 16. The edges of the hole in the main tube may be somewhat raised up (A and B), or the end of the branch may be flared out and fitted to a correspondingly larger hole in the main tube (C). By these three methods the presence of obstructions such as sharp corners, which would restrict the flow of gases or liquids, is avoided, and on this account the simplest method, namely the butt tee joint (D), is rarely used with copper tubes.

The Treatment of Copper Welds.

Welded seams in copper are similar in appearance to those in steel except that they are broader, and in the case of thick sheets, have also a greater thickness of weld metal. This difference is necessary to provide increased transverse strength and to fit the seams for the treatment which they undergo after the actual welding is completed. Such treatment consists of hammering V-seams on one side and X-seams on both sides, first with the rounded and then with the flat face of the hammer, so as to give the seams a smooth convex shape.

Fig. 17 shows the appearance of a welded seam in a $\frac{3}{8}$-in. copper sheet after cleaning with a wire brush only. As the thickness of the sheet and the breadth of the seam increase, the characteristic scaly formation gradually disappears and is replaced by a somewhat smoother, though still irregular, surface appearance, similar to that obtained with steel of equal thickness.

The subsequent treatment of the welded seam has for its object either one or both of the following : (*a*) improving the appearance of the surface, (*b*) strengthening the welded joint. Irregularities in the weld course of thin sheets can be removed by scraping, grinding and light hammering, while thicker sheets, as already mentioned, are generally hammered while still hot, and afterwards smoothed as well as possible in the cold with pneumatic tools. The improvements in the properties of the weld by subsequent treatment are much more important, and include the increase of density, the refinement of the structure, and the increase of workability, strength, elongation and notch impact strength.

Every crude weld possesses the characteristics of a casting, the properties of which compare unfavourably with those of the rolled material. Hammering and annealing are the means adopted to improve the weld ; hammering refines the grain and so causes a marked increase in the tensile strength and notch impact value, and annealing

—although it lowers the strength of the hammered seam—improves the ductility and enables the weld to be more readily worked by drawing, bending, etc. The methods adopted for improving the weld can therefore be varied according to the mechanical properties which are required in the joint.

In cases where specially high strength is required, the thickness of metal at the joint is increased by the methods illustrated in Fig. 18.

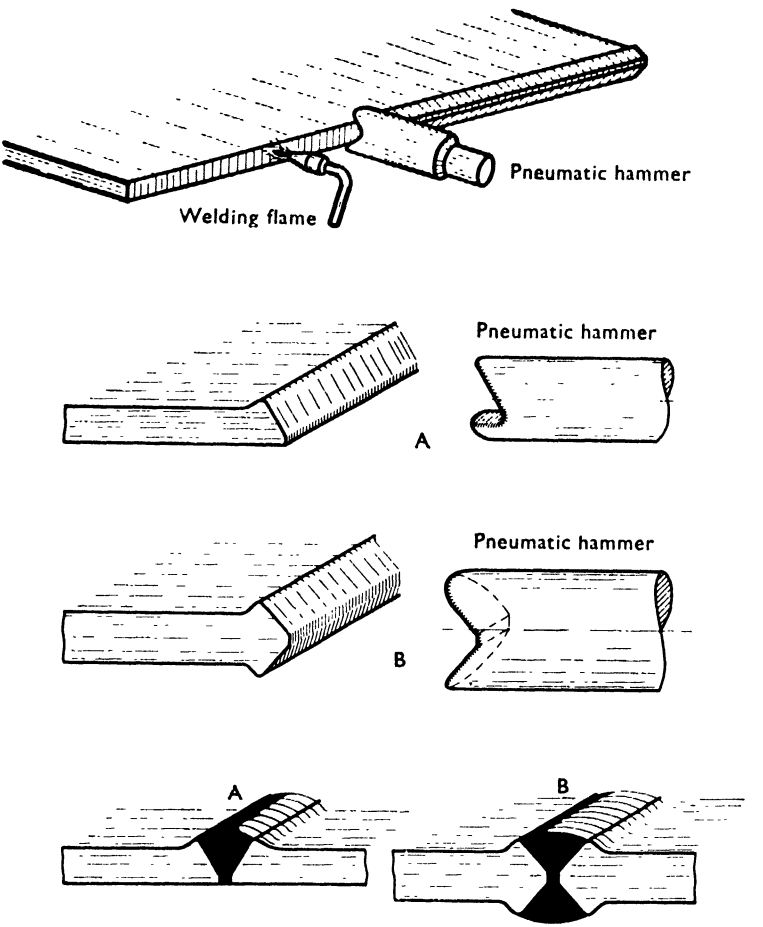


FIG. 18.—Preparation of sheet edges with special tools.

The edges to be welded are heated with the blowpipe and worked up with a pneumatic hammer, the head of which varies in shape according to whether V- or X-seam welding is to be used. When the edges of the metal have been prepared in this way a considerable increase in thickness is produced on welding, and though little extra welding rod is required, the weld is still considerably thicker than the sheet metal, even after hammering. Advantages of this method of

welding are the narrower heat zone and the fact that recrystallisation only occurs in a small area. The width of the zone in which grain coarsening is produced during welding is small enough, so that the metal in this zone can be again refined by the hammering which follows. Externally, this type of seam is characterised by a narrow weld course and an increased cross-section of the sheet.

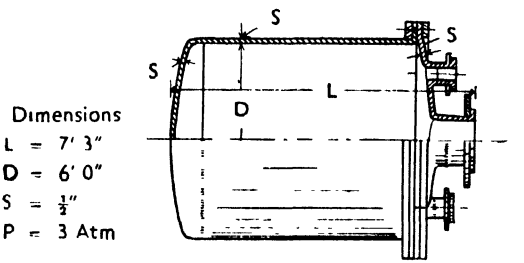


Fig. 19.

Fig. 18 illustrates at A and B sheet edges prepared in this manner, while the lower part of the photo shows the finished welds.

An example of a large copper autoclave made by the aid of the oxy-acetylene welding process is seen in Fig. 19. A large copper brewery pan is seen in Fig. 20.

Bronze Welding of Copper.

In some instances both the oxy-acetylene and electric arc welding processes are more conveniently effected with copper alloy filler rods of lower melting point than the copper to be joined, and the process is then known as " bronze welding."

Bronze welding is carried out with a variety of copper-tin and copper-zinc alloys, usually containing additions of silicon or phosphorus. Phosphor bronze, and 60/40 brass with silicon or phosphorus, are two alloys widely used as filler rods. In the oxy-acetylene process the technique is very similar in principle to that employed in autogenous welding, but the flame is of a less-intense type and the speed of welding is consequently rather reduced. With bronze welding, however, there is less liability of damage to the work by accidental fusion of the copper, and less skill is required than with autogenous welding. The use of deoxidised copper is not so necessary for bronze welding, but fluxes of the borax type should be used.

Bronze welding is especially applicable when welding in awkward positions, as in pipe joints and overhead structures, for there is then more certainty of securing a sound joint. The final difference between joints bronze welded with a modified 60/40 brass filler rod, and brazed joints, is largely one of appearance, for the bronze welded seam usually shows a succession of waves due to local application of metal, instead of the smooth finish obtainable by heating a larger area, as in brazing.

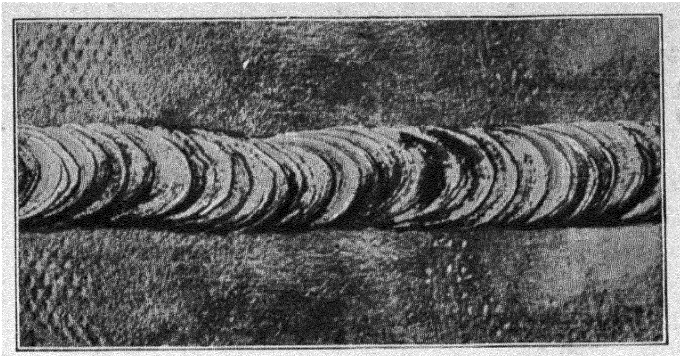


FIG. 17.—Weld in $\frac{3}{8}$-in. copper sheet.

[*See page* 18.

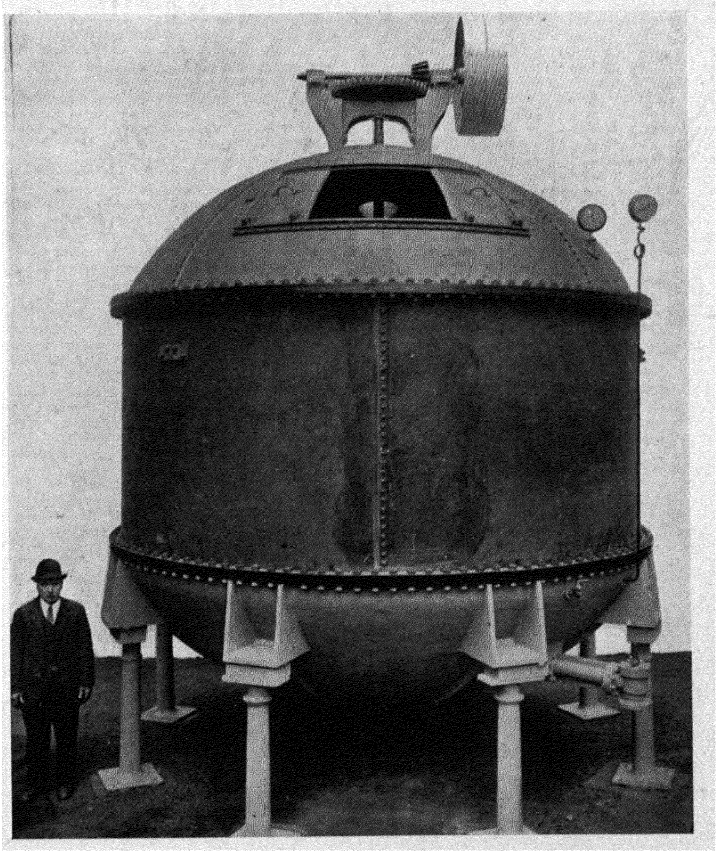


FIG. 20.—Large brewery pan by Blair's, Ltd.

[*To face page* 20.

Metallic Coatings on Copper.

There are some processes which, considered purely from the standpoint of chemical resistance, would demand as constructional materials metals which are, however, impracticable either on economic or mechanical grounds. In such cases it is a common procedure to utilise the chemically desirable metal as a lining on a backing metal which has the requisite mechanical properties, and by making a suitable choice for this underlying metal, the composite unit can be made to function with the advantages of both metals.

For a coating to be successful, certain conditions should be fulfilled. The foundation metal must form a good bond with the coating, so that changes in temperature or mechanical movement will not destroy the continuity of the coating; the base metal should be relatively resistant to chemical attack, so that any cracks which may develop in the coating will not lead to rapid corrosion of the apparatus; also it should be possible to apply the coating readily with the certainty that it will be continuous and homogeneous. Considerations such as these have led to the widespread adoption of copper as a base for coating with the more expensive metals, such as tin, silver, nickel and chromium.

Tin Coatings.

Tin is used as a coating to a large extent owing to its immunity from attack by many reagents, and because its low melting point and readiness to alloy with copper render it an easy metal to apply. The most general use of tinned copper is in the processing of milk and certain foodstuffs, where it is not the corrosion of copper *per se* which has to be guarded against, but the passing of minute traces of copper into the manufactured product, which, though regarded as harmless, may thereby acquire an undesirable flavour or taste.

The life of a tin coating in food equipment may be seriously curtailed by the action of the detergents used in cleaning, and the use of abrasives which will rapidly wear away the relatively soft tin should be avoided. The most usual cleanser is a sodium carbonate solution, and it has been suggested that the addition of sodium bisulphite would be advantageous, as it markedly decreases the action of the sodium carbonate on the tin (R. Kerr, *Jour. Soc. Chem. Ind.*, 1935, **54**, 217–21 T).

The four methods of tinning in common use are :—(*a*) electrodeposition, (*b*) hot dipping, (*c*) wiping, (*d*) spraying.

(*a*) *Electrodeposition* is commonly used for small articles which are made the cathode in a bath of a suitable electrolyte for the time necessary to give the coating required. Tin coatings applied in this way are more porous than those obtained by the other methods, but

they are generally made thicker, and are therefore satisfactory for the purpose intended. The tin does not form an alloy with the underlying copper.

(*b*) *Hot dipping* consists in dipping the copper after suitable cleaning and fluxing into a bath of molten tin. This method gives a good coating free from porosity, and is useful for medium-sized articles, particularly when repetition work is being carried out. It is also the recognised method for coating tubes. It is important to avoid inclusions of solid flux in the coated article, and therefore the tinning should not be done at too low a temperature. Though the melting point of tin is 232° C., and that of solders may vary down to 181° C., it is generally advisable to use a minimum tinning temperature of 300° C., as below this temperature flux inclusions are liable to occur when using "killed spirits" (zinc chloride) either with or without addition of ammonium chloride. If the flux consists of a mixture of 1 part zinc chloride and 3 parts ammonium chloride (a eutectic mixture the melting point of which is 179° C.), the tinning temperature may be lowered somewhat. The coating actually consists of a layer of tin (or solder) on the top of a layer of tin-copper alloy, the thickness of which depends on the time of dipping.

(*c*) *Wiping* is the most commonly adopted process for tinning plant, as this is usually too large for either of the above two methods to be employed. The copper is cleaned, heated and fluxed, and then molten tin is poured on and wiped over the surface. The coating so produced is non-porous, and this method of production is applicable to any shape or size of unit. A tin alloy layer is formed during wiping just as in dipping, and in many cases the actual wiping operation may remove practically all the tin layer and leave only the alloy layer; this may also happen when wiping is carried out after hot dipping. Wiping is frequently applied locally to fill in any capillary cavities which may exist around rivets, or at the junction of two portions of plant.

Should a tin coating show signs of wear, it can readily be repaired, as normally no deterioration of the underlying copper takes place by chemical action, and electrolytic action between copper and tin is in most practical applications negligible.

(*d*) *Spraying.*—In this method a wire of tin is melted and sprayed on to the article from a gun by a current of air. A coating of any required thickness can be built up, and there is no limit to the size of plant which can be treated in this manner. A copper-tin alloy layer is not produced by this process.

Silver Coatings.

From the standpoint of working properties and thermal conductivity, silver is similar to copper, but its high initial cost often prohibits

its use as the sole constructional material. It has, however, in some cases greater resistance to corrosive action, and advantage may be taken of this property when required by coating the plant with silver.

Copper is nearly always used as the backing metal, for in addition to the advantages which have already been mentioned, the proximity of silver and copper in the electrochemical series practically eliminates any risk of electrolytic corrosion at any junctions. Furthermore, the excellent working properties of both metals enable them to be sweated together as strip, and rolled or worked together without difficulty.

The methods in general use for silver coating are electrodeposition and lining. The former is used on a wide scale in the manufacture of silver plate, though for chemical process work the coating, unless made comparatively thick, is liable to be porous, with the added disadvantage that the heavier the coating the more liable it is to peel off under service conditions. This may lead to failure and expensive resilvering, especially with large or inaccessible parts of a plant. The method is much more applicable to small parts, which are easy to clean and not costly to recoat.

In the latter process a complete lining is made of sheet silver of the order of 0·03 in. in thickness, which is sweated or hammered on to the copper. This method of manufacture ensures an entirely non-porous silver coating. Silvered copper may be used for condensers for acetic acid, and for food preparations using acetic or other organic acids when a product of the highest purity is required.

Copper tubes, coated on one or both sides, can be made by sweating together silver and copper tubes and drawing to the required size.

Nickel and Chromium Coatings.

Coatings of these metals on copper are applied electrolytically, and find their main application as an ornamental finish for equipment such as water heaters, dry-cleaning units, sterilizers, etc., as well as having innumerable uses unconnected with chemical industries.

Alloys of Copper.

Copper-Zinc Alloys—Brasses.

For general engineering work this is the most important group of copper alloys. While the zinc content varies up to 45 per cent., the most widely encountered alloys have a copper content within the limits 57–70 per cent. Small amounts of many other elements, such as tin, manganese, aluminium, iron, lead, are often added to produce special properties. The brasses have greater strength than copper, and by choosing the appropriate composition, such mechanical properties as ductility, strength, machinability, etc., can be varied and combined within fairly wide limits.

The 60 per cent. copper, 40 per cent. zinc alloy—to which small percentages of other elements are frequently added—furnishes an excellent material for castings, hot stampings and machining, and for this reason it is very widely used for fittings, valves and similar parts. The 70 per cent. copper, 30 per cent. zinc alloy is a strong, very ductile alloy suitable for cold working, and is therefore extensively used for the manufacture of tubes and of sheet and strip for general cold press-work operations. As a general rule the corrosion resistance of brass is not equal to that of copper, and therefore the latter is preferred for service with corrosive liquids.

Brass (as well as copper) tubes find considerable application in evaporators in such industries as sugar and salt manufacture, where the smoothness, strength and ductility of the metal allied with adequate corrosion resistance and heat conductivity make it a very suitable material.

The addition of tin to brasses to obtain increased corrosion and abrasion resistance is a common practice, and Admiralty brass (70 per cent. copper, 29 per cent. zinc, 1 per cent. tin) and Naval brass (61 per cent. copper minimum, 38 per cent. or less zinc, 1 per cent. tin) are, for instance, largely used in marine work. Aluminium in small proportions is also frequently added to the copper-zinc alloys, and one well-known alloy, 76 per cent. copper, 22 per cent. zinc, 2 per cent. aluminium, is widely employed for condenser tubes in marine and other installations on account of its resistance to corrosion and impingement attack by sea water.

Brasses containing less than 85 per cent. copper when exposed to acidic media frequently fail in a characteristic manner termed "dezincification." Failures of this kind are identified by the appearance of spongy areas of copper in the form of either layers or so-called "plugs" on the affected surface. This spongy copper is a consequence of the solution of fractions of the alloy in the media and a redeposition of the copper by chemical displacement. Generally speaking, dezincification is confined to the brasses of higher zinc content, while those of higher copper content, such as 85/15 brass, commonly give satisfactory service in applications where the former are prone to failure through dezincification.

Copper-Tin Alloys—Bronzes.

These have a tin content varying from about 2 per cent. up to 12 per cent., though the compositions most commonly encountered are those containing about 5 per cent. and 10 per cent. of tin, the former being used in wrought form, and the latter in the cast condition. Phosphorus in small quantities is frequently added to copper-tin alloys, giving the phosphor bronzes.

TABLE 2.

Physical Properties of the Brasses.

Material.	Tensile Strength (lbs. per sq. in.).		Elastic Limit (lbs. per sq. in.).		Elongation (per cent.).		Rockwell B Hardness.		Melting Point (° C.).	Density (lbs. per cu. in.).	Coefficient of Expansion (° C.).	Electrical Conductivity.*	Thermal Conductivity.†	Modulus of Elasticity (lbs. per sq. in.).
	Hard.	Soft.	Hard.	Soft.	Hard	Soft.	Hard.	Soft.						
Red brass (85 Cu, 15 Zn)	89,000	45,000	85,000	15,000	4·5	43	89	3	1020	0·316	0·0000187	37·0	0·38	15×10^6
70–30 Brass (70 Cu, 30 Zn)	95,000	53,000	91,000	16,000	7	51	93	15	955	0·308	0·0000199	27·58	0·290	15×10^6
High brass (65 Cu, 35 Zn)	93,000	51,000	73,700	18,500	2	50	90	30	930	0·306	0·0000202	26·8	0·285	15×10^6
Admiralty (71 Cu, 28 Zn, 1 Sn)	100,000	53,000	98,000	18,000	4	67	95	15	935	0·308	0·0000202	24·65	0·263	15×10^6
Aluminium brass (76 Cu, 22 Zn, 2 Al)	83,000	62,000	75,000	16,000	5	52	86	33	970	0·301	0·0000185	22·56	0·240	15×10^6
Muntz metal (60 Cu, 40 Zn)	88,000	59,000	82,000	15,000	5	52	91	24	905	0·304	0·0000208	28·60	0·300	15×10^6
Commercial bronze (90 Cu, 10 Zn)	67,000	37,600	55,000	15,000	3	40	75	1	1045	0·318	0·0000182	40·90	0·446	15×10^6
Roman or Tobin bronze (60 Cu, 39·25 Zn, 0·75 Sn)	90,000	54,000	70,000	15,000	4	40	93	55	885	0·304	0·0000211	24·93	0·279	15×10^6

Data based on information published by the Revere Copper and Brass, Inc., American Brass Company, and Chase Brass and Copper Company.

* Per cent. of International Annealed Copper Standard.

† Cal. per sq. cm. per cm. per sec. per ° C. at 20° C.

TABLE 3.

Physical Properties of the Bronzes.

Material.	Tensile Strength (lbs. per sq. in.).		Elastic Limit (lbs. per sq. in.).		Elongation (per cent.).		Rockwell B Hardness.		Melting Point (° C.).	Density (lbs. per cu. in.).	Coefficient of Expansion (° C.).	Electrical Conductivity.*	Thermal Conductivity.†	Modulus of Elasticity (lbs. per sq. in.).
	Hard.	Soft.	Hard.	Soft.	Hard.	Soft	Hard.	Soft.						
5 per cent. phosphor bronze . . . . (95 Cu, 5 Sn, 0·05 P)	105,000	51,000	85,000	15,000	7	55	91	30	1050	0·320	0·0000178	18	0·20	15×10^6
8 per cent. phosphor bronze . . . . (92 Cu, 8 Sn, 0·05 P)	110,000	55,000	90,000	15,000	3	60	99	38	1030	0·319	0·0000182	13·61	0·154	14×10^6
10 per cent. phosphor bronze . . . . (89·5 Cu, 10·5 Sn)	115,000	60,000	95,000	16,000	5	65	100	52	1000	0·317	0·0000183	10·6	0·121	15×10^6
Aluminium bronze . . (92 Cu, 8 Al)	134,000	76,000	110,000	30,000	13	55	99	69	1060	0·293	0·0000165	15·23	0·173	15×10^6

Data based on information published by Revere Copper and Brass, Inc., American Brass Company, and Chase Brass and Copper Company.

* Per cent. of International Annealed Copper Standard.

† Cal. per sq. cm. per cm. per sec. per ° C. at 20° C.

The corrosion resistance of bronzes is normally similar to that of copper, but under certain conditions may be much greater. The strength and hardness in the cast or softened condition are intermediate between that of annealed and hard copper, and as bronzes can also be readily cast and machined they find extensive applications for pumps, valves, flanges and other duty under corrosive conditions.

Zinc is frequently added in small proportion to form gunmetal, and the composition 88 per cent. copper, 10 per cent. tin, 2 per cent. zinc, gives the well-known Admiralty gunmetal, though other compositions are also extensively used. The gunmetals are very satisfactory metals for the foundry, and are therefore used for marine fittings and other castings requiring good mechanical and corrosion-resisting properties.

Small additions of other metals such as nickel and lead are also made to the copper-tin alloys in order to modify their mechanical or corrosion-resisting properties and render them suitable for special applications.

An example of a bronze autoclave is seen in Fig. 21. It weighs nearly 5 tons, and the material from which it was made had the following analysis: Copper 88, Tin 10, Zinc 2, and $\frac{1}{2}$ per cent. nickel had been added to assist pressure tightness.

Copper-Aluminium Alloys—Aluminium Bronzes.

These usually contain 5–11 per cent. aluminium, though the most common alloys contain about 10 per cent. These have high tensile strength, which in the cast state is about 35 tons per sq. in., while by heat treatment this can be increased to over 40 tons. This heat treatment consists in heating to about 850° C., quenching in water, reheating to about 650° C., and allowing to cool slowly. Small additions of other metals such as iron, manganese and nickel are sometimes made to aluminium bronze in order to improve certain mechanical properties.

Owing to the formation of a protective film of aluminium oxide, aluminium bronzes have very good corrosion resistance, especially in the presence of certain acids, and this property enables them to be used in contact with hot and cold sulphuric acid in moderate strengths under conditions which would be too onerous for copper alone. They make good castings, provided that certain precautions are taken, and as they have good hot forging properties and mechanical strength the alloys are also used for valves, pumps or parts of these fittings where corrosive liquids are encountered.

A further property of which advantage is frequently taken is the resistance to oxidation at high temperatures.

TABLE 4.

TYPICAL USES OF CAST BRASS AND BRONZES IN CHEMICAL EQUIPMENT.

Agent.	Parts.	Class of Alloy.
Hydrochloric acid (dilute)	Pumps and air lifts	Aluminium bronzes, phosphor bronzes
Sulphuric acid (6 per cent.)	Pickling-tank equipment	Aluminium bronzes
Dilute (below 75 per cent.)	Pumps	Aluminium bronzes
Cold and hot below 50 per cent.	Storage	Silicon bronzes
Sulphurous acid	Pumps	Aluminium bronzes
Alums	Pumps	Leaded bronze
Aluminium sulphate	Pumps	Leaded bronze
Copper nitrate	Pumps	Bronze
Copper sulphate	Pumps	Aluminium bronze
Ferrous sulphate	Filters	Bronze
Potassium chloride	Pumps	Bronze, aluminium bronze
Sodium chloride	Piping and pumps	Naval brass
Sodium sulphate	Pumps	Bronze
Zinc chloride	Evaporators	Silicon bronze
Zinc nitrate	Pumps	60–38–2 Cu, Zn, Sn bronze Bronze, aluminium bronze
Zinc sulphate	Pumps	Bronze, aluminium bronze
Potassium hydroxide	Storage	Aluminium bronze
Oxygen	Valves	Bronze
Sulphur dioxide	Fans	Bronze, aluminium bronze
Sulphur dioxide (moist gas) below 300° F.	Piping	Aluminium bronze
Sulphite liquor	Pumps, valves	Bronze
Acetic acid	Filters	Bronze
Acetic acid	Piping	Aluminium bronze
Acetic acid (glacial)	Piping	Aluminium bronze
Acetic acid (glacial)	Pumps	Aluminium bronze
Fatty acids	Condensers, pumps	Aluminium bronze
Gallic acid	Pumps	Bronze
Lactic acid	Pumps	Bronze
Salicylic acid	Pumps	Bronze
Alcohols	Pumps	Bronze

(R. A. Wilkins, *Mechanical Engineering*, 1936, p. 809.)

Copper-Nickel Alloys.

The addition of small percentages of nickel to copper has a pronounced effect on the mechanical and physical properties of the latter. This is shown particularly in the results obtained by impact tests. For instance, the addition of only 1·5 per cent. of nickel doubles the impact value obtained for pure copper.

An improvement in tensile properties is also obtained. The maximum strength of the alloys increases with increasing nickel content

to a maximum at between 60 and 70 per cent. nickel. There is, however, very little difference in strength in the annealed condition over the range of 50 to 80 per cent. nickel. At the same time, these alloys retain remarkably good elongation and reduction of area values, indicating good malleability and ductility. The most ductile alloy of the whole range is probably the 80/20 nickel-copper alloy.

An important property of this series is the retention of strength at elevated temperatures. This is noticeable even in the 2 per cent. nickel alloy, but the strongest alloy of the whole series at high temperatures is that containing approximately 70 per cent. nickel. This alloy has a limiting creep stress of some 20 tons per sq. in. at a temperature of 400° C. It also retains remarkably good resistance to shock, having an impact value of 112 ft.-lbs. at 500° C.

In combination with good mechanical properties they also show remarkably good resistance to corrosive attack by a very wide range of reagents; the resistance, generally speaking, improving with increasing nickel content. In particular, they show excellent resistance to attack by the alkalis such as sodium hydroxide, are practically unaffected by sea-water, and have good resistance to attack by organic acids and sulphuric and hydrochloric acids, but do not resist nitric and sulphurous acids.

While a wide range of compositions is now commercially available, there are a few which are of outstanding interest and more generally used, namely 2, 20, 30, 45 and 68 per cent. nickel alloys.

The alloy containing 2 per cent. nickel is used principally for locomotive fire-box stays and boiler tubes.

Alloys containing approximately 45 per cent. nickel have long been used in the form of wire under the trade names of "Ferry," "Constantan," "Eureka," etc., for electrical purposes. They have a high specific resistance and practically a zero temperature coefficient, which makes them invaluable for the construction of resistances such as are used for speed and voltage regulators. They are also used for thermocouple pyrometers in conjunction with copper and iron. The most common of these copper-nickel alloys are those containing 80 per cent. copper and 20 per cent. nickel, and 70 per cent. copper and 30 per cent. nickel. Each of these has excellent physical and chemical properties. Table 5 gives the mechanical properties of certain of the most important copper nickel alloys.

There has been a considerable use (in U.S.A.) of cupronickel tubes which have been modified as to properties by the inclusion in the alloy of zinc in amounts up to 5 and 6 per cent. While the imparting of a beneficial effect in respect to resistance to corrosion by the inclusion of zinc is somewhat open to question, there is no conclusive evidence that any notably deleterious effect is caused by so modifying the alloy.

TABLE 5.

Physical Properties of the Copper-Nickel Alloys.

Material.	Tensile Strength (lbs. per sq. in.).		Elastic Limit (lbs. per sq. in.).		Elongation (per cent.).		Rockwell B Hardness.		Melting Point (° C.).	Density (lbs. per cu. in.).	Coefficient of Expansion.	Electrical Conductivity.*	Thermal Conductivity.†	Modulus of Elasticity (lbs. per sq. in.) × 10^6.
	Hard.	Soft.	Hard.	Soft.	Hard.	Soft.	Hard.	Soft.						
Cupronickel (80 Cu, 20 Ni)	80,000	49,000	75,000	18,000	3	42	87	21	1200	0·321	0·0000159	6·47	0·087	17·0
Cupronickel (70 Cu, 30 Ni)	84,000	49,000	80,000	18,000	4	50	87	20	1220	0·323	0·0000162	4·75	0·093	17·0
20 per cent. nickel silver (70 Cu, 10 Zn, 20 Ni)	81,000	49,500	78,000	16,500	5	44	86	12	1150	0·321	0·0000164	4·8	0·069	18·0
18 per cent. nickel silver (64 Cu, 18 Ni, 18 Zn)	100,000	54,500	80,000	18,000	5·5	42	94·5	40	1110	0·316	—	5·91	0·080	18·0
10 per cent. nickel silver (65 Cu, 25 Zn, 10 Ni)	90,000	50,000	75,000	18,000	3	45	90	52	1010	0·313	—	8·27	0·110	17·5

Data based on information published by Revere Copper and Brass, Inc., American Brass Company, and Chase Brass and Copper Company.

* Per cent. of International Annealed Copper Standard.

† Cal. per sq. cm. per cm. per sec. per ° C. at 20° C.

Characteristically, the cupronickels are notably resistant to general chemical attack, impingement attack, and erosion. Where operating conditions are particularly severe, the desirable characteristics of the 70/30 cupronickel condenser tubes are leading to its extensive use.

While it is true that the aluminium brasses, in respect of their ability to withstand impingement corrosion, closely approximate cupronickel and are less costly, cupronickel nevertheless offers outstanding advantages when compared with aluminium brasses as more severe operating conditions are encountered. When impingement corrosion or erosion alone are to be considered, aluminium brass might constitute a sound economic engineering choice, but where chemical action is accelerated operating temperatures in excess of 100° F., the aluminium brasses can, and on occasion do, fail rapidly.

For these reasons the cupronickels are being increasingly applied in the form of heat-exchanger tubes in the oil and other processing industries, in cases where operating and tube-wall temperatures are sufficiently high to cause rapid deterioration of Admiralty, aluminium brass, and similar modified brass tubes.

The so-called nickel silvers may be considered as brasses in which varying percentages of the copper content have been replaced by nickel.

There is some application of sheet and strip nickel silver in the food-processing industries, but these alloys in wrought form are not commonly used in the construction of industrial equipment. They are widely used for tableware and the like.

Copper-Silicon Alloys.

In general, the copper-silicon alloys combine with the corrosion-resisting properties of copper, physical properties and structural qualities quite comparable to those of mild steel.

It is to be noted that from a *corrosion-resisting* point of view, where copper would be satisfactory, the copper-silicon alloys would be equally satisfactory, and that where copper would be unsatisfactory there is little probability that the copper-silicon alloys would be otherwise.

Table 6 presents data on the physical properties of a typical copper-silicon alloy. This table does not refer to the product of any particular manufacturer, but is intended to be representative of this entire class of product. While the corrosion-resisting properties of copper have been retained in the copper-silicon alloys and excellent physical properties introduced, it will be noted from an inspection of this table that the high thermal and electrical conductivities characteristic of copper have been drastically reduced and are, together with the strength of the alloy, comparable to mild steel. The reduction of

TABLE 6.

Physical Properties of the Copper Silicon Alloys.

Material.	Tensile Strength (lbs. per sq. in.).		Elastic Limit (lbs. per sq. in.).		Elongation (per cent.).		Rockwell B Hardness.		Melting Point (° C.).	Density (lbs. per cu. in.).	Coefficient of Expansion (° C.).	Electrical Conductivity.*	Thermal Conductivity.†
	Hard.	Soft.	Hard.	Soft.	Hard	Soft.	Hard	Soft.					
Silicon bronze, Type A . . .	120,000	67,000	103.000	24,000	10	60	99	65	1000	0·308	0·000017	8·07	0·086
Silicon bronze, Type B . . .	90,000	42,000	80.000	12,000	10	60	84	20	1030	0·313	0·000017	11·0	0·116

Data based on information published by Revere Copper and Brass, Inc., American Brass Company, and Chase Brass and Copper Company.

* Per cent. of International Annealed Copper Standard.

† Cal. per sq. cm. per cm. per sec. per ° C. at 20° C.

Note.—Examples of commercial copper silicon alloys are "Everdur," the two principal types of which contain 3·0 per cent. silicon and 1·0 per cent. manganese, and 1·5 per cent. silicon and 0·25 per cent. manganese respectively; and the product "Herculoy" as made by the Revere Copper and Brass, Inc. Particulars of "Herculoy" are as follows:

	Si.	Sn.	Mn.	Cu.
Herculoy 418	3·0/3·5	0·5	Nil	Balance
Herculoy 419	2·0/2·5	0·25	Nil	Balance
Herculoy 420	3·0/3·25	Nil	1·0	Balance
Herculoy 421	1·5/2·0	Nil	0·25	Balance

the thermal conductivity is of considerable significance in connection with these alloys, as it is a large factor in rendering them easily welded, either with the gas torch, the electric arc, or by resistance methods. Welded joints so obtained are substantially autogenous in character and introduce none of the corrosion problems which are so frequently incidental to the use of soldered or brazed joints.

There are many industrial applications in which welded copper-silicon alloy constructions are superseding, with substantial economy, steel constructions lined or covered with copper or other corrosion-resistant material.

There are many other fields of application in which the use of copper-silicon alloys in the form of structural members such as bolts, screws, tie rods, etc., will reduce maintenance and replacement costs to an extent which will more than justify an initial higher material cost. In the past, the use of brasses in such applications has often proved unsatisfactory because of inadequate strength and insufficient resistance to corrosion.

Nickel.

Nickel and its alloys have long been known as valuable metals for certain definite purposes in both laboratory and large-scale equipment. The physical and mechanical properties of nickel are as follows :—

Physical Properties.

Specific gravity			8·9
Melting point			1455° C.
Thermal Conductivity (cal./cm.³/sec./° C.)		100° C.	0·145
		290° C.	0·128
		490° C.	0·128
Specific heat (cal./gram/° C.)	Mean	0–100° C.	0·1147
Coeff. of linear expansion		25–100° C.	$13·3 \times 10^{-6}$
		25–300° C.	$14·4 \times 10^{-6}$

Mechanical Properties.

TENSILE PROPERTIES.

Condition.	Proportional Limit.	Yield Point.	Ultimate Strength.	Elongation (2 ins., per cent.).	Redn. Area (per cent.).
	tons per sq. in.				
Rolled and annealed	5·6–10·3	9–13	29–33	43–53	65–75
Cold or hard rolled	up to 33	up to 45	up to 63	—	—
Cast	—	9–13	27–31	15–35	30–50

HARDNESS.

Condition.	Brinell Hardness 3000 kg. Load 10 mm. ball.
Rolled and annealed	75–95
Cold or hard rolled	up to 150
Cast	80–100

Modulus of elasticity	13,000-14,000 tons per sq. in.
Poissons ratio	0·33
Pattern makers' shrinkage	¼″ per ft.

Nickel can be cast, forged, machined, spun and drawn into wire, welded, brazed soft and silver soldered with the same ease as mild steel.

Nickel owes much of its corrosion resistance to its tendency to become passive under highly corrosive conditions. Among the more important products handled in nickel equipment are caustic soda, photographic emulsions, essential oils, cellulose acetate, pharmaceutical products, the raw materials for the artificial silk industry, rectifying equipment for carbon tetrachloride and similar solvents, foods such as milk and extracts. Pure nickel is used for all pipes and parts handling the hot ammonia in the ammonia oxidation process, and it is also used in handling ammonium hydroxide in process solutions.

Nickel has a high degree of resistance to solutions of the alkaline earths and related salts such as chlorides, carbonates, sulphates and nitrates of sodium, calcium, zinc, etc. Chlorinated hydrocarbons are in general well resisted by nickel, though in the presence of moisture some corrosion may occur.

Nickel cannot be recommended for use with nitric and sulphurous acids, ferric salts, stannic mercuric and silver salts, alkaline hypochlorite solution and hot sulphur compounds.

Fig. 22 shows a large pure nickel vacuum distillation kettle and is given as an example of the size of equipment now practicable in this metal.

Nickel-Clad Steel.

Nickel-clad steel plates consist of mild steel protected on one side by a covering of malleable nickel. This covering, which has all the corrosion-resisting and other properties of ordinary commercial hot-rolled nickel sheet, is firmly bonded to the steel, and the mechanical properties of the composite plate are such that it can be treated as a solid steel plate, practically any formed shape being obtainable from it. For heavy plant, where a separate lining of nickel is at present employed, the use of the solid material presents obvious

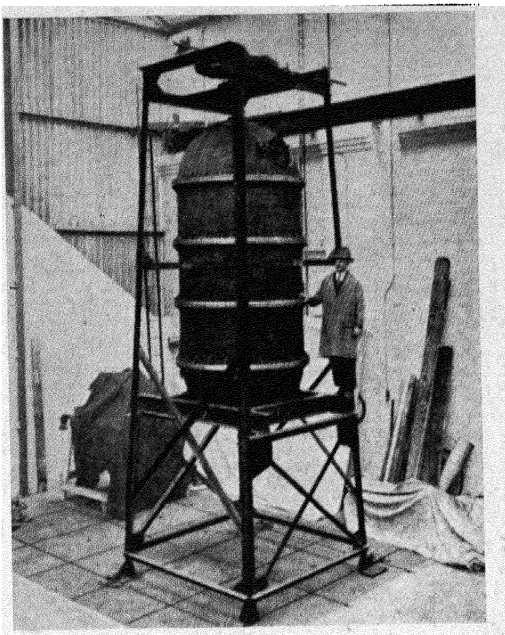


FIG. 21.

[*See page* 27.

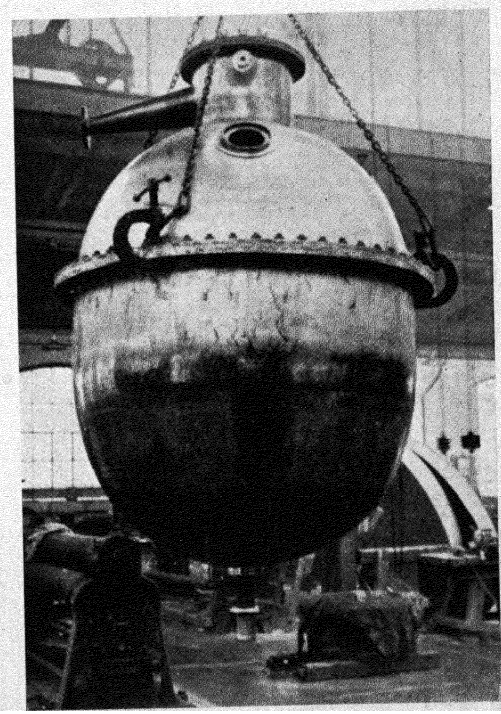


FIG. 22.

[*To face page* 34.

advantages, particularly where heat-transfer is of some importance. Pure nickel and steel have practically the same coefficients of expansion, an important advantage during manufacture, whilst, in service, when changes in temperature are involved, no strains are set up.

It should be pointed out that the surface of the nickel on nickel-clad steel plates is that obtained as a result of hot-rolling and it should not be confused with the bright and lustrous surface of thinner cold-rolled nickel sheets. The corrosion-resistance of the hot-rolled nickel surface is, however, quite as good as (and under certain conditions may even be superior to) that of cold-rolled nickel. For the heavy type of plant for which nickel-clad steel is recommended, this surface is entirely suitable.

Making Nickel-Clad Steel Plates.

The process of manufacturing these plates is essentially one of hot-rolling. Careful attention to detail is required from start to finish, particularly in the heating-up process prior to hot-rolling. A large and powerful mill is necessary for the rolling operation.

First of all, steel and nickel slabs, of thicknesses calculated to give the required ratio in the finished plate, are specially prepared and fixed together so that no separation can occur during rolling. After bringing the composite pack up to the high temperature necessary for rolling, it is quickly transferred to the rolls and reduced to the required thickness.

At the temperature of rolling, the nickel and steel surfaces weld together under the pressure of the rolls and form a strong intermetallic bond so that no separation of the nickel from the steel can subsequently occur.

Nickel-clad steel plates are available in a variety of sizes. It has been found, however, that $\frac{1}{4}$-in. thick plate, having a layer of 0·025-in. nickel (10 per cent. of the total thickness), is satisfactory for most requirements and this thickness of plate is standardised for many applications.

Plates down to $\frac{3}{16}$ in. can be rolled, but to ensure adequate protection of the steel at this thickness, the nickel layer is maintained at 0·025 in. Standard thicknesses in excess of $\frac{1}{4}$ in. are available in steps of $\frac{1}{16}$ in. up to $\frac{1}{2}$ in., and in steps of $\frac{1}{8}$ in. from $\frac{1}{2}$ in. to 1 in., the thickness of nickel being progressively increased to a maximum of 0·060 in. for 1-in. thick plate.

Applications of Nickel-Clad Steel.

Textile Industry.

Typical examples of the use of nickel-clad steel are viscose refining and homogenising tanks used in the artificial silk industry, dyestuff

mixing tanks, dye tanks, and other parts of dyeing plant, peroxide bleaching kiers (where the suitability of pure nickel for handling peroxide has led to extensive employment of nickel-clad steel), size-mixing kettles and transport tanks used in connection with cloth weaving and, of course, for any plant handling caustic soda, etc.

Soap Manufacture.

Apart from its suitability for handling caustic alkalies, nickel-clad steel has further uses in soap-manufacturing equipment. It is in use for soap-cooling plates, for storage tanks and for soap-boiling kettles. Pressure vessels for handling palm oil are also being made in nickel-clad steel. In all its applications for handling soap or soap products, the nickel surface ensures that no harmful metallic impurities shall enter and impair the quality of the soap.

Miscellaneous Applications.

Varnish Kettles.—The conditions to which these vessels are subjected are severe, and demand a material which will resist deterioration by heat and products of combustion, and also by corrosion from boiling oil and gum, so that there is no discoloration of the varnish from metallic contamination. The steel side of the nickel-clad steel plate gives protection from furnace flames and gases and the nickel side in contact with the varnish is unattacked.

For transporting and handling essential oils, phenol and various products containing fatty acids, nickel-clad steel is finding a rapidly extending field of application. This applies also to the food industry where it can be used for equipment handling fruit and vegetable juices, butter, oleo-margarine, syrups, beer, organic acids, etc.

Nickel-clad steel has considerable application in the leather industry for sulphonating equipment, in the paper industry for parts of soda-recovery plant, in salt manufacture for driers, etc., and for tanks handling photographic emulsions, metal polishes, alum, sodium silicate, rubber latex, etc.

Fabricating Plant in Nickel-Clad Steel.

Cold operations such as bending, flanging, forming, shearing, bevelling and the like are performed exactly as in common steel plate-work. If the cold working is severe, such as in pressing heads and dye work, plates softened by annealing are generally required. Heating the plate to a temperature of 870°–930° C., holding at this temperature for two or three minutes and cooling in air, gives satisfactory annealing, providing the necessary precautions are taken in the furnace.

Joining methods are of especial importance in fabricating plant

from nickel-clad steel. The nickel surface must remain unbroken and continuity is obtained by welding with nickel. If riveting is used in conjunction with welding, nickel rivets must, of course, be used. Any iron edges left unprotected tend to set up galvanic action with the nickel and premature failure is promoted: hence it is important that this factor be stressed in connection with the fabrication of this material. For example, in lap welding, the bare iron edge on the nickel side must be protected by depositing nickel on it by welding. Small fittings such as tubes, cocks, etc., to be used in connection with nickel-clad steel plant should be made of solid nickel if they are in contact with the corroding medium. Large fittings may be fabricated from nickel-clad steel.

Welding can be carried out either by electric or gas welding. The metallic arc method, being most generally employed for heavy steel platework, is readily adaptable to nickel-clad steel. In using the arc method, the mild steel side is first welded almost to the full thickness of the plate, using the usual preparation method employed for steel. In welding the nickel side, satisfactory welds are obtained only by adhering to the closely defined methods already established for nickel. Reliable results are also obtained by the carbon arc method, particularly for vertical joints.

Oxy-acetylene welding is also suited to nickel-clad steel. As in metallic arc welding, the steel weld is usually made first by the normal method employed for steel. In welding the nickel, however, it is important to maintain a slightly reducing flame. A flux may be used if preferred, but is not essential. Welding by the atomic hydrogen method has also produced excellent welds in nickel-clad steel.

Nickel-Molybdenum Alloys.

The Haynes Stellite Co. have developed a series of nickel-molybdenum-iron alloys which are remarkably resistant to many corrosive materials. They are Hastelloy "A," "C" and "D."

Hastelloy A.

Hastelloy A is a nickel-molybdenum-iron alloy of high strength and good ductility, developed primarily for its resistance to hydrochloric (muriatic) acid. It may be forged and rolled into sheet or other simple shapes, is machinable, makes excellent castings, and may be welded by either the oxy-acetylene or electric arc methods. In addition to being strong at ordinary temperatures it is unusually strong at high temperatures, withstanding a load of 1500 lbs. per sq. in. at 900° C. (1652° F.) with a creep not greater than 1 per cent. per year. Where the creep must be less than 1 per cent. per year, the maximum load will be proportionately less. Hastelloy A may be

softened or annealed by heating to a high temperature and quenching in water. Quenching from 1100 to 1150° C. (2012 to 2102° F.) will give the best results. Cold work hardens the alloy and raises the yield point and ultimate strength with a corresponding reduction in ductility.

Hastelloy A is particularly resistant to hydrochloric acid. It withstands this acid in any concentration and at any temperature up to the boiling point, although the rate of attack increases with the temperature. It is resistant to sulphuric acid of practically any concentration at temperatures up to 70° C. (158° F.) or slightly higher, but at the boiling point of acids containing 50 per cent. or more sulphuric acid the attack becomes considerably more rapid. It is also resistant to acetic, formic and certain other acids, but not to nitric acid, and its use where free chlorine is present is not recommended. It stands up well in a salt spray and is practically unattacked by alkalis.

Physical Properties.

Specific gravity, forged	8·8
Weight per cu. in., lbs.	0·318
Melting range	1300–1330° C. 2372–2426° F.
Coefficient of expansion, ins. per ° C. from 200 to 600° C.	0·0000107
Coefficient of expansion, ins. per ° F. from 392 to 1112° F.	0·0000059
Thermal conductivity, per ° C., cal./sq. cm./cm./sec.	0·04
Thermal conductivity, per ° F., B.Th.U./sq. ft./in./hr.	116
Electrical resistivity, microhms/cm. cube at 24° C.	126·7
Electrical resistivity, microhms/in. cube at 75° F.	49·8
Electrical conductivity, per cent. that of copper at 24° C. (75° F.)	1·4
Forgings, as forged :—	
Yield point, lbs./sq. in.	50,000–115,000
Ultimate strength, lbs./sq. in.	100,000–150,000
Elongation in 2 ins., per cent.	18–48
Reduction in area, per cent.	18–35
Fully annealed :—	
Yield point, lbs./sq. in.	47,000–52,000
Ultimate strength, lbs./sq. in.	110,000–120,000
Elongation in 2 ins., per cent.	30–48
Reduction in area, per cent.	35–54
Impact, Izod, ft.-lbs.	45–50
Brinell hardness, average	207

Hastelloy C.

Hastelloy C, a nickel-molybdenum-chromium-iron alloy, is a modification of Hastelloy A. The effect of this modification on the physical properties has been to reduce the malleability and it is not feasible to work the alloy either hot or cold on a commercial scale. Good

castings may be made, however, and these are machinable at moderate cutting speeds. The alloy is tough, but not hard, and the toughness makes it necessary to use low cutting speeds in machining. Speeds of from 20 to 40 surface ft. per min. are recommended and the feed should be moderate. Hastelloy C may be welded by either the oxy-acetylene or electric arc methods.

Hastelloy C is particularly resistant to strong oxidising agents such as nitric acid, free chlorine and acid solutions of salts such as ferric and cupric salts. It has practically the same resistance to hydrochloric acid as Hastelloy A, and it is slightly more resistant to sulphuric acid. It is also resistant to acetic, formic and sulphurous acids and quite resistant to phosphoric acid.

Physical Properties.

Specific gravity		8·94
Weight per cu. in., lbs.		0·323
Melting range		1270–1305° C. 2318 2381° F.
Coefficient of expansion	ins. per ° C. from 200 to 600° C.	0·0000142
	ins. per ° F. from 392 to 1112° F.	0·0000079
Thermal conductivity	per ° C., cal./sq. cm./cm./sec.	0·03
	per ° F., B.Th.U./sq. ft./in./hr.	87
Electrical resistivity	microhms/cm. cube at 24° C.	133·0
	microhms/in. cube at 75° F.	52·4
Electrical conductivity, per cent. that of copper at 24° C. (75° F.)		1·3

Castings :—

Yield point, lbs./sq. in.	42,000–47,000
Ultimate strength, lbs./sq. in.	55,000–79,000
Elongation in 2 ins., per cent.	3–11
Reduction in area, per cent.	5–15
Brinell hardness, average	217

HASTELLOY D.

Hastelloy D is a cast alloy composed of nickel, silicon, copper and aluminium. It is resistant to hot and cold sulphuric acid. The alloy is strong and tough, having a high transverse strength with good deflection. Good castings can be made, but the alloy is not workable either hot or cold. It is not machinable in the usual sense of the term, but simple machining operations such as the facing off of a flange can be done with tungsten-carbide cutting tools if grinding is not convenient. Welding can be done by either the oxy-acetylene or electric arc methods, but a special flux is of considerable assistance.

In addition to being resistant to sulphuric acid, Hastelloy D shows good resistance to hydrochloric acid at moderate temperatures as well as to acetic, formic and phosphoric acids. It is not resistant to nitric acid or to free chlorine.

Physical Properties.

Specific gravity		7·8
Weight per cu. in., lbs.		0·282
Melting range		1110–1120° C.
		2030 -2048° F.
Coefficient of expansion	ins. per ° C. from 200 to 600° C.	0·0000116
	ins. per ° F. from 392 to 1112° F.	0·0000064
Thermal conductivity	per ° C. cal./sq. cm./cm./sec.	0·05
	per ° F., B.Th.U./sq. ft./in./hr.	145
Electrical resistivity	microhms/cm. cube at 24° C.	113·0
	microhms/in. cube at 75° F.	44·5
Temperature-resistance coefficient	per ° C.	0·0013
	per ° F.	0·00072
Electrical conductivity, per cent. that of copper at 24° C. (75° F.)		1·6
Brinell hardness		364

Monel Metal.

This alloy contains about two-thirds nickel, and the balance copper except for a small percentage of other metals, chiefly iron, and manganese with small and carefully controlled quantities of silicon and carbon. It takes its name from that of Mr. Ambrose Monell, who was president of the International Nickel Company at the time the alloy was first produced in 1905. This company had for many years been engaged in mining and smelting the nickel ores from the Sudbury district of Ontario, Canada. One very large belt of ore was found to contain, in addition to the nickel, a relatively high percentage of copper. As the separation of these metals was both difficult and expensive it was decided to smelt out the two metals simultaneously and examine the commercial merits of the resulting alloy. This alloy was found to possess approximately the composition given above, and on investigation it showed itself to be superior in many ways to pure nickel, both in its mechanical properties, and its resistance to many corrosive media.

Physical Properties.

Specific gravity		8·80
Melting point		1350° C. (2640° F.)
Specific heat	20–400° C.	0·127
Coefficient of linear expansion	25 -100° C.	0·000014
	25–300° C.	0·000015
Heat conductivity		0·13 B.Th.U./sq. ft./in./° F./sec.
Young's modulus		26×10^6

Mechanical Properties.

Note.—Monel metal cannot be hardened by thermal treatment, but its mechanical properties can be enhanced by cold working, and for certain purposes it is definitely advantageous to employ it in the hard-rolled or hard-drawn condition. There are, however, varieties of this metal, i.e. silicon Monel and "K" Monel, which do readily respond to thermal hardening.

TABLE 7.

MONEL METAL—MECHANICAL PROPERTIES.

Type.	Condition.	Ultimate Strength (tons/sq. in.).	Yield Point (tons/sq. in.).	Per cent. Elongation on 4 $\sqrt{\text{Area}}$.	Hardness.
Hot-rolled rounds, squares, rectangles or hexagon: forgings	Normal	34–38	15–18	35	120–140 Brinell
Cold-drawn rounds or hexagons	(A) Hard	40–45	35–40	18–20	190–210 Brinell
Cold-rolled squares or rectangles	(A) Annealed	30–35	14–17	35	110–120 Brinell
Full-finish sheet	Normal	30–33	14–16	30	18–20 Scleroscope
Cold-rolled sheet or strip	(A) Hard	45–50	40–45	15	38–42 Scleroscope
	(A) Annealed	29–30	14–16	30	16–18 Scleroscope
Cold-drawn wire	(A) Hard for springs	55–60	50–55	5–10	—
	(A) Annealed	29–33	14–16	35	—
Castings:— Normal quality	As cast	19–23	12–15	12	110–130 Brinell
Special silicon quality	Thermally hardened	38–40	22–25	10–15	190–210 Brinell

Monel metal can be cast, or forged, machined, welded by either oxy-acetylene or electric processes, soft or silver soldered, brazed drawn into wire, and spun. Certain of these processes require a little modification of the technique ordinarily applied to mild steel or copper, but such changes are in the main well within the capacity of skilled operatives after a little experience.

Corrosion Resistance.

Monel metal is not seriously affected by the elements, and is unaffected by sea and estuarine waters, even in tropical countries.

It is impervious to the action of alkalis, and is in consequence much used for evaporators and other plants in the production and recovery of caustic soda. It is but little affected by ammonia, and excluding nitric and sulphurous acids, it offers useful resistance to acids at concentrations and strengths usually found in industry.

Monel metal centrifugal baskets are widely used for drying sulphate of ammonia, and wedge wire screens in this alloy are frequently used for freeing fine-washed coal from dust and water. It is also much used for pickling plants, drying plants, and for pump contact parts in the handling of hot tar and tar products.

Monel metal filter cloth is being increasingly used, and this alloy is also adopted for the lining of autoclaves for the manufacture of dyestuffs. Another application is in plant for the paint and varnish industry, including contact parts of colloid mills.

Fig. 23 shows a group of pump impellers for handling corrosive liquors.

A recent development in connection with Monel metal is the alloy known as " K " Monel metal. By the addition of aluminium and careful adjustment of the composition, this alloy can by heat treatment be rendered hard and strong, or soft at will, whilst still retaining the corrosion-resisting properties of Monel metal.

Physical Properties of " K " Monel Metal.

Density		8·58
Weight, lb./cu. in.		0·31
Melting point		1315/1345° C.
Specific heat (20–400°)		0·127
Coefficient of expansion	25–100° C.	0·000014 per 1° C.
	25–300° C.	0·000015 „ „
	25–600° C.	0·000016 „ „
Elastic modulus (tension)		26,000,000 lbs./sq. in.

Mechanical Properties of " K " Monel Metal.

" K " Monel metal can be supplied in four different conditions :—

(*a*) as hot-rolled and softened ;
(*b*) as hot-rolled, softened and thermally hardened ;
(*c*) cold-worked and ready for thermal hardening after machining or fabrication ;
(*d*) cold-worked and thermally hardened.

The latter condition, whereby thermal hardening is superimposed on " cold-worked " hardness, gives the greatest degree of hardness and the highest ultimate strength.

Typical properties for these three conditions are shown in the following table :—

Condition.	Ultimate Strength (tons/sq. in.).	Yield Point (tons/sq. in.).	Elongation (per cent. on 2 ins.).	Izod (ft./lb.).	Brinell.
Hot-rolled and softened	39	19	35	100	140
Hot-rolled, softened and thermally hardened	60	43	30	70	270
Cold-worked and thermally hardened .	72	60	15	50	320

Heat-Treatment.

To soften " K " Monel metal it should be heated to a temperature of approximately 800° C. for a sufficient time to ensure complete soaking, and quenched in water or oil.

To harden, the material should be reheated to a temperature of 590° C. and slowly cooled. The degree of hardness developed varies to some extent with the time of exposure at this temperature. Four hours is generally sufficiently long to develop practically full hardness, but slightly increased hardness results from holding at this temperature for six or eight hours. The hardening treatment can be applied to softened, hot-rolled or cold-worked material.

Availability.

Initial demands have naturally been mainly for hot-rolled or cold-drawn rod, wire, forgings and turbine blade profiles, and the production of these is already established.

Uses.

The uses of " K " Monel metal are essentially those which demand high strength and/or hardness combined with high corrosion resistance or immunity from rusting.

Typical examples which may be cited are, valves and seats in pumps handling oil containing brines and sodium sulphide (here " K " Monel has outlasted high alloy corrosion-resisting steels with a service life of 4 to 1 in favour of " K " Monel), valves and seats on " starting-air " bottles for Diesel engines, blades for paper-making machinery, and impulse blading of steam turbines, operating at high pressures and superheats.

In addition, its " non-magnetic " high-strength qualities make it suitable for aircraft, instrument or radio work, where corrosion resistance, coupled with high strength or hardness, is essential for parts which must be non-magnetic.

Other Alloys of Nickel.

(1) Nickel-Iron Alloys.

The addition of nickel to pure iron gives a continuous series of alloys possessing many interesting and unique properties which are briefly as follows :—

Magnetic Properties.

The alloys in this series possess unusual magnetic and electrical properties, for the addition of nickel to iron results in a gradual reduction in the magnetic properties of the latter, until at about 28 per cent. to 30 per cent. of nickel, the alloys are practically non-magnetic. These alloys, which in commercial form generally contain a certain amount of carbon, and are accordingly high nickel steels, possess good mechanical strength, and are consequently of increasing interest in electrical engineering. When used for structural portions of machines and plant which are subjected to fluctuating magnetic fields, the energy loss due to electro-magnetic influence is reduced to a minimum and interference with the magnetic fields is eliminated. This is of importance in applications such as end-plates for alternator rotors, and for parts for use with switch gear and power transmission systems. These alloys, under suitable conditions, may be readily worked and possess a high degree of corrosion resistance.

The further addition of nickel to iron results in a series of alloys capable of developing high magnetic permeability, when suitably heat-treated, coupled with a low hysteresis loss, a combination of properties rendering the alloys of great importance in special branches of electrical engineering. The magnetic permeability of these alloys is high over a wide range of nickel content, and reaches a maximum at about 78·5 per cent. of nickel. The best of these alloys, after suitable heat treatment, have been found to possess maximum permeabilities many times that of the best alloys previously known. Their permeability is obtained at low field values with a saturation only slightly less than that of pure iron ; this will approach magnetic saturation in the earth's field.

Investigation of alloys of this type has resulted in the development of many modifications such as the various " Permalloys," " Mumetal," " Rhometal," " Hypernik," " Radio Metal," etc.

Dilatation Properties.

A further property of this series of alloys lies in a wide range of variation of thermal expansion. The coefficient of expansion of the alloys with nickel additions above 25 per cent. falls rapidly, until in

the region of about 35 per cent. a minimum is reached at which it becomes practically zero. With further additions of nickel, the coefficient increases again, rapidly at first, then more gradually, to the value obtained with pure nickel itself.

The alloy of minimum coefficient, well known under the name of "Invar," is used for clock pendulums and measuring tapes, and in the construction of thermostats and similar control apparatus, where the differential expansion between this and other materials, such as copper, is usefully employed to control applied energy.

The demand for alloys showing special coefficients of expansion, as, for example, in making glass to metal joints and in inserting lead-in wires for electric lamps, is met by the use of alloys in this series, a wide range of coefficients of expansion being available at different compositions of nickel.

(2) Nickel-Chromium Alloys.

While pure nickel itself shows a fairly good resistance to oxidation at temperatures below 600° C., this property is greatly improved by the addition of chromium. The improvement is progressive up to at least 20 per cent. chromium, at which composition an alloy is obtainable which will give a very long life, when exposed to oxidation at temperatures up to 1000° C., while a useful period of service is possible up to about 1200° C. This remarkable resistance to oxidation results from the formation of a smooth, closely adherent, thin oxide film, which protects the underlying metal from further attack.

Another advantage of adding chromium is that the electrical resistance of the material progressively improves, the 80/20 alloy having a resistance of more than eleven times that of nickel. This is accompanied by a low-temperature coefficient.

These useful properties are further enhanced by really remarkable tensile properties. At ordinary room temperatures the 80/20 alloy has a strength of about 50 tons per sq. in., and at elevated temperatures it still retains high tensile properties. Its limiting creep stress, which is the property of importance at elevated temperatures, is much higher than that of any of the other non-ferrous alloys, although it is approached by some special nickel-chromium-iron alloys. (See also Chap. IV, p. 131.)

The combination of resistance to oxidation, high electrical resistance and strength at high temperatures, has resulted in these alloys being widely adopted for electrically heated appliances, which have to operate continuously at temperatures of over 850° C. In the electrically heated muffle type of furnace the alloys are used in the form of wire or tape for the heating elements, as sheet or cast plates for the furnace bottoms, as cast grids for protecting the heating elements

from coming into contact with the charge, as tubes for thermocouple sheaths and as wire or tube for one of the thermocouple elements. They are also the standard wire material for the heating elements of domestic fires, and many other small domestic appliances.

While the straight nickel-chromium alloys are probably the best of the heat-resisting materials available, a wide range of nickel-chromium-iron alloys is now in use where slightly less-severe conditions prevail. These alloys vary in nickel content from 20 to 67 per cent., in chromium from 12 to 25 per cent., the remainder being iron. Many such alloys containing small quantities of iron are used for similar purposes to the 80/20 nickel-chromium alloy, usually where the working temperatures are lower than 1000° C., while those containing small quantities of iron, together with other alloy additions, are being employed for service conditions where temperatures of approximately 1000° C. prevail. Typical applications include carburising boxes, retorts, conveyor chains in furnaces, furnace rails, furnace gratings, boiler baffle plates and supports for superheater tubes.

Fig. 24 shows a large calcination retort in nickel-chromium heat-resisting alloy for service at 800–1000° C. The retort weighs nearly two tons, and the length between the bearings is about 11 ft. 0 in.

Inconel.

Inconel is a relatively new alloy possessing good mechanical properties combined with important corrosion- and heat-resisting properties.

It consists of approximately 80 per cent. nickel, 14 per cent. chromium and 6 per cent. iron. The physical and mechanical properties of this alloy are as follows :—

Inconel.

Physical Constants.

Specific Gravity	8·55
Coefficient of expansion :—	
100–200° F. range—	
per ° F.	0·0000064
per ° C.	0·0000115
100–1400° F. range—	
per ° F.	0·00000896
per ° C.	0·0000161
Heat conductivity	3·5 per cent. that of copper
Specific heat (77–212° F.)	0·109
Melting point :—	
° F.	2540
° C.	1388
Modulus of elasticity	32,000,000
Modulus of torsion	10,300,000

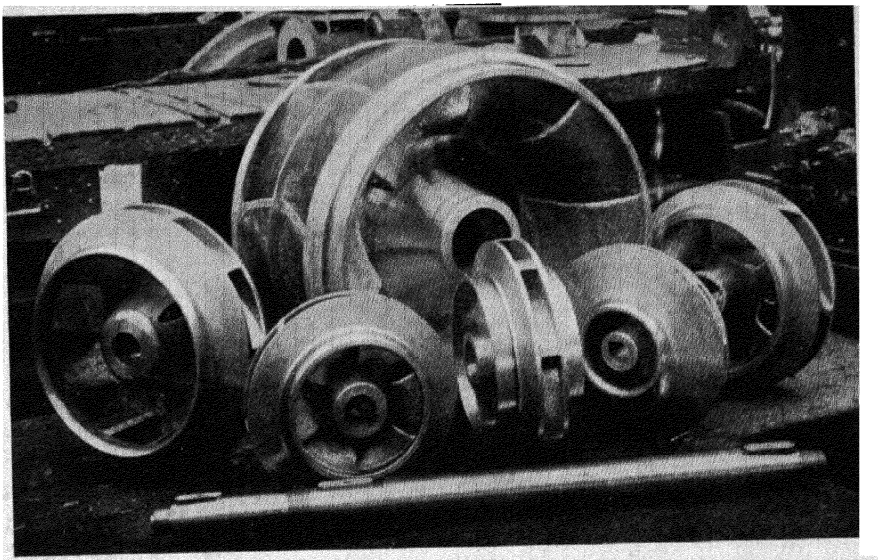


FIG. 23.—Monel Metal pump impellers.

[*See page* 42.

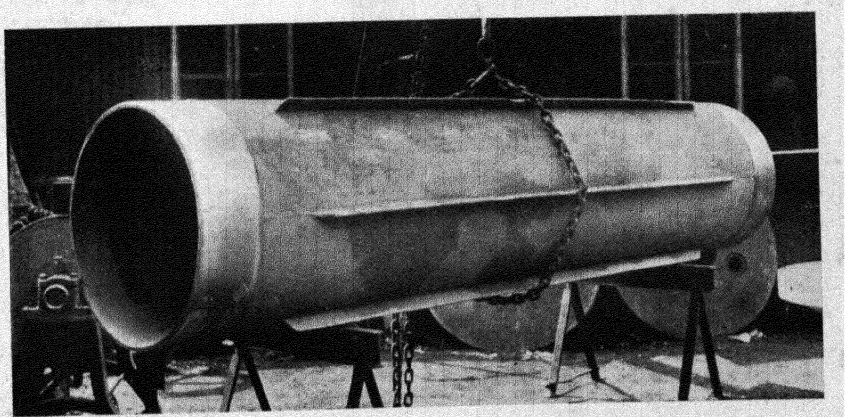


FIG. 24.—Large calcination retort in nickel chromium alloy by the Cronite Foundry Co., Ltd.

[*To face page* 46.

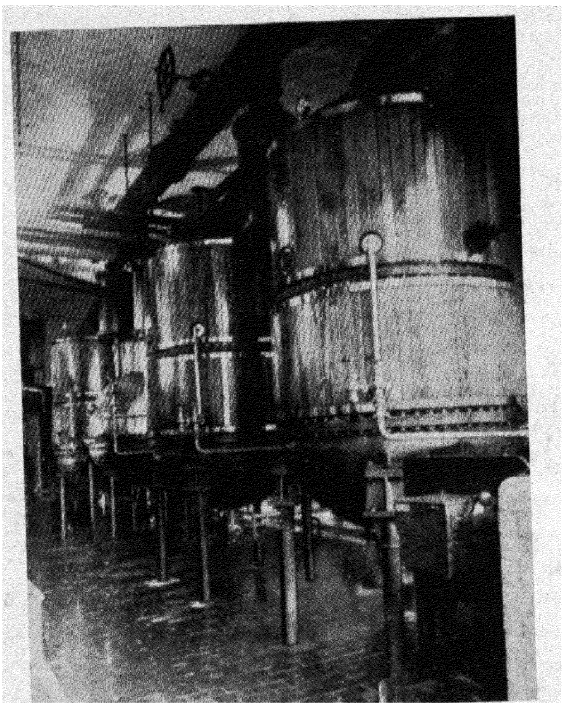


FIG. 25.—Jacketed stills made in "Inconel."

[*To face page* 47.

TABLE 8.

INCONEL.

Mechanical Properties.

	Tensile Strength (tons/sq. in.).	Yield Point (tons/sq. in.).	Elongation (per cent.).
Sheet and strip annealed	35–40	13–15	45–55
Rod :—			
Annealed	35–40	13–15	45–55
Cold drawn	45–50	35–40	20–30
Wire :—			
Annealed	35–40	13–15	45–55
Spring temper	78–85	—	—

Inconel can be obtained in sheet, strip, rod, wire and cast form, and it can be welded, riveted, brazed, pressed and soldered. It offers practical immunity from heat oxidation at temperatures up to 900° C.

This alloy is being increasingly used in the food processing industry, particularly milk and milk products. Fig. 25 shows vessels made of this interesting nickel alloy.

Aluminium.

Physical Properties.

Specific gravity rolled or drawn		2·703
Cast		2·703
Melting point	658·7° C.	1217·7° F.
Coefficient of linear expansion :—		
per ° C.		$22·6 \times 10^{-6}$
per ° F.		$12·5 \times 10^{-6}$
Specific heat at 20° C.		0·214
Thermal conductivity at 18° C.		0·504 cal./cm.³/° C./sec.

Mechanical Properties of Aluminium.

Tensile strength of sheet, tons/sq. in. :—	
Annealed	5–6½
Half-hard	7–8½
Hard	9
Brinell hardness (cast)	23–28
Elongation in 2-in. pure castings sand	20–30
„ „ „ „ „ chill	30–40
„ „ „ pure sheet annealed	12–40
„ „ „ half-hard	5–12
„ „ „ hard	2–8
„ „ „ H.D. wire	4–7
Modulus of elasticity	$9·9 \times 10^6$
Poisson's ratio	0·36

The commercial production of aluminium necessitates cheap electric power and an abundant supply of bauxite. Since the pure metal can only be obtained from the purest of raw materials it is first necessary to purify the bauxite, and this is done by either the Bayer or the Pedersen process. The former consists in treatment of the ore under pressure with caustic soda, conversion into aluminium hydrate, and calcination in a rotary furnace at a temperature of 1100° C. The Pedersen process is employed at Höyanger, Norway, and consists in smelting the bauxite with limestone and coke in large electric furnaces. The slag formed contains the bauxite in the form of aluminates of lime, and the iron compounds of the bauxite are converted into pig iron of good quality. The slag is pulverised and treated with soda solution, and finally nearly pure aluminium hydrate is precipitated and calcined. (*Times—Trade and Engineering*, March, 1937.)

The reduction of alumina is carried out by electrolysis at a temperature of 1800° F. in a melt consisting of a solution of alumina in molten cryolite. The metal produced gathers at the bottom of the electrolytic cell and is tapped off at intervals.

Joining Methods for Aluminium.

The requirements of the many industries in which aluminium and its alloys are finding an increasing number of applications have stimulated the development and improvement of joining methods of all kinds, but because of the characteristic properties of the metal, mainly its avidity for oxygen and its high thermal conductivity, not all of these methods have been found commercially successful. Of the various welding processes, oxy-acetylene welding holds by far the most important place, although oxy-hydrogen, atomic hydrogen, and arc welding are making material progress, while electric resistance welding machines specifically designed for aluminium and its alloys have been made available within the past few years.

Soldering, again, presents considerable difficulties on account of the oxide coating which is invariably formed on the surface of aluminium, while the problem of producing a soldered joint in aluminium which will not suffer the ill effects of corrosion has still to be solved. Three distinct methods of soldering are, however, in current use, and will be described in due course.

In riveting aluminium and its alloys it is necessary to employ rivets of the same composition as the material being joined, and the technique required is quite different from that employed in riveting steel.

Welding of Aluminium.

A considerable proportion of the total amount of aluminium welding carried out consists of the oxy-acetylene welding of aluminium sheet,

particularly in the production of kitchen utensils and plant for the food processing industries. For these purposes the welding rod should be of the same composition as the sheet and of the same diameter as the thickness of the sheet. The edges of sheets less than $\frac{1}{8}$ in. in thickness should have the two edges flanged, or turned up at right angles, for about $\frac{1}{16}$ in., the metal in the flanges being used instead of a welding rod. Above this thickness, the edges should be bevelled to give a clean vee of about 80° inclusive angle, and the metal must be thoroughly cleaned for a distance of about $\frac{3}{4}$ in. on each side of the joint with either emery paper or a wire brush. The oxide film is removed with a flux, many kinds of which are now on the market. The speed of welding is greater than in the case of mild steel, and must be increased as the job proceeds and the metal becomes hotter. After welding, the excess flux must be carefully removed by washing with warm water, else corrosion will result.

Electric Arc and Atomic Hydrogen.

During the past few years the arc welding of aluminium has been successfully carried out, although the intense local heating is a disadvantage with this metal, and satisfactory electrode coatings are difficult to obtain. Arc welding, however, permits of a much higher speed of welding, and large objects can be welded without preheating.

The atomic hydrogen process utilises the heat of combination of hydrogen atoms produced by passing the gas through a tungsten arc. A very high temperature—over 3700° C.—is attained, and no oxygen is required. The atomic hydrogen also acts as a flux in many cases, but with aluminium the usual type of flux is necessary. The process, however, is not as yet very widely used for welding aluminium, and it is difficult to form a clear opinion of its potentialities in this connection.

Spot and Seam Welding.

For quantity production work in the joining of components made from sheet or strip, the use of the resistance welding processes has made exceptional headway during the past few years. These processes, which depend upon the heating effect of a low-voltage alternating current passing through the pieces of metal which are to be joined, was developed originally for use with mild steel, but to-day it is possible to spot and seam weld brass, bronze and aluminium quite satisfactorily. The difficulties at first encountered with the non-ferrous metals lie in their much greater thermal and electrical conductivities, which naturally make it necessary to use much higher currents, while the time of application of the current must be as short as possible. With the development of more precise methods of control—automatic devices for applying and switching off the welding current—the

resistance welding of aluminium has become more or less commonplace, and the process is used extensively, particularly on the Continent, in the construction of aeroplanes, flying boats, railway rolling stock, etc.

One particular machine, developed in France, enables the pressure between the electrodes to be varied. From a high initial value, to force the surfaces into good contact, the pressure falls considerably during the actual welding operation, and rises again after the current has been cut off, thus giving a type of forging operation to the weld.

Long seams may be welded by means of a succession of spot welds, the welding electrodes in this case consisting of rollers. In a thyratron-controlled seam welder just developed no fewer than 1500 welds a minute can be made, the speed of welding varying from 2 ft. 6 ins. to 10 ft. a minute, according to the material.

Soldering.

There are three distinct methods of soldering aluminium and its alloys, known respectively as hard or high-temperature, soft or low-temperature and reaction soldering. In the first method, the solder consists generally of an aluminium-silicon alloy, and the operation is carried out at a temperature of 550–600° C. A flux must be used to remove the oxide film, and a gas blowpipe is employed for heating. Otherwise the process does not differ materially from the soldering of brass.

In soft soldering a much lower temperature—about 350° C.—is employed, and the solder consists usually of a tin-zinc alloy, sometimes containing a small percentage of aluminium. In spite of a popular impression to the contrary, no material difficulty is involved in the soft soldering of aluminium. Where difficulty is encountered, however, is in the production of a soldered joint in aluminium capable of withstanding corrosion. This has never yet been really achieved, and soft-soldered joints can be employed only in cases where there is no likelihood of corrosion occurring to any appreciable extent.

A process which has recently been developed, and has become known as reaction soldering, depends upon the chemical deposition of the soldering metal upon the joint from a mixture of salts, which also behave as a flux. The mixture, consisting, for example, of zinc chloride, ammonium bromide and sodium fluoride, is spread on the parts to be soldered and heated by means of a blowpipe. Chemical reaction takes place, resulting in the deposition of molten zinc on the joint. An excellent joint is obtained in this way, and is reasonably resistant to corrosion. The disadvantages of the method lie in the evolution of copious white fumes and the spreading of the salts over the surface of the articles to be joined. The joint must be washed in warm water to remove these salts.

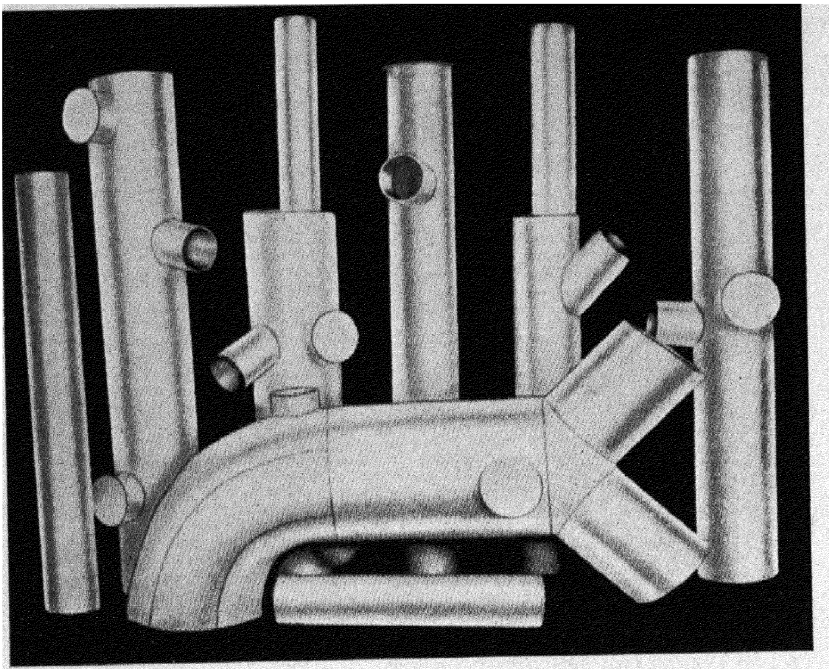


FIG. 26.

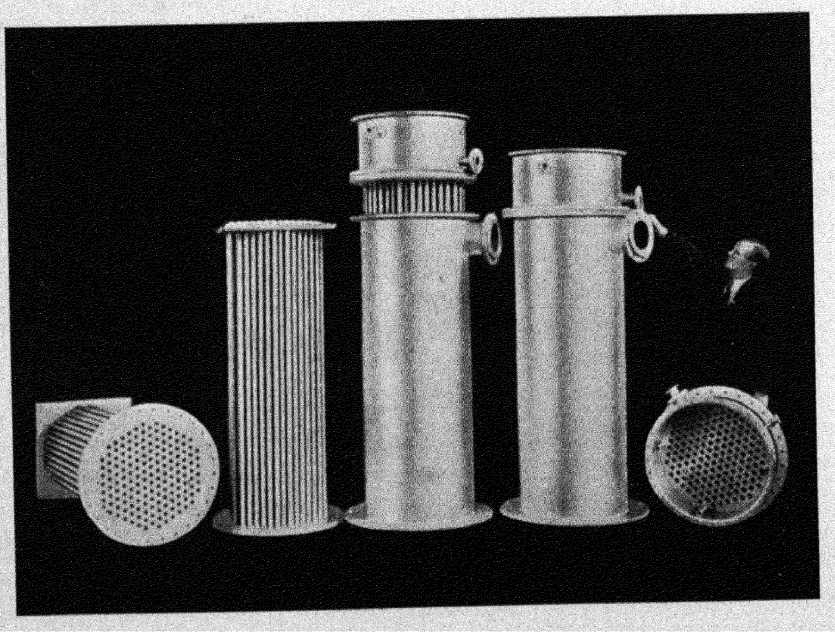


FIG. 27.

[*To face page* 51.

Riveting.

In riveting, again, only material of the same composition as the parts to be joined must be employed. One important advantage of this method, however, is that there is no danger of impairing the properties of heat-treated alloys, as in welding. The process is normally carried out cold, but Duralumin rivets may be driven hot provided that the temperature used is the normal heat-treatment temperature of the alloy. (For design, see page 231.)

In general, a round-headed rivet is employed, and the overlap should be not less than four or five times the diameter of the shank. It is customary in riveting a long seam to " tack " the two sheets by means of a few rivets here and there before completing the line, in order to avoid the undue spreading of the material.

A recent development in aluminium riveting is the countersunk method, employing Duralumin rivets. This method, which was employed in the construction of the Empire flying-boats, gives a clean, smooth appearance to the largest of riveted surfaces. Fig. 26 shows some fabricated pipe work in aluminium, and Fig. 27 shows a series of condensers in aluminium. These illustrate the variety of ways in which aluminium may be fabricated.

Use of Aluminium in Chemical Engineering.

Aluminium is a metal which is very reactive chemically. It owes its corrosion-resisting properties to the film of oxide which forms readily on the surface and can be strengthened by suitable treatment such as anodic oxidation. The resistance of aluminium to corrosion is therefore dependent upon the maintenance of this film or its renewal through the action of the substances to which it is exposed. Purely mechanical agencies may also exert an effect, as, for example, where a rapid circulation of liquid may result in a constant abrasion of the film and continued attack of the metal surface thus repeatedly exposed. Amalgamation with mercury also prevents the formation of the oxide film, and for this reason it is essential to guard against the accidental introduction of mercury into aluminium plant through the breakage of thermometers.

Minimum Purity.

The formation and maintenance of the oxide film and the consequent resistance of the metal to corrosion depend to a great extent upon the purity of the aluminium. For chemical plant under corrosive conditions it is desirable to use aluminium with a minimum purity of 99·8 per cent., the absence of copper and zinc as impurities being particularly important. Where aluminium plant is manufactured in works which deal also with other metals such as copper and brass,

special care has to be taken to prevent small particles of these metals from being rolled or hammered into the surface of the aluminium, as they would set up a local electrolytic action and severe corrosion of the aluminium. Similarly, copper or bronze parts should never be incorporated in aluminium plant on account of the local electrolytic action which may be set up.

Aluminium alloys are extensively used in many industries on account of their improved mechanical properties, which may be 50–100 per cent. better than those of pure aluminium. In the chemical industry, however, the use of these alloys is much more restricted, as the corrosion resistance of aluminium alloys is generally inferior to that of the pure metal and only a limited number of alloys have found any substantial application. Considerable improvements have taken place in recent years in the production of aluminium alloys with satisfactory corrosion-resisting properties, and there is no reason to doubt that further research and experiment will result in further advances. The length of time required to establish the corrosion-resisting properties of a metal in industrial practice necessarily means that the testing and introduction of a new alloy proceed slowly.

In general, it may be said that the alloying elements which do not reduce the corrosion resistance of aluminium are magnesium, chromium, manganese and antimony. Of the wrought-aluminium alloys which have a satisfactory resistance to corrosion and have found application in the chemical industry, may be mentioned one which contains 2·5 per cent. of magnesium and 0·25 per cent. of chromium, another which contains 1·25 per cent. of magnesium, 0·25 per cent. of chromium, and 0·7 per cent. of silicon, and another containing 1·2 per cent. of magnesium, 1·2 per cent. of manganese, 0·3–1 per cent. of silicon, and less than 1 per cent. of antimony. These alloys have given satisfactory service where resistance to corrosion by sea water is required.

Casting Alloys.

The best aluminium casting alloys for use under corrosive conditions appear to be those containing 12–13·5 per cent. of silicon, 0·4–0·6 per cent. of iron, and a trace of sodium or other alkali metal and others containing 3·75 per cent. and 6 per cent. of magnesium respectively. Such alloys are used for stirrers and mixers and for the impellers of fans handling gases which contain sulphur compounds or acid vapours. A modification of this 13 per cent. silicon alloy is one known as " Birmasil Special," which contains about 3 per cent. nickel. It has a much higher yield point than the low value associated with the 13 per cent. silicon alloy. Particular care is necessary in the manufacture of aluminium alloys to ensure uniformity of composition. A use of aluminium alloys which has found application in other industries and may have scope in the chemical industry takes the form of a

composite metal where the alloy is protected by a thin surface layer of pure aluminium or another alloy which has a solution potential such that it electrolytically protects the underlying alloy. Any corrosion which takes place is in the surface layer, and in the event of this layer being perforated by pitting, the pitting does not extend beyond the interface, as the electrolytic action is such that the protective metal layer is corroded preferentially to the underlying metal.

In order to ensure maximum resistance to corrosion in aluminium plant, careful fabrication is necessary. The welding of aluminium is a particularly important operation in this respect. Aluminium is welded either by hammer welding or, more usually, by autogenous welding. In the former process the metal is softened by heat and the weld made by hammering. Great care is necessary to prevent deterioration of the metal through overheating and to avoid the formation of an oxide skin which prevents a proper union of the two parts and leads to mechanical weakness at the weld. If hammer welding is properly carried out, it gives a weld with high-corrosion resistance. In autogenous welding, by the oxy-acetylene or oxy-hydrogen flame, the choice of the right composition of the welding rod and the complete removal of all flux when the operation is finished are important points. The quality of the weld is considerably improved by hammering.

Protective Coating.

Aluminium also finds application in the chemical industry as a protective coating for other metals, particularly in cases where protection against oxidation at high temperatures is required. The metal to be treated is either heated in aluminium powder or is coated with aluminium by spraying and then heated. Under the action of heat a superficial alloy of the aluminium with the underlying metal is formed which on exposure to an oxidising atmosphere gives a protective film of aluminium oxide which protects the metal against further oxidation.

Aluminium is also used in the chemical industry for thermal insulation. On account of its high reflectivity, aluminium foil separated by air spaces forms a very effective insulating material for use on plant which is heated or refrigerated. This type of insulation has the advantages of being light in weight, non-combustible and vermin-proof. Aluminium paint, on account of its high reflectivity, is also widely used to reduce heat losses or heat absorption. In the case of petrol storage tanks, the application of aluminium paint reduces temperature fluctuations and the consequent evaporation losses. Such tanks have also been covered with aluminium foil, which is even more effective than aluminium paint, but a more usual practice is to paint the sides of the tank with aluminium paint and to cover the roof with aluminium foil. Some tests carried out over a

period of three months showed that, compared with an unpainted tank, the evaporation loss was reduced to two-thirds when the sides and roof were painted with aluminium paint and to one-quarter when the sides were painted with aluminium paint and the roof was covered with aluminium foil. (Dr. Underwood, *Times—Trade and Engineering*, March, 1937.)

A large quantity of aluminium is used in the manufacture and preparation of foodstuffs, lactic, acetic and citric acids, etc.

The following list states briefly the suitability or otherwise of aluminium for use with other substances :—

Acetanilide :—Does not react with aluminium at any temperature. Aluminium acetylating tanks have been successfully used, even though aniline does attack aluminium near the boiling point.

Acetic Acid :—Aluminium equipment is used in handling acetic acid in a wide range of concentrations and at temperatures up to boiling point. Acetic acid produced in aluminium apparatus and stored and shipped in aluminium containers commands a higher price because of its greater purity.

Propionic, Butyric, etc. :—Behave similarly to acetic acid, but greater care is required if they are free from water.

Acetic Anhydride :—Aluminium containers are used for storing and shipping acetic anhydride, but mixtures of acetic acid with the anhydride should not be handled in aluminium if they contain more than 10 per cent. acid.

Acetone :—The storage of re-distilled acetone causes a slight local attack on aluminium.

Alcohols :—There is disagreement as to the suitability of aluminium, but generally aluminium distilling apparatus is satisfactory for alcohol.

Alum and Aluminium Sulphate :—Cooling trays of aluminium are used in the preparation of these substances and give satisfactory service, though they are not entirely immune from attack.

Ammonia and Ammonium Hydroxide :—Gaseous ammonia does not attack aluminium, but ammonium hydroxide attacks the metal and forms a protective coating which prevents further action provided the solution is free from alkali metal salts. Aluminium is used in ammonia recovery equipment, in coal gas plants, and in refrigerating systems using ammonia.

Ammonium Bicarbonate, Carbamate, Carbonate :—Aluminium is specially suitable for the subliming apparatus used in the production of these compounds because of its good thermal conductivity.

Ammonium Nitrate :—Equipment used in neutralising of nitric acid with ammonia, in concentrating the liquors and crystallising the salt, is made of aluminium. The fact that aluminium does not form sparks when struck is an advantage when mixing the nitrate to form explosive mixtures.

Ammonium, Polysulphide, Sulphide and Thiocyanate :—Do not attack aluminium.

Aniline and other Amino-Hydrocarbons :—Attack aluminium at temperatures near boiling point.

Benzoic Acid :—May be sublimed in aluminium apparatus.

Benzol :—Is without action on aluminium.

Boric Acid :—The rate of attack is slow and dependent on the concentration of the acid.

Bromine :—Attacks aluminium vigorously.

Calcium Chloride :—Solutions tend to cause corrosion of aluminium. Chlorides as impurities in other materials are often responsible for chemical attacks on aluminium equipment.

Carbon Disulphide :—Does not attack aluminium.

Carbon Dioxide :—The gas does not attack aluminium, but with carbonated waters there is some attack, though aluminium equipment is often used successfully.

Carbon Tetrachloride :—With water hydrolyses slightly and has a corrosive action on aluminium, especially at high temperatures.

Chlorine :—Dry, it does not attack aluminium, but under ordinary conditions the attack is vigorous.

Edible Oils and Fats :—Do not appreciably attack aluminium which is used in the preparation, storage, transportation, deodorising and purification of these products. A slight contamination with aluminium salts is not regarded as objectionable in food products.

Ethyl Acetate :—Is handled satisfactorily in aluminium provided it is practically free from water.

Ethylene Dichloride :—May be used in contact with aluminium.

Fatty Acids, such as Oleic, Palmitic and Stearic :—Do not attack aluminium up to a temperature of 300° C., provided a small amount of water is present.

Formaldehyde :—Aluminium is used in the distillation, storage and shipment of this substance.

Formic Acid :—Attacks aluminium and as an impurity in acetic acid or formaldehyde may cause serious corrosion.

Gelatine and Glue :—In the manufacture of gelatine and glue, aluminium is used in many of the processes, being one of the few metals which can be used for edible gelatine.

Glycerol :—Is without action on aluminium.

Heavy Metal Salt Solutions :—Cannot be handled in aluminium owing to the electrochemical action which takes place.

Hydrocyanic Acid :—Does attack aluminium, but aluminium shipping containers can be recommended.

Hydrogen Sulphide :—Does not corrode aluminium.

Iodine :—Attacks aluminium.

Mercury and Mercury Salts :—Aluminium is not readily wetted by mercury, but once amalgamation starts, the destruction of the metal proceeds rapidly.

Nitric Acid :—The large pipe-lines used in the manufacture of nitric acid from atmospheric nitrogen, the storage and shipping tanks and drums, are all made of aluminium ; if, however, the acid is made from Chili saltpetre serious corrosion may result.

Nitrous Gases :—Can be handled in aluminium. Aluminium covers for nitrating tanks, fume hoods and ventilating ducts are used where nitrogen gases are handled.

Oxalic Acid :—In all concentrations causes slow solution of aluminium.

Phenols and Creosotes :—Do not attack aluminium provided they are not completely anhydrous. In the absence of water, the action is vigorous at high temperatures. The use of aluminium stills for the distillation of tars is due to the fact that they are seldom anhydrous.

Phosphoric Acids :—Attack aluminium.

Picric Acid :—Fused acid does not react with aluminium, but its solutions are rapidly reduced by the metal.

Potassium Chlorate :—Is dried in aluminium trays.

Salicylates and Salicylic Acid :—May be handled in aluminium.

Sodium Carbonate :—Solutions attack aluminium, but small additions of sodium silicate inhibit this action.

Sodium Chloride :—Has a corrosive action on aluminium.

Sulphur :—Does not attack aluminium except at very high temperatures.

Sulphur Dioxide and Sulphurous Acid :—Sulphur dioxide does not attack aluminium even at high temperatures as in flue gases, vulcanising chambers or petroleum refining stills. Aluminium is used extensively in the rubber industry. If liquid sulphur dioxide is dry it can also be handled in aluminium, and for this reason is being used in the refrigeration industry.

Sulphuric Acid :—In dilute solutions and at ordinary temperatures does not seriously attack aluminium, the rate of attack increasing with the degree of concentration and the temperature.

Tartaric Acid :—Has some action on aluminium, but the latter is used where this acid is in food products.

Trinitrotoluene :—Aluminium is used for melting this product.

Turpentine :—Does not attack aluminium, which is used for the rectifying and condensing plants for turpentine.

Ultramarine :— Is dried in aluminium trays as the sulphur does not attack the metal and discolour the pigment.

Varnishes :—Many substances used in the manufacture of varnishes do not attack aluminium, and the fact that aluminium salts are colourless is a great advantage.

Water : —In the pure state does not attack aluminium, and the latter is used for condensing coils, storage tanks, and pipe lines for distilled water.

Aluminium conduit is often used to protect electrical wiring from chemical fumes. For a similar reason electric cables and wires are often made of aluminium.

There are also important nickel aluminium alloys which are much used in mechanical and automobile engineering. These are " Y " alloys, and the well-known R.R. alloys, the latter with suitable heat treatment having a high tensile strength.

Tantalum.

Twenty years ago this metallic element was a scientific curiosity, but due in no small measure to the Fansteel Metallurgical Corporation of Chicago, it has recently become available in commercial quantities and forms for plant construction.

It has unusual properties, as will be noted from the following data kindly supplied by the Fansteel Corporation.

Physical Properties of Tantalum.

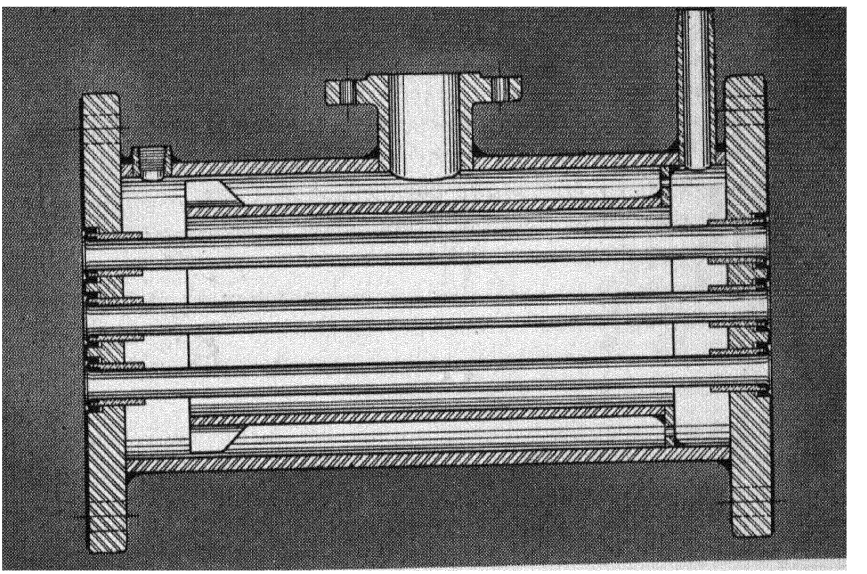
Specific gravity at 20° C.	16·6
Melting point	2850° C.
Thermal conductivity	0·130 cal./cm.^{3}/ sec./° C. at 18° C.
Specific heat at 0° C.	0·0365
Coefficient of linear expansion	6·5 $\times 10^{-6}$° C. 3·57 $\times 10^{-6}$° F.

Mechanical Properties.

Tensile strength	130·000 lbs./sq. in.
Brinell hardness	75–125
Young's modulus	29,000,000 lbs./sq. in.

Tantalum is made from the ore tantalite, which is an iron manganese tantalate. This ore is found in limited quantities in many localities, but the only deposits where it is in sufficient concentration to permit commercial production of the metal is in Western Australia.

Tantalum cannot be produced by a simple smelting process, because its melting point is far higher than any available crucible, and it cannot be dissolved in any reagent. Also it has an affinity for oxygen and other gases at a dull red heat which further complicates matters.



Heat interchanger with tantalum seamless tubes and tantalum-protected tube sheets. Cross-section shows method of inserting tubes into tantalum-capped ferrules, and expanding assemblies into tube sheet, forming tight, tantalum-protected joints.

FIG. 28.

No details are available of the highly specialised technique obviously necessary. It can, however, be stated that when the pure tantalum powder is obtained, the ingots are prepared by pressing the sintered powder at extremely high temperatures, followed by hammering and swageing. Subsequent operations, such as swageing and wire drawing, sheet rolling and seamless tube drawing, are done cold with vacuum annealing at certain stages.

Tantalum can be welded, machined, formed, etc. It can also be welded to nickel by electric spot, butt seam and roller processes under water.

Obviously tantalum is an expensive metal, but it has certain definite and unique properties which make it a welcome addition to

corrosion-resisting materials, and even at the high price it has been found commercially practicable in many processes.

Table 9 below gives details of corrosion tests on tantalum.

It is worthy of note that tantalum is inert to all the halogens except fluorine. Bromine, hydrobromic acid, organic bromides and chlorides, ammonium chloride, ferric and stannic chlorides can be treated in heat exchangers, and lined stills of tantalum without contamination or corrosion.

Tantalum cannot, however :—

(1) be universally used in contact with alkalis ;
(2) be heated in air or other than pure noble gases or vacuum to temperatures above 450° C. ;
(3) be completely fabricated into complicated forms in the field ;
(4) be soldered or brazed except by a special process which is limited to small parts and not applicable to the field ;
(5) be plated by any known commercial process ;
(6) be used with hydrogen at atmospheric or higher pressures at temperatures above 100° C.

Fig. 28 shows a heat exchanger in which the contact parts are in tantalum.

Lead.

Lead is sold from the refineries in the form of pigs, or bars which usually weigh from 80 to 120 lbs., and are used as raw material by lead manufacturers in producing lead pipe, sheet lead, and the other commercial forms of lead and lead products.

Lead is bluish-grey in colour, and when freshly cut or melted has a bright metallic lustre which tarnishes with exposure to the air. The tarnishing is caused by the action of oxygen and carbonic acid gas (CO_2) and water vapour in the air, which produces a fine film over the surface of the metal, acting as a protective coating to the lead beneath.

It is a heavy metal, soft, malleable, easily worked and readily cut, with a low tensile strength but a high coefficient of expansion, and its resistance to various acids is such that it is much used in chemical works.

Density of Lead.

Ordinary lead, 327·4° C. just solid	11·005 gms./cu. cm.
327·4° C. just liquid	10·686 gms./cu. cm.
550° C.	10·418 gms./cu. cm.
800° C.	10·132 gms./cu. cm.
Rolled sheet, 20° C.	11·35 to 11·37 gms./cu. cm.
Pure cast lead, 20° C.	11·34 gms./cu. cm.
Lead vapour is monatomic.	
Hardness—Moh's scale	1·5

TABLE 9.

Corrosion Resistance Tests of Tantalum.

Test No.	Substance.	Time.	Temperature (° C.)	Per cent. Loss in Weight per month.	Depth of Corrosion (cm. per Month × 10^{-4}).	Estimated Life based on 50 per cent. Corrosion Loss.
1	Hydrochloric acid, HCl conc.	4·5 mos.	19–26	None	None	—
2	Sulphuric acid, H_2SO_4 conc.	4·5 ,,	19–26	None	None	—
3	Nitric acid, HNO_3 conc.	4·5 ,,	19–26	None	None	—
4	Phenol sat. sol. H_2O, C_6H_5OH	4·5 ,,	19–26	None	None	—
5	Aniline C.P., $C_6H_5NH_2$	4·5 ,,	19–26	None	None	—
6	Cleaning solution, $H_2SO_4 + K_2Cr_2O_7$	4·5 ,,	19–26	None	None	—
7	Iodine, KI—H_2O sat. I_2	4·5 ,,	19–26	None	None	—
8	Bromine (liq.), Br	4·5 ,,	19–26	None	None	—
9	Barium hydroxide, $Ba(OH)_2$ (sat.)	4·5 ,,	19–26	None	None	—
10	Ferric chloride, $FeCl_3$ conc. sol.	4·5 ,,	19–26	None	None	—
11	Muriatic acid, HCl (com'l)	4·5 ,,	19–26	None	None	—
12	Stannic chloride, $SnCl_4$ sol. (sat.)	4·5 ,,	19–26	None	None	—
13	Acetic acid. $HC_2H_3O_2$ glacial	4·5 ,,	19–26	None	None	—
14	Lactic acid, 85 per cent. sol.	4·5 ,,	19–26	None	None	—
15	Oxalic acid, sat. sol.	4·5 ,,	19–26	None	None	—
16	Acetone $(CH_3)_2CO$	4·5 ,,	19–26	None	None	—
18	Phosphoric acid, H_3PO_4 conc.	3 ,,	145	0·014	0·099	870 yrs.
19, 20 *						
21	Chromium plating sol., CrO_3 in dil. H_2SO_4	3 ,,	98	0·007	0·050	1688 ,,
22	Sodium sulphate, Na_2SO_4 (sat. sol.)	3 ,,	101	0·007 gain	†	—
23	Sodium chloride, NaCl (sat. sol.)	3 ,,	100	None	None	—
24	Potassium chloride, KCl (sat. sol.)	3 ,,	94	None	None	—
25	Sodium tungstate, Na_2WO_4—$2H_2O$ (sat. sol.)	3 ,,	97	None	None	—
26	Silver nitrate, $AgNO_3$ 50 gms. per. 100 c.c. sol.	3 ,,	102	None	None	—
27	Cleaning solution, H_2SO_4—$K_2Cr_2O_7$ sol.	3 ,,	150	0·013	0·09	955 yrs.
28	Oxalic acid, $H_2C_2O_4$ (sat. sol.)	3 ,,	96	0·03	0·21	410 ,,
29	Sodium hydroxide, NaOH (5 per cent. sol.)	2 ,,	100	‡ 1·13	8·10	13 ,,
30	Potassium hydroxide, KOH (5 per cent. sol.)	2 ,,	100	0·01	§ 0·072	1250 ,,
17	Sulphuric acid, H_2SO_4 conc.	3 ,,	147	0·013	0·09	955 ,,
0	Sulphuric acid, H_2SO_4 conc.	1 mo.	175	0·324	0·27	32 ,,
05	Sulphuric acid, H_2SO_4 conc.	1 ,,	200	3·7	32·4	2·5 ,,
03	Sulphuric acid, H_2SO_4 conc.	6 hrs.	250	71·2	600	1·75 mos.

* *Note.*—Tests 19 and 20, 40 per cent. water solution, NaOH and KOH at 110° C. completely corroded away in two days.
† Very slight tarnish. ‡ Slight coating. § Forms protective coating.

Weight.

Pure cast lead, 20° C. calculated	0·4092 lbs./cu. in.
Equivalent to	707 lbs./cu. ft.
Rolled (density, 11·37) calculated	709 lbs./cu. ft.
Liquid, 327·4° C., calculated	666 lbs./cu. ft.
Sheet lead, 1 ft. sq. and $\frac{1}{64}$-in. thick, weighs approx.	1 lb.
Volume of 1 lb. of cast lead, 20° C. calculated	2·44 cu. ins.

Thermal Properties.

Melting point	327·4° C. (621° F.)
To melt 1 lb. of lead, heating from 20° C. requires	7100 gm. cal., or 28·4 B.Th.U.
Latent heat of vaporisation, per gram	223 gm. cal.
Thermal conductivity (silver = 100)	8·2

Thermal conductivity, per ° C./sec./cu. cm. :—

Temp. ° C.	*Gm. Cal.*
− 247·1	0·117
− 160	0·092
0	0·083
100	0·081
200	0·077
300	0·074
400	0·038
500	0·037
600	0·036

Coefficient of linear expansion (− 190 to 19° C.)	0·0000265 per ° C.
Coefficient of linear expansion (17 to 100° C.)	0·0000293 per ° C.

Mechanical Properties.

Brinell number, 1 cm. ball, 30 sec., 100 kg. load :—

Ordinary soft lead	3·2 to 4·5

Tensile strength—Soft lead :—

(Extension rate of 0·2 in./in./min.)	2000–2400 lbs./sq. in.
(Extension rate of 0·02–0·03 in./in./min.)	1980 lbs./sq. in.

Effect of temperature on tensile strength (extension rate of 0·02–0·03 in./in./min.) :—

	Tensile Strength (lbs./sq. in.).	*Elongation on 6 ins.*
Soft lead at atmospheric temperature	1980	39 per cent.
Soft lead at 100° C.	804	51 per cent.

Sheet Lead.

Rolled or Milled Sheet.

The greater part of the sheet in use to-day is produced by rolling or milling and is called milled sheet lead.

The process involves the melting down of pigs of lead and casting into slabs approximately 5 ins. thick. The slabs are then passed through heavy rollers and rolled out to a thickness of approximately 1 in. These thin slabs or sheets are then cut into suitable sizes, and each piece is rolled backwards and forwards through the final rolling mill, until it is reduced to a sheet of the required weight and thickness.

Lead sheet is known and specified by its weight per sq. ft. thus : 3-lb. lead, 4-lb. lead and so on, the weight given always indicating the weight of 1 sq. ft. of the sheet.

The weights of milled sheet lead most used in building work are given in the following table ; heavier weights (up to 60 lbs.) are used mainly in electrical and chemical work :—

Weight in lbs. per sq. ft.	Thickness in ins.	Nearest Imperial Standard Wire Gauge.	Thickness in mm.
2½	0·042	19	1·07
3	0·051	18	1·3
3½	0·059	17	1·5
4	0·068	16	1·73
4½	0·076	15	1·93
5	0·085	14	2·16
6	0·101	12	2·57
7	0·118	11	3·00
8	0·135	10	3·43
10	0·169	7	4·29

Sizes of Sheet Lead.

The usual commercial size for milled sheet is from 15 ft. to 40 ft. in length and from 7 ft. to 9 ft. in width, but sheets up to 60 ft. long or 12 ft. wide may be obtained if required.

Sheet lead may be obtained cut to special shape or size, or in standard size sheets suitable for cutting afterwards.

Table of Thickness and Weights of Milled Sheet Lead.

The following table gives the approximate thickness of milled sheet lead up to 60 lbs. per sq. ft.

Thickness (in ins.).	Weight (in lbs. per sq. ft.).	Thickness (in mm.).	Thickness (in ins.).	Weight (in lbs. per sq. ft.).	Thickness (in mm.).
1/16	3·71	1·58	1/2	29·67	12·7
1/8	7·42	3·175	5/8	37·08	15·875
1/4	14·83	6·35	3/4	44·50	19·05
5/16	18·54	7·93	7/8	51·92	22·22
3/8	22·25	9·52	1	59·33	25·4

Lead in Chemical Plant. (D. W. Jones, *Chemical Age*, May 9, 1936.)

Lead as a medium for the construction of chemical plant has been in use since the earliest days of chemical practice. For example, it was used in sulphuric acid plant quite early in the eighteenth century.

The latest British Standard Specification No. 334 of 1934 for chemical lead provides for two types. Type " A " is a pure material containing not less than 99·99 of lead, whereas type " B " is described as a " chemical lead containing protective elements, the composition of which material shall be agreed between the manufacturers and the purchaser but shall not contain more than 0·005 per cent. bismuth."

The introduction of copper (up to 0·5 per cent.) to lead to increase corrosion resistance has been practised for many years. C. E. Barrs showed in 1919 that copper acted beneficially in creating resistance to attack by concentrated sulphuric acid over 300° C., and found that tellurium had the same effect. It was thought that increased strength was imparted to lead by the small amount of copper used, but it is certain that the tendency to recrystallisation at working temperatures in various processes where lead is used was not prevented, and when under stress inter-crystalline cracking of lead containing copper could occur. It is interesting in this connection to note that in the United States the most acceptable grade of chemical lead is one derived from the smelting of natural ores and not submitted to special refining, and which contains copper up to 0·08 per cent., silver 0·02 per cent.

Of more recent origin and developed in Germany is a nickel lead which contains a maximum amount of 0·05 per cent. nickel, the nickel being deliberately introduced. Nickel lead as made in England has a maximum content of 0·005 per cent. Here again, although resistance to corrosion is of a high order, the physical characteristics of this lead are not markedly changed.

The British Non-Ferrous Metals Research Association has developed the so-called ternary alloys of lead, of which there are three. Nos. 1 and 2 are best known and the composition and some physical properties are given below :—

No.	Per cent. Tin.	Composition.		Lead.	Tensile Strength (lbs. per sq. in.).	Fatigue Resistance (Haigh Fatigue Test) (tons per sq. in.).
		Per cent. Antimony.	Per cent. Cadmium.			
1 .	—	0·50	0·25	Remainder	3696	0·74
2 .	1·50	—	0·25	,,	—	—
3 .	0·40	—	0·15	,,	3024	0·35

These figures indicate tensile strength about twice that of pure lead. Sheet and pipe made in ternary alloys are stiffer than lead sheet and pipe, but are tractable in working and offer no difficulty in burning or soldering. The material may not be sufficiently resistant to corrosion to warrant extensive use in the chemical trade, but has been applied to water services and the like where vibration has to be with-

stood. Ternary alloys are more expensive per unit weight than ordinary lead, but are put into service in lighter weight than ordinary lead. There is therefore no wide difference from the point of view of cost. Ternary alloy sheet is not used to any great extent.

Antimonial Lead Alloys.

In almost every conceivable proportion, up to 30 per cent., antimony is alloyed with lead for purposes of constructing chemical plant. The alloy containing over 8 per cent. antimony is generally used in the cast form. An alloy under 8 per cent. antimony may be cast, extruded or rolled. Very many small parts are produced by die-casting. Heavy vessels, sometimes made up from antimonial lead sheet and 1-in. section, are frequently used and are sufficiently rigid to find a place in film evaporators, for storage purposes, and many pipes in the alloy are also employed. Antimonial lead can be joined in the usual way by the lead burning process.

An alloy containing 4 per cent. antimony or more can be satisfactorily screw-cut, but there is a danger of seizure when nuts are drawn up very tightly on threads in antimony-lead alloys. Valves, injectors and cocks made from lead with 12 to 20 per cent. antimony are very extensively used in controlling the flow of cold sulphuric acid.

The artificial silk industry makes extensive use of antimonial lead alloys. Nozzles with a large number of fine holes can be made from an alloy of 28 per cent. antimony. Rounder ends—a tubular and shaped connection which will swivel through an angle of 90°—are made in antimonial lead, which resists corrosion by 10 per cent. sulphuric acid, and possesses sufficient strength to permit of frequent movement. Other and more expensive materials have been replaced by the alloy for this particular purpose.

Homogeneously Lead-lined Plant.

The advantage of a strong outer shell with a rigid lining of corrosion-resisting lead is obvious, and homogeneous lead-lined plant is particularly applicable to operations conducted at fairly high pressure or under vacuum, and where temperature alternates between 100° C. and atmospheric. When a piece of plant is in two parts and jointing is by flanges and bolts, the edges at and near the flanges are sometimes coated with antimonial lead which, being harder, resists the effect of pressure when bolts are drawn up very strongly. Alloys of the order of 4 per cent. antimony are best suited to this purpose.

Tellurium Lead.

The most important development in alloys of lead in recent years is based on the observations that so small a quantity as 0·05 to 0·065 per cent. tellurium introduced into lead effects profound changes in

the physical properties of the metal without sacrifice in corrosion resistance, whilst still preserving the essential properties of lead.

Tellurium added to lead effects the following fundamental changes in the physical structure of the material :—(1) grain is refined in a remarkable way ; (2) the temperature at which recrystallisation occurs is raised very appreciably ; (3) work-toughening properties are imparted ; (4) tensile strength is practically doubled and more than doubled at 100° C. ; (5) resistance to fatigue is increased almost three times at ordinary temperature and four times at 100° C. when compared with ordinary lead used under the same conditions.

Tellurium lead is in general much more resistant to corrosion than ordinary lead. Trials made in various chemical plants have proved that often it has many times greater resistance to corrosion than the best chemical lead. (Singleton, *Inst. of Plumb.*, Dec., 1933.)

Attention has recently been directed to the plumbo-solvent action of drinking-waters on lead pipes, and it is important to record that extensive experimental work using drinking-waters from numerous towns and cities in Great Britain has shown that tellurium lead has in general much greater resistance to the solvent action of water than ordinary lead. This greater resistance is most marked with waters usually regarded as having a highly solvent action on ordinary lead.

These properties of tellurium lead are of considerable practical importance. The ability of tellurium lead to toughen when strained results in strain being evenly distributed because any part of a pipe subjected to strain immediately develops strength to resist that strain, which in consequence is transferred to some other part, so that a general strengthening takes place automatically. Ordinary lead does not toughen and therefore, in similar circumstances, the strain concentrates in one point and failure takes place. Because of this property tellurium lead has greater resistance to hydraulic bursting as the following figures, obtained by independent authorities, show :—

Type of Lead.	Normal Weight per yd.-lbs.	Maximum Pressure (lbs./in²).	Per Cent. Expansion before Bursting.
Pipes of ½-in. Bore.			
Ordinary lead	6 lbs.	1025	31·3
Tellurium lead	4 „	990	52·4
Tellurium lead	6 „	1278	71·1
Pipes of 1-in. Bore.			
Ordinary lead	12 lbs.	610	22·2
Tellurium lead	8 „	600	50·0
Tellurium lead	12 „	775	47·8

These results show the greater resistance of tellurium lead to hydraulic bursting and that tellurium lead pipes of ½ in. by 4 lbs. and 1 in. by 8 lbs. are approximately equal to ordinary lead pipes of ½ in. by 6 lbs. and 1 in. by 12 lbs. respectively, in resistance to hydraulic bursting. The expansion figures illustrate the much greater distortion withstood by a tellurium lead before bursting.

Lead-Burning in Chemical Plant Construction and Repair.

Lead-burning (lead-welding) has of necessity to be used very extensively in the repair and maintenance of chemical plants owing to the fact that both sheet and lead pipes are used in large quantities for chemical plant construction. The different types or systems of flame lead-burning available for the chemical plumber are as follows :—

Gas System.	*Flame Temp.* (° C.).
Generated hydrogen—atmospheric air . .	Approx. 1700
Coal gas—oxygen	,, 2000
Hydrogen (compressed)—oxygen . . .	,, 2400
Acetylene (compressed)—oxygen . . .	,, 3600

The first-named system is now being rapidly displaced by the other methods, due to the fact that they possess many advantages from both a portability and cleanliness point of view. When the oxy-acetylene system was first introduced it was thought that the temperature of the flame would be far too hot for the welding of lead. Experience has, however, proved that the high temperature is an asset, experiments having shown that sheet lead, even though it be as thin as $\frac{1}{16}$th of an inch (3 lbs. per ft. super), can be jointed in all positions, including both underhand and overhead seams. Going to the other extreme, plate lead (30 lbs. per ft. super and above) can be jointed very rapidly and efficiently by this method.

Preparation for Lead Burning. (Partington, *Chem. Age*, May 9, 1936.)

Repairs and renewals to leadwork in chemical works have to be executed under all kinds of conditions. Very often it is necessary to have to carry out a quick repair whilst the plant is working, as in chamber repairs. Here the temperature of the lead may be between 70° to 110° C. To repair a defect on the side of a chamber under these conditions the operator must be skilled in the art of lead-burning, otherwise he will soon realise that the lead falls away or collapses before he has time to fuse it.

In executing a repair of this character, the first thing to be done is to see that the surface of the lead is thoroughly cleaned, and all oxides, sulphates or foreign matter removed. A very useful substance to have handy is " dry powdered lime." This should be rubbed over the part to be welded with a piece of coarse sacking. The effect

of the lime is two-fold; firstly, to neutralise any acid that may be about; and secondly, to scour the lead and give it a bright metallic surface.

Just a word of warning, however, before attempting to commence the lead-burning. Owing to the corrosive action on the lead taking place from the inside of the chamber, the defect is not noticeable from the outside until the sheet lead is very thin, and pinholes appear on the outer surface. This means that the lead to be fused with the flame is very weak, and only equivalent to 3 lbs. per ft. super in places. Bearing this in mind, when fitting the lead patch on to it, the lead need not be more than 5 lbs. per ft. super, otherwise the difficulty of having to weld thick lead to very thin presents itself.

In lead-burning a patch on the vertical sides of a chamber, and assuming that the lead edges have been thoroughly cleaned, the first thing to be done is to produce a small "sharp" flame at the blowpipe tip. This is projected on to the lead, and the underhand seam is fused as quickly as possible. The underhand seam is lead-burned first for the reason that the longer the flame is projected on to the lead it expands and opens the fracture, thus allowing any acid in the vicinity to trickle in between the two surfaces of lead and make the fusion very difficult. The secret of making a satisfactory weld in this particular instance lies in the flame setting. It is vital that a very small sharp flame be produced, and not a large "soft" flame, as is often the case with the beginner.

Repairs to Tanks and Vats.

The repairing of tanks and vats forms a large part of the chemical plumber's activities. These vary very considerably in size and shape. Unlike chamber-work, the corrosive action of the acid upon the lead is visible each time the container is emptied. This enables the chemical plumber to effect a necessary repair before the lead gets too thin, so that the difficulties mentioned in chamber repairs are obviated. Here, however, he meets with different conditions. Due to the expansion and contraction of the lead brought about by fluctuations in temperature, the lead very often creeps and stretches at various points. This continues until a fracture occurs. Or, as very often happens in lead-lined iron vessels used for mixing acids, etc., the lead is punctured, either by a mechanical defect during working, or by excessive friction of the acids during the mixing process.

With the former (lead-lined tanks) the majority of these are constructed of stout timber casings, with the result that a defect or leak in the leadwork very soon shows itself on the outside. But with the latter (iron vessels and vats) a defect does not show itself so readily, owing to the ironwork being made water- and acid-tight during construction, unless it is emptied fairly frequently. This

means that the lead lining, if left unsuspected, bulges and comes away from the iron shell, and allows acids and foreign matter to get in between the iron and the lead casing.

To effect a satisfactory repair in a wooden tank, it is first of all necessary to clean the tank out thoroughly with either water or steam to get rid of all traces of acid. The lead in the vicinity of the fracture is then cleaned, as previously stated, by using powdered lime. Should the fracture be on the vertical sides of the tank, it is necessary to fit a new piece of lead over it.

There are several methods of fitting a piece of lead to produce an efficient repair. To obviate difficult lead-burning some chemical

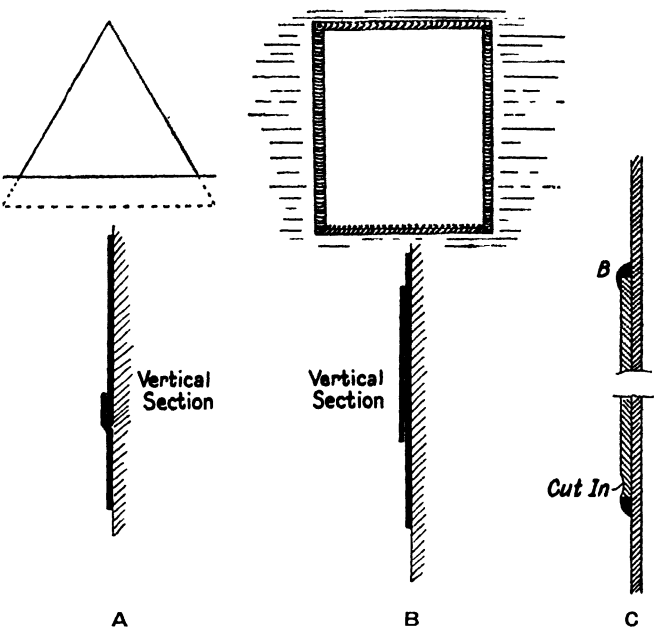


Fig. 29.

plumbers fit a patch as shown in Fig. 29A. This method does away with both vertical and underhand work, and makes a very simple proposition regarding the lead-burning. On the other hand, highly skilled lead-burners prefer to fit a rectangular patch (Fig. 29B). When the latter method is adopted, the main point to watch is that the lead-burning is not " cut in " at any point. This usually occurs at the edge of the weld on the overlapping portion and weakens the joint considerably. A strong joint should appear as shown by " B " (Fig. 29C), from which it will readily be seen that the joint is the strongest point.

Where the defect is in the bottom of the tank, the plumber can either cut the fractured portion clean out and insert a new piece with

the edges abutting, or he can lay a piece of sheet lead over the fracture and fuse same to the base metal. The former method is to be preferred, as it enables thorough penetration of the two pieces of lead when welding, and also keeps the lead patch flush with the remaining portion of the bottom of the tank. But as time is very often the important factor, the latter method is very often adopted for speed.

Before commencing to repair a fracture in a lead-lined iron vessel, the lead should be cut in the form of a cross and the four corners turned outwards to enable any foreign matter that may have accumulated being removed from between the lead and the iron. When this has been done the lead is carefully dressed back to the iron shell and the repair carried out in exactly the same manner as would apply to a wooden tank. Owing to the heat conductivity of the iron it will be found necessary to use a slightly larger flame than would be used when executing a fusion weld where there is a wooden casing. Fig. 30 shows a lead-lined digester, the interior of which is submitted alternately to 90 lbs. pressure and 28″ vacuum.

Silver.

Silver as used for the fabrication of chemical plant contains 99·97 per cent. silver, and in this degree of purity is resistant to corrosion by practically all the organic acids and their salts, and by certain mineral acids.

It is very ductile and can be worked easily into any shape. It has a very high thermal conductivity and is easily fabricated by spinning, drawing, soldered either with soft or silver solder and joined by autogenous gas welding.

Silver equipment is generally made entirely of one metal. Fine silver (999) is preferred. Silver-lined equipment is employed when vacuum or high pressure is required, in which case three types of lining are available :—(1) linings placed within the vessel but not permanently attached to the vessel wall ; (2) electro-plated linings ; and (3) clad metal walls. Cast silver equipment is not often used. Pure silver is comparatively soft, being harder than gold but not so hard as copper. The specific heat of silver is 0·05 and the relative thermal conductivities of silver and copper are 100 : 91. For general purposes the tensile strength of the metal in the annealed condition is 7 tons/sq. in. and the elongation about 60 per cent. The chemical properties of silver are discussed by Macdonald (*Proc. Chem. Eng. Group of the Soc. Chem. Ind.*, 1931, XIII, 50), and the following is a brief summary thereof :—

Silver is non-oxidisable by oxygen, and there is no evidence that either water or steam at any temperature below the decomposition

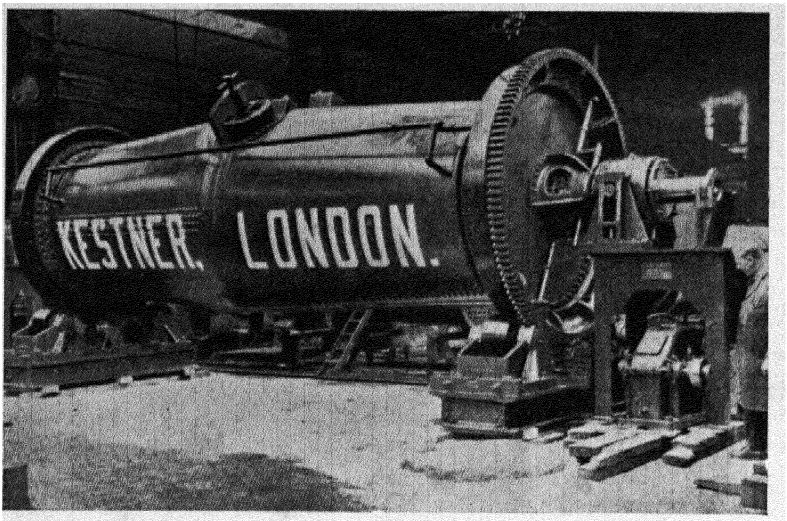


FIG. 30.—Lead-lined digester.

[*See page* 68.

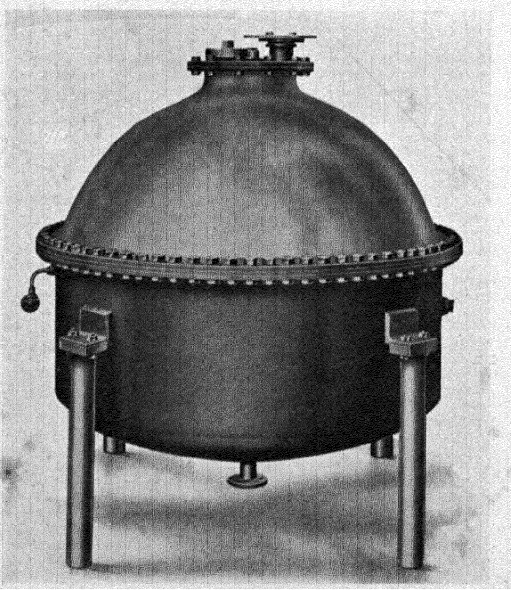


FIG. 31.—Silver-lined copper still.

[*To face page* 69.

point of the latter has any effect upon the pure metal. All halogens attack silver to a greater or less extent, depending upon the temperature and moisture conditions. Hydrobromic and hydroiodic acids both as gases and in solution attack silver at all temperatures. Strong solutions of hydrofluoric acid do not attack the metal at ordinary temperatures, but at the boiling point this acid corrodes silver slowly and there is no formation of a protective coating. Solution of caustic alkalis do not attack silver, and in the solid form they can be melted safely in vessels made of this metal.

Sulphur slowly corrodes silver at ordinary temperature by mere contact. Pure dry sulphurretted hydrogen is said to be without action on it, but the presence of a mere trace of oxygen causes rapid formation of silver sulphide. Silver is freely soluble in nitric acid of all strengths, but solution of the neutral nitrates are without effect on the metal. At ordinary temperature neither diluted nor concentrated sulphuric acid has any effect upon silver unless oxidising agents such as ferric sulphate or hydrogen peroxide are present. On boiling, however, sulphuric acid has some little action on silver, and hot concentrated sulphuric acid dissolves the metal freely.

Applications of Silver to Chemical Plant.—Fine silver is available, in sheet form in all gauges, in tubes of all diameters (in weldless tubes below 2 ins. dia.), and in the form of wire from which screens or wire mesh can be fabricated. The metal can be readily joined by oxy-acetylene welding. The most extensive application of silver in chemical plant is in the condensation and handling of acetic acid, in the distilled vinegar industry, food and allied process work, and for parts of equipment in the manufacture of acetate rayon silk.

Fig. 31 shows a silver-lined copper still by Johnson Matthey & Co. Ltd.

Platinum and Allied Metals.

All the metals of the platinum group, viz. platinum, palladium, iridium, osmium, ruthenium and rhodium, resemble platinum in appearance.

Platinum and palladium, as would be expected from their proximity to gold and silver respectively, are the most ductile and workable of the group. Rhodium and iridium are more difficult to work, whereas ruthenium is extremely difficult to work and there is no record of osmium having been worked at all

All six metals when in the compact form are permanent in air under normal atmospheric conditions, but at elevated temperatures ruthenium and osmium form volatile tetroxides, whilst palladium and platinum are the noblest of their respective triads in this respect. Perhaps due to the intervention of passivity phenomena, platinum and palladium are not the noblest in all respects. For instance,

rhodium, ruthenium and iridium are not attacked by aqua regia; platinum is dissolved by aqua regia but is not attacked by any single acid; palladium is easily soluble in aqua regia, it is attacked by hot concentrated sulphuric acid and to a less degree by nitric acid, but with these exceptions it is resistant to the common acids. The metals in the finely divided state are less resistant to chemical attack than the compact metals; for instance, osmium black dissolves in nitric acid and rhodium black is attacked by hot concentrated sulphuric acid.

Johnson and Atkinson (*Inst. Chem. Eng.*, Adv. Proof, May, 1937) recently gave some interesting data on the uses of platinum metals in the chemical industry, a summary of which is as follows: —

Uses of Platinum Metals with Special Emphasis on Uses in Chemical Industry.

Platinum has been of technical importance for more than a century.

Charles Knight produced platinum sheet on a commercial scale in 1800 by welding or sintering platinum sponge, and this method was greatly improved by Wollaston. There arose a considerable business in the manufacture of platinum vessels for the concentration of sulphuric acid, which had previously been done in glass retorts. The first still of platinum appears to have been made in 1809 in London; it weighed 423 ozs.* Later on platinum stills weighing from 66 to 112 lbs. were made, holding 4 to 6 tons of vitriol and costing from £1600 to £2000. This large sum did not deter manufacturers from using platinum for the final concentration of sulphuric acid, because they were convinced at once of the large amount, facility and safety of the work of concentration which could be carried on in them.

The fusion of platinum became possible through the invention of the oxy-hydrogen blowpipe by Robert Hare in 1801, who recounted his experiences in melting platinum in quantities of 28 ozs. in 1836. However, it was not until the work of Deville and Debray in 1856 that the melting of platinum by this method assumed technical importance. In particular, the sound ingots produced by this method resulted in very much more satisfactory retorts. Further, the use of the blowpipe made it possible to produce welded platinum joints and dispense with the use of gold, which had previously been employed for soldering platinum.

Lunge † gives a very full account of the use of platinum stills for the purpose of concentrating sulphuric acid.

Vitreosil vessels were introduced for the concentration of sulphuric acid about 1911,‡ though the use of platinum continued until

* *Chem. News*, 1878, Vol. 38, p. 43.

† *Sulphuric Acid and Alkali*, 4th ed., Vol. 1, Part III.

‡ *Chemical Trade Journal*, 1911, Vol. 48, p. 85.

about 1914. One of the authors (R. H. A.) saw a large platinum still in use in an acid works in Berlin in the latter year.

According to Dr. T. H. Durrans,* platinum condensers are used in the manufacture of hydrofluoric acid. Apart from this special case, so far as the authors are aware, plant made of platinum is no longer used industrially for concentrating or distilling acids.

There were very considerable amounts of platinum in use in acid works; according to Dr. W. Cullen,† there were between 60,000 and 80,000 ozs. of platinum retorts at the Modderfontein Explosives Factory in South Africa, a great deal of which was in use up to about the year 1906. This platinum had been brought at a very low price, so when it was sold a very considerable profit was realised by the Company.

Coincident with the decrease in the use of platinum for concentrating sulphuric acid, there was an increased demand for it in the catalytic production of the same acid. Chemists had been aware of the important catalytic properties of platinum from an early date, for in 1812 Davy suggested that platinum sponge would be a suitable catalyst for the oxidation of sulphur dioxide to produce sulphuric acid, and in 1831 this suggestion was tried out by Phillips on a commercial scale. Difficulties were encountered, but in 1875 Square and Messel, using purer SO_2, were successful and produced commercial quantities of sulphuric acid and oleum. The equilibrium relations involved in this process were thoroughly investigated by Knietsch and Kraus in 1901, and work by these investigators, and by Tentelew and others, led to further improvements in the platinum catalyst itself, so that this catalyst became firmly established in the industry for the production of oleum and high purity concentrated sulphuric acid.

Under the stimulus of competition from vanadium pentoxide catalysts the performance of platinum catalysts has been improved, and according to Fairlie ‡ the amount of platinum now required in U.S. plants per ton day of 100 per cent. sulphuric acid is from 5·5 to 7 ozs. troy for platinised asbestos or platinised magnesium sulphate, compared with 13 to 16 ozs. during the War, whilst it is only 1·5 to 2·1 ozs. for platinised silica gel, a new type of catalyst first used on the factory scale in 1926. It is claimed that the latter catalyst is immune to arsenic poisoning. Fairlie gives further information about these platinum catalysts in his book.

Fairlie states that the weight of platinum in catalyst masses at contact plants in the United States in 1929 was 37,512 ozs. troy. There do not appear to be any corresponding data for Great Britain.

The possibilities of producing nitric acid by the catalytic oxidation

* Private communication. † Private communication.

‡ A. M. Fairlie, *Sulphuric Acid Manufacture*, American Chemical Soc., Monograph Series, 1936.

of ammonia on platinum were considered by F. Kuhlmann in 1839, but it was not until 1903, when Ostwald and Brauer investigated this problem, that it became commercially important. With the further advances of Frank and Caro, Kaiser and others, and with the success of Haber's synthetic ammonia process, this method of producing nitric acid became so successful that it has wellnigh supplanted natural nitrates as a source of nitric acid and is displacing them for fertilisers.

The ammonia oxidation unit employs a catalyst gauze of platinum, or preferably a platinum-rhodium alloy, wire 0·003 ins. in diameter, with 80 meshes per lineal in. This gauze of four or more layers is in the form of a flat pad or a cylinder, through which the mixture of ammonia and air passes. The area of the gauze depends on the type of converter. The gauze may attain a temperature of 900° C. in service, but platinum alloys withstand high temperatures so well that a single catalyst unit will produce upwards of 4,000,000 lbs. of nitric acid before requiring attention.

S. L. Handforth and J. N. Tilley * made a very thorough examination of catalysts for the oxidation of ammonia to oxides of nitrogen, as a result of which they found that platinum-rhodium alloys gave a low loss of metal and high capacity under the operating conditions required for the maintenance of high-conversion efficiency. The pure 10 per cent. rhodium-platinum alloy appears to be the most advantageous and economical of any thus far proposed, and is in world-wide use.

They found that at 900° C. the conversion efficiency and loss of weight of certain catalysts were as follows :—

TABLE 10.

CONVERSION EFFICIENCY AND LOSS OF WEIGHT OF AMMONIA OXIDATION CATALYSTS.

Catalyst.	Loss of Weight in ozs. for 100,000 lbs. Ammonia.	Conversion Efficiency (per cent.).
Pure platinum	0·88	92·5 to 97·5
98 Pt, 2 Rh	0·80	96 ,, 98
90 Pt, 10 Rh	0·53	97 ,, 99
98 Pt, 1·6 Ru, 0·4 Co	0·89	—[1]

[1] The alloy containing cobalt started well, but the conversion dropped until it was unsatisfactory.

Small units for ammonia oxidation are now commonly used to supply oxides of nitrogen in plants manufacturing sulphuric acid by

* *Ind. Eng. Chem.*, 1934, 26, 1287.

the chamber process. The catalyst unit operates with little attention and replaces a whole battery of nitre pots.

The use of platinum spinnerets in the viscose process for the manufacturing of rayon or artificial silk depends on its resistance to chemical corrosion combined with good machining properties. Much use is also made of the platinum-gold and palladium-gold alloys.

The most important industrial application of the platinum metals in Japan is in manufacturing rayon, and it is estimated that the amount of platinum in use in the form of spinnerets made of 80 per cent. Au, 20 per cent. Pt alloy to be approximately 350 kilos, or 11,000 ozs. troy.

CHAPTER II.

CAST IRON AND ALLOYS.

Cast Iron.

On account of its cheapness, strength, ease with which it may be melted and cast into intricate shapes, ease with which its hardness may be varied, cast iron remains one of the most popular and useful of structural materials at the service of the chemical engineer.

Briefly, cast iron may be defined as an iron containing so much carbon or its equivalent that it is not malleable in the cast condition. The physical and mechanical properties of cast iron are to a large extent dependent upon the condition of the carbon content. The carbon may occur either in a free state, as graphite, or in combination with the iron as a carbide of iron, or of iron and manganese. Graphitisation of the carbide tends to increase with the temperature, with the deceleration of cooling, with the silicon content, and with the total carbon content, whereas graphitisation is reduced by the presence of sulphur or oxygen, by the presence of manganese in certain circumstances, and by acceleration of the cooling rate.

The mechanical properties of cast iron are influenced greatly by the relative properties of carbide and graphite, and an increase in the ratio $\frac{\text{carbide}}{\text{graphite}}$ gives an increase in hardness, brittleness and density, with a decrease in machinability and ductility. The strength of cast iron reaches a maximum when the combined carbon content is 0·8 per cent. to 1·0 per cent.

Grey cast iron, so-called from the colour of its fracture, is a cast iron wherein the total carbon is about 3·0 per cent. and the combined carbon not higher than 0·7 per cent. and is the type usually employed for cylinders of steam engines and similar structures. If molten cast iron is suddenly cooled, nearly all the carbon is retained in the combined state, and such irons are known as white cast irons. They are very hard and difficult to machine. Such white irons are used for linings of ball and tube mills and where high degree of hardness is essential. Localised sudden cooling of cast iron during casting can be obtained by lining such parts of the mould with metal which conducts heat away rapidly. Such castings are known as " chilled " iron castings.

One of the factors that limits the use of ordinary cast iron in high

temperature chemical service is that the graphitisation of the metal does not attain equilibrium when the castings are cooled in the mould. As a result, when the metal is heated graphitisation will be resumed and the casting will increase in volume and warp.

A second disadvantage of ordinary coarse-grained cast iron is that when exposed to corrosive chemicals the large areas of graphite permit an infiltration of the corrosive constituents into the body of the casting. This attack can be reduced by lowering the silicon content to a point when there is just sufficient silicon to graphitise the excess carbide and leave a eutectoid matrix of lamellar pearlite. Cast iron with this type of microstructure shows a twofold improvement -the graphite is more finely divided and hence more resistant to chemical attack, and the matrix has a more continuous matrix with higher strength.

Special Structural Cast Irons.

High-duty pearlitic cast irons for important structural castings are made by patented processes, such as Lantz, Emmel (Continental), Meehanite (U.S.A.).

Lantz Iron.—Average composition : total carbon 3·0, silicon 0·9, phosphorus 0·35, manganese 0·7.

The process consists of a temperature control of the mould correlated to the section of the casting. Tensile strength 20 tons per sq. in., with high shock-resisting qualities.

Emmel Iron.—Consists of pouring specially melted and controlled mixtures into ordinary sand moulds.

Typical analysis : total carbon 2·6, combined carbon 0·75, silicon 2·3, phosphorus 0·15, manganese 1·0, sulphur 0·11. Average tensile strength 22 tons per sq. in.

Meehanite Iron.—Of such a composition as would produce a white iron as it appears at the spout of the furnace. Graphitisation is effected by the addition of silicide of calcium.

Typical analysis (grey iron) : total carbon 2·4 to 2·7, silicon 1·0 to 1·5, phosphorus 0·1 to 0·2, sulphur 0·05 to 0·14, manganese 0·65 to 1·0.

Tensile strength 20 to 30 tons per sq. in.

Of recent years the development of alloy cast irons to resist shock, to withstand high stress and for corrosive conditions, has placed at the disposal of the chemical engineer a wide range of materials of great and increasing usefulness, as will be seen from the following notes on these alloy cast irons.

(1) *Low-Alloy Cast Iron.*

The usefulness of cast iron has been greatly extended by the addition of small amounts of nickel, additional silicon, chromium, etc., making it suitable for both large and small castings where in-

creased strength is required, together with relatively high hardness, good wearing quality and good machinability. Such alloy cast irons are most useful for gas and oil engine cylinder liners and accessories, air and gas compressor cylinders, etc., and also for frames of machinery where great strength is required. To overcome the "growth" of ordinary cast iron when used at high temperature, additions of nickel and chromium are made, e.g. carbon 3·30 per cent., silicon 1·00, nickel 2·00, chromium 0·75, manganese 0·68. For caustic service straight nickel cast irons or chrome nickel cast irons are widely used, e.g. (1) a nickel cast iron—carbon 3·30, silicon 0·70, manganese 0·50, nickel 2·00; (2) chrome nickel iron—carbon 3·30, silicon 0·70, manganese 0·50, nickel 1·50, chromium 0·60.

The *white cast irons* can be made especially hard by the addition of nickel and chromium.

Since nickel tends to graphitise an iron, it is usually desirable to accompany each nickel addition with a corresponding proportion of chromium or, where possible, to effect a reduction in silicon, so as to maintain an unchanging degree of whiteness in the casting. The nickel-chromium addition is, perhaps, the more convenient and, as before, the combined addition is made in the proportion of two to three parts of nickel to each part of chromium. The function of the nickel-chromium addition, as in the case of the grey irons, is to refine the matrix of the iron and to convert it progressively from pearlite to sorbite and then to martensite.

The hardness of the white cementitic part of the structure of the iron is generally believed to be of the order of 700 Brinell, whilst the pearlitic matrix in an ordinary white iron is, usually, somewhere between 200 and 250 Brinell. Whatever the effect of the special additions on the cementite, they serve progressively to increase the hardness of the matrix until the latter is almost as hard as the cementite part itself, and thus the net hardness of the casting as a whole is gradually increased until it approaches a figure somewhere in the region of 700, with an addition of about 4·5 per cent. nickel and 1·5 per cent. chromium.* At the same time, as hardness is increased the strength of the iron gradually improves, so that an increase in strength as great as 100 per cent. may be obtained.

This hardened white cast iron is proving of considerable interest, for example in the mining industry, for crusher balls and plates, milling wheels and parts of crushing and mining machinery subject to abrasive wear. Many of these parts are made from a white iron base without the use of chills, but special advantages are also available in irons which are maintained in the white condition by chilling.

The iron has been used in many cases to replace white irons, or even special steels, in such parts as pump liners and impellers, which are used

* Many of these alloy compositions are protected by patents.

for the hydraulic handling of gravel, ash and other abrasives, whilst the iron is advantageously employed for other components in hydraulic systems where severe abrasion occurs, such, for example, as for bends and junctions in pipe-lines.

Iron of this type is suitable for castings in which a combination of a hard chilled face, supported by a tough, grey backing, is required, as, for example, in chilled crusher jaws, chilled rolls and car wheels.

(2) *Austenitic Cast Irons.*

It has recently been realised that the production of the austenitic structure in cast iron by the use of large amounts of nickel, copper and manganese provides materials which have marked corrosion and heat-resisting properties.

The outstanding characteristics of the austenitic cast iron as compared with ordinary cast iron are as follows :—

(*a*) A marked degree of corrosion-resistance.
(*b*) A superior resistance to the effects of heat.
(*c*) With suitable compositions—non-magnetic.
(*d*) A high electrical resistance with a low temperature coefficient.
(*e*) A high coefficient of thermal expansion.

In mechanical properties the austenitic irons are not very dissimilar from ordinary cast iron. Their strength, whilst naturally depending on composition, is in some cases as high as for a good-quality engineering cast iron. They are also tough, as shown, for example, by the repeated impact test, while Izod test figures confirm their superiority over the more ordinary material. These irons also have measurable ductility, 2 or 3 per cent. elongation frequently being recorded in tensile test. The hardness of the pure austenitic structure is low, figures down to 100 Brinell frequently being obtained, but the Brinell hardness of the castings can be varied at will by modifications of composition.

The austenitic iron presents no special difficulty in the foundry and the resultant castings are generally readily machinable. They can also be easily welded but, on account of peculiarities of structure, cannot generally be heat-treated.

Composition Required to Produce the Austenitic Structure in Cast Iron.

Nickel.

Early researches, confirmed by more recent practical experiences, have shown that a minimum of 20 per cent. of nickel must be added to an ordinary cast-iron base to render the castings austenitic. It is generally found desirable, however, to increase the amount of nickel or other austenite-forming element to 3 or 5 per cent. above this minimum value, in order to ensure that the castings are fully austenitic and therefore readily machinable in all sections and under all conditions of treatment.

Copper.

Copper assists in the formation of the austenitic structure in the cast iron, but unfortunately copper by itself is of little value, since only about 1½ or 2 per cent. of this element can generally be alloyed with cast iron. It has been found, however, that in the presence of nickel the solubility of copper is increased and that a combination of two parts of nickel with one part of copper can be alloyed with cast iron in all proportions. Under these conditions the copper assists the nickel in the production of the austenitic structure, so that, in its presence, a lower proportion of nickel will give the desired result.

Commercial austenitic cast irons have been developed with such proportions of special elements as 14 per cent. nickel, 7 per cent. copper. This composition is of practical importance, since it can be readily produced by the direct addition of the well-known alloy "Monel metal," which consists of nickel and copper in the required proportions of two parts to one.

Manganese.

Manganese may also be used in conjunction with nickel in the austenitic cast irons, one part of manganese being roughly equivalent to two parts of nickel. In this case again, a practical limit is found to the amount of manganese which may be added, this limit being about 5 per cent. Above this percentage the presence of manganese carbides impairs the machinability of the castings. Manganese enters into the composition of the non-magnetic cast iron which is marketed in Great Britain under the name of "Nomag," the austenitic structure being developed by the addition of slightly more than 10 per cent. of nickel and 5 per cent. of manganese.

Chromium.

Chromium up to 5 or 6 per cent. may be added to most of the above alloys with beneficial effects on strength, corrosion- and heat-resistance. Above about 6 per cent. there is a tendency to the formation of structures containing chromium carbide which are, in consequence, exceedingly hard and brittle.

The compositions just discussed are only sufficient to give structures just in the austenitic range. It is frequently desirable to increase the proportions considerably above these figures, as, for example, in the case of special corrosion-resistant cast iron containing up to 40 per cent. of nickel with 15 per cent. of chromium.

Corrosion-resistance.

The most important feature of the austenitic cast irons is their resistance to corrosive attack. By modifying the compositions of

austenitic cast irons, alloys presenting a very useful resistance to many corrosive media are available.

In cast irons rendered austenitic by the addition of nickel alone, specially good resistance is obtained to attack not only by the atmosphere, but by many chemical reagents such as caustic alkalis and by weak sulphuric and hydrochloric acids. The alloys containing copper show similar properties, except that in many industrial applications the presence of copper is not desired. Such a case is that of caustic alkalis, since the slightest trace of contamination leads to discoloration of the chemical products.

Austenitic cast irons containing manganese are of least interest from the point of view of corrosion-resistance and are not usually considered where this property is desired. Chromium, on the other hand, frequently confers very considerable resistance to most types of attack.

In corrosion-resisting applications the austenitic cast irons containing proportions of nickel, copper and chromium have received most attention. Table 11 gives the results of corrosion tests carried out on alloys of this type, and shows the superiority of austenitic over ordinary cast iron whilst, at the same time, it reveals the fact that, under many conditions, austenitic cast iron can be regarded as behaving in a similar manner to such non-ferrous alloys as bronze. There are, of course, notable exceptions, as, for example, attack by hydrochloric acid, in which austenitic cast iron offers the best resistance among the alloys studied.

Austenitic cast irons are of special interest in their resistance to attack by weak sulphuric acid. The figures given show that the rate of attack on the special iron is one-fiftieth that of the ordinary material. Results obtained from independent sources indicate the resistance of austenitic iron to be sometimes as much as 500 times that of the ordinary iron.

The figures given in Table 11 refer to an alloy of the " Ni-Resist " type, containing approximately 14 per cent. nickel, 6 per cent. chromium, 5 per cent. copper and 1 per cent. manganese.

It must be noted that the figures given in the table below refer in each case to the resistance of only one particular alloy in the austenitic cast-iron series. It is frequently found that, when a special corrosion problem has to be met, other compositions of austenitic cast iron offer perhaps superior service. Thus in certain types of chemical equipment where castings are in contact with strong acids or alkalis, higher alloy cast irons such as already mentioned as containing up to 40 per cent. of nickel, generally with additions of chromium up to 10 or 15 per cent., have been found to offer very successful and economic service. For chemical plant the austenitic cast irons are available as castings of all types, the metal being as adaptable as ordinary cast iron, and the accompanying illustration gives some idea of the type of equipment for which the irons have proved specially suitable. (Fig. 33).

TABLE 11.

CORROSION TEST RESULTS * ON AN AUSTENITIC CAST IRON ("NI-RESIST" TYPE) COMPARED WITH PHOSPHOR BRONZE AND ORDINARY CAST IRON.

Figures represent the loss in milligrammes per square decimetre per day under static conditions at 20° C.

Corrosive Medium.	Austenitic Cast Iron.	Cast Iron.	Phosphor Bronze.
Acetic acid, 33 per cent.	17·0	840	18·6
Boracic acid, 10 per cent.	7·7	57·4	4·6
Citric acid, 5 per cent.	9·3	1,492	4·6
Formic acid	13·9	138	13·9
Hydrochloric acid, 1 per cent.	32·5	1,007	41·8
Hydrochloric acid, 5 per cent.	54·2	3,360	57·3
Hydrochloric acid, 20 per cent.	62·0	11,180	60·5
Nitric acid, 1 per cent.	620	697	2,446
Nitric acid, 5 per cent.	4,060	4,680	12,420
Nitric acid, 20 per cent.	7,830	10,092	Dissolved
Oxalic acid, 5 per cent.	6·2	55·8	12·4
Phosphoric acid, 50 per cent.	26·4	4,650	7·7
Sulphuric acid, 1 per cent.	26·4	1,642	18·6
Sulphuric acid, 5 per cent.	37·2	6,880	37·2
Sulphuric acid, 20 per cent.	41·8	13,720	38·8
Sulphurous acid	240	1,032	9·3
Tartaric acid, 5 per cent.	10·8	1,040	10·8
Vinegar	4·6	104	4·6
Acetone	1·5	4·6	1·5
Aluminium sulphate, 5 per cent.	20·0	96·0	10·8
Ammonium chloride, 5 per cent.	10·8	35·6	57·4
Ammonium nitrate, 5 per cent.	51·2	163	57·4
Ammonium sulphate, 10 per cent.	9·3	32·6	13·9
Ammonium sulphate + 5 per cent. sulphuric acid	26·3	11,160	21·7
Carbon tetrachloride	1·5	3·0	3·0
Copper chloride, 10 per cent.	1,394	8,030	543
Ferric chloride, 5 per cent.	667	1,038	347
Fuel oil	1·5	1·5	1·5
Hydrogen peroxide, 20 vols.	6·3	9·3	1·5
Magnesium chloride, 10 per cent.	7·7	18·6	6·2
Magnesium suphate, 10 per cent.	3·1	14·0	3·1
Potassium alum, 10 per cent.	15·5	372	20·2
Sea water	6·2	23·2	6·2
Sodium chloride, 3 per cent.	7·7	12·4	3·1
Sodium hypochlorite	223	688	80·6
Sodium sulphate, 5 per cent.	9·3	7·7	9·3
Sodium sulphite, 10 per cent.	3·1	6·2	1·5
Sodium sulphite, 5 per cent.	1·5	1·5	17·0

* Kindly supplied by Messrs. Mather & Platt, Ltd.

Erosion-Resistance.

Emphasis has already been laid on the necessity of using slightly more than the minimum composition of alloys essential to produce the austenitic structure. For below this minimum, traces of martensite are liable to be found in the metal, while in machining an iron with just the minimum alloy content, a distinct tendency for the metal to harden under the tool is encountered. This phenomenon is similar to that met in machining some of the austenitic steels, when the structure of the metal tends to revert to the martensitic state on being deformed. This may prove troublesome in the machine shop and use should be made of sufficient alloy elements to avoid it.

In many cases—an example being pump parts castings are required to be not only corrosion-resistant, but also to show a certain amount of erosion-resistance in order to resist impingement of fluids carrying solids in suspension, as in the case of sandy water. Some of the austenitic irons show a markedly improved resistance to erosion under these conditions, as compared with that usually obtained with the more ordinary materials ; the resistance is indeed sometimes even superior to that shown by the manganese steels ; at the same time, it must be remembered that the austenitic cast irons possess the additional advantage of superior corrosion-resistance. It is probable that the improved resistance to erosion is due in part to the surface-hardening mentioned above, which in turn is caused by the formation of a martensitic skin under repeated impingement.

Messrs. Mather & Platt, Ltd., measure resistance to abrasion as encountered in pumps by running discs of the metal under observation at 3000 r.p.m. in the abrasive mixture. The test discs are 10 ins. in diameter and $\frac{1}{2}$ in. thick. The weight loss after 24 hours is taken as an index of the quality of the metal. The figures given in Table 12 show a comparison between the weight loss with their No. 7 Alloy (austenitic cast iron) and ordinary cast iron.

TABLE 12.

WEIGHT LOSS OF AUSTENITIC AND ORDINARY CAST IRONS UNDER EROSIVE CONDITIONS.

(Messrs. Mather & Platt, Ltd.)

Mixture.	Austenitic Cast Iron.	Cast Iron.
Sand and water 50/50 . . .	145	320
Coal dust and water 50/50 . .	18	84
Clinker and water 50/50 . . .	144	320

The resistance of the irons to combined corrosion and erosion is of value in chemical operations where crystallising solutions have to be

passed through pumps and other equipment, and present special problems in which both corrosion and erosion of the combined liquid and solid play a considerable part.

Heat-Resistance of Austenitic Cast Irons.

The austenitic cast irons show marked superiority over ordinary cast iron when subjected to elevated temperatures. It is well known that, when castings in ordinary cast iron are repeatedly heated, the metal scales badly and burns away, the castings becoming distorted and weakened by growth and internal oxidation.

In ordinary cast iron it is now generally believed that the incidence of the critical range round about a temperature of 700° C.—which causes internal structural change of the metal, accompanied by volume change—tends on repeated heating and cooling to open up the metal, thus permitting access of the atmosphere with resultant internal oxidation and deterioration. This internal oxidation is accompanied by a permanent increase in volume, which causes distortion and frequently fracture.

Due to the nature of the structure of the austenitic cast irons, there are no critical changes corresponding to those found in ordinary cast iron, so that there is no tendency for the metal to open up on heating. Further, the austenitic structure is found to be more resistant to oxidation, so that the castings do not tend to scale and burn as in the case of ordinary iron. Consequently the austenitic cast irons prove suitable for applications at elevated temperatures when the ordinary iron is inadequate.

For heat-resisting applications it is found beneficial to use chromium up to the highest limit compatible with the strength and machining requirements of the castings, chromium assisting in improving the oxidation-resistance of the body of the metal. Generally up to 5 per cent. of chromium may be used in compositions such as are discussed above without introducing too much difficulty in machining. Where the castings do not have to be machined, even higher proportions of chromium may be added with further benefit to the heat-resisting properties of the iron.

As heat-resisting materials the austenitic cast irons are finding many applications, including furnace castings for the chemical industry, where combined heat- and corrosion-resistance is desired, and in many other parts in industrial equipment where ordinary cast iron is not good enough.

A recent development in this field is the austenitic nickel-silicon cast iron known as " Nicrosilal." This alloy, which has been developed by the British Cast Iron Research Association, consists essentially of an iron in the austenitic condition by virtue of the presence of 18 per cent. of nickel. The heat- and scale-resistance of the alloy has

been enhanced by the use of a small proportion of chromium and an abnormally high silicon content, the latter being as much as 6 per cent.

Non-Magnetic and Electrical Properties of Austenitic Cast Irons.

The demand of the electrical industry for castings which are non-magnetic was originally supplied by the use of such non-ferrous alloys as brass and bronze. The austenitic cast irons now offer a satisfactory solution of the problem, the irons being, for all practical purposes, non-magnetic.

Although the nickel-manganese austenitic cast iron developed under the name of " Nomag " was originally intended especially for use in this field, it is now realised that the non-magnetic property is a feature of the austenitic cast irons as a group, so that many of them, under suitable control of composition, can be used in this application.

Generally it is found that the austenitic cast irons possess a specific electrical resistance about 50 per cent. higher than that of ordinary cast iron, whilst at the same time they have the added advantage of a relatively low resistance-temperature coefficient.

Austenitic Cast Irons of High Expansion.

The coefficient of thermal expansion of the austenitic cast irons is generally about 18 or 20 millionths as compared with about 12 millionths for ordinary cast iron. This has proved of value where cast iron is required to work in conjunction with alloys possessing a high expansion, under conditions of varying or elevated temperatures.

The more important alloy cast irons are summarised in Table 13.

Iron Castings for Vitreous Enamelling.—An iron fairly high in silicon is generally used. It is essential that the castings should be of regular and uniform composition. Typical analysis: total carbon 3·50, silicon 2·5 to 3·0, sulphur 0·08, phosphorus 1·5, manganese 0·3.

In continental and American practice the phosphorus is usually about 0·5 and manganese up to 1·0. A combination of high phosphorus and high manganese should be avoided.

High-Silicon Acid-resisting Cast Irons.

The first successful corrosion-resisting irons were of the high-silicon type (12 per cent. Si and above), as in spite of many shortcomings such alloys were found to possess valuable corrosion-resisting properties. Although the raw materials are not expensive, yet the process of casting is difficult and the cost of such castings is rather higher than ordinary cast iron.

TABLE 13.

Composition and Properties of Alloy Cast Irons.

Key Letter.	Description of Iron.		Total Carbon.	Silicon.	Manganese.	Nickel.	Chromium.	Tensile Strength (tons/sq. in.).	Brinell Hardness.	Heat Treatment.
A	NICKEL CAST IRON for Light Sections	for machinability, density, strength and wearing quality	3·3	1·8	0·7	1·5	—	18	220	—
B	NICKEL CAST IRON for Medium Sections		3·2	1·2	0·7	1·25	—	18	210	Y
C	NICKEL-CHROMIUM CAST IRON for Medium Sections		3·2	1·6	0·7	1·25	0·5	18	220	Y
D	NICKEL-CHROMIUM CAST IRON for Heavy Sections		3·2	1·0	0·7	1·25	0·5	18	200	Y
E	NICKEL-CHROMIUM CAST IRON	for heat resistance	3·2	1·2	0·8	1·0	1·0	17	250	Y
F	NI-TENSYL	for maximum strength	2·9	1·5	0·8	1·5	—	22	220	Y
G	HARD GREY IRON	for maximum wearing quality and machinability without heat treatment	3·3	1·2	0·8	3·0	0·5	20	300	Y
H	MARTENSITIC IRON	for wearing quality where maximum hardness as cast is required	3·3	1·2	0·8	5·0	0·75	20	400	
J	HEAT-TREATABLE CAST IRON for Light Sections	for wearing quality and strength after heat-treatment	3·3	1·6	0·7	2·0	—	25	350	Z
K	HEAT-TREATABLE CAST IRON for Heavy Sections		3·2	1·4	0·7	2·5	0·5	25	300	Z
L	NICKEL WHITE IRON	for improved toughness and hardness in white iron castings	3·0	0·7	0·8	1·5	0·5	22	450	—
M	NI-HARD ‡	for high-hardness and toughness in white or chilled cast iron	3·0	0·7	0·8	3·0	0·75	22	550	—
P	NI-HARD ‡	for maximum hardness and toughness in white or chilled cast iron	3·0	0·7	0·8	4·5	1·5	22	650	—
R	NOMAG	for non-magnetic castings	3·0	1·5	7·0	11·0	—	16	180	—
S	NI-RESIST	for resistance to heat and corrosion	3·0	1·5	1·0	14·0 *	2·0	16	180	—
T	NICROSILAL ‡	for maximum heat-resistance	1·7	4·5	0·8	18·0	2·0 †	16	180	—
V	LOW EXPANSION CAST IRON		2·2	1·5	0·8	34·0	2·0	14	180	—

NOTES.

* Normal "Ni-Resist" contains also 7·0 per cent. of copper. If copper-free metal is desired increase nickel to 22·0 per cent.

† For hard grades chromium may be increased to 5·0 per cent.

‡ The production of these irons is covered by Letters Patent.

HEAT TREATMENT.

Y—for complicated castings a normalising treatment is recommended. Heat at 450–500° C. for ½–4 hours according to mass.

Z—oil quench from 850° C., temper at 350° C.

Since the properties of cast iron are influenced to a high degree by the size of the casting or section thickness, the properties given should be taken only as a rough guide. If modification of the properties is desired, the adjacent suggestions will be found helpful when dealing with the grey iron castings containing nickel up to 2 per cent.

IF CASTINGS ARE TOO HARD
Increase nickel or decrease chromium.

IF CASTINGS ARE TOO SOFT OR WEAK
Increase both nickel and chromium or decrease Silicon.

Further improvement in strength and toughness can be obtained in many of the compositions by the use of up to 0·5 per cent. of molybdenum.

Kowalke in America has carried out a comprehensive series of tests with irons of varying silicon content with the following results :—

TABLE 14.

SILICON IRONS.

LOSS IN 10 PER CENT. SULPHURIC ACID.

Si (per cent.).	Area (sq. cm.).	Cumulative Loss (per cent.).		
		51 hrs.	75 hrs.	141 hrs.
2·5	15·7	1·6	4·1	6·5
3·3	21·9	64·9	87·5	92·8
7·4	11·5	31·0	48·9	62·0
9·9	12·7	10·7	19·8	23·1
11·1	13·0	5·0	8·8	13·1
12·4	9·2	1·2	2·1	2·4
13·6	16·6	0·2	0·6	0·9
14·8	18·0	0·03	0·05	0·05
16·1	10·2	0·03	0·04	0·04
17·3	11·9	0·03	0·03	0·03
19·8	9·6	0·13	0·2	0·25

TABLE 15.

LOSS IN 10 PER CENT. NITRIC ACID.

Si (per cent.).	Area (sq. cm.).	Cumulative Loss (per cent.).		
		115 hrs.	166 hrs.	14 days.
2·5	8·4	20·8	48·0	53·5
3·3	11·8	13·3	21·6	22·1
7·4	11·2	8·9	11·1	11·4
9·9	7·3	5·9	8·7	8·9
11·1	10·4	2·4	3·5	3·6
12·4	13·1	2·3	4·6	4·6
13·6	11·7	0·05	0·1	0·1
14·8	6·3	0·013	0·02	0·02
16·1	11·4	0·006	0·003	0·0015
17·3	11·2	0·006	0·007	0·007
18·5	8·9	0·037	0·044	0·046
19·8	13·8	0·01	0·01	0·01

TABLE 16.

LOSS IN 10 PER CENT. HYDROCHLORIC ACID.

Si (per cent.).	Area (sq. cm.).	Cumulative Loss (per cent.).		
		7 days.	10 days.	21 days.
2·5	8·4	2·4	10·0	15·7
3·3	11·8	9·71	38·7	60·8
7·4	11·2	5·2	19·0	27·3
9·9	7·3	7·1	16·4	21·1
11·1	10·4	4·9	8·1	9·4
12·4	13·1	1·4	2·7	4·0
13·6	11·7	0·18	0·51	0·67
14·8	6·3	0·12	0·31	0·42
16·1	11·4	0·12	0·27	0·36
17·3	11·2	0·31	0·40	0·41
18·5	8·9	0·03	0·03	0·04
19·8	10·8	0·1	0·28	0·28

(Tungay, *J.S.C.I.*, 1918, *37*, 81T.)

It will be noted from the foregoing tables that silicon, if present in a lesser quantity than 12 per cent., does not promote really satisfactory corrosion resistance, and when the silicon content exceeds 19 per cent. the corrosion-resistance appears to fall again.

Although pipes of high-silicon iron were used in France in 1903 for the direct condensation of nitric acid, it was only after a great deal of patient research that the high-silicon iron became commercially successful and consistently reliable; the early difficulties were chiefly in regard to close control of the silicon content, and troubles due to the considerable shrinkage during cooling.

It was also soon found that low carbon and phosphorus was essential to the production of successful castings with high-silicon content. The early difficulties of manufacture can now definitely be said to have been overcome, and firms specialising in such high-silicon irons can guarantee consistent results in both large and small castings. Recently, some makers are adding a small quantity of copper or nickel to the regular mixture, and it is stated that such additions improve the corrosion-resistance. Another type is one which is low in carbon, high in manganese, and with an aluminium content of 0·25 per cent. In the manufacture of picric acid and for moderate concentrations of sulphuric and nitric acids 15 per cent. silicon content is often used.

For resistance to hydrochloric acid, 20/21 per cent. silicon content is often employed. For the chlorination and concentration of

nitric acid and for acetic acid, 16 per cent. silicon content is often used.

All the high-silicon irons are very hard and brittle and therefore cannot be machined except by high-speed grinding. Hence certain definite points must be held in mind in designing parts of plant or apparatus for manufacture in these acid resisting irons. All joints in pipe-work and vessels should be formed by means of flanges or spigot and socket, since the metal is too hard to screw or to take a screwed thread, and it is preferable so to design pipes and cored castings, that the use of chaplets can be avoided as far as possible. Another point in design is that all sharp corners must as far as possible be avoided, owing to the considerable shrinkage in cooling which has already been mentioned, otherwise sharp corners will become a source of weakness, and the vessel is very likely to sustain a fracture through strains set up by shrinkage in cooling. For the same reason, all vessels such as boiling-pans, receivers, stills, should be made curved at the bottom, as large flat surfaces present difficulties through contraction of the castings.

Few of these acid-resisting irons can be recommended for vessels which are required to be worked at high internal pressures, and it is not usually considered safe to use such pressure vessels for an internal pressure higher than 50 lbs. per sq. in., except in cases where the vessels are of small dimensions.

It is to be noted that the high-silicon irons are not suitable for bromine, fused alkalis or hot caustic solutions.

The high-silicon irons can be welded by the oxy-acetylene process, if the parts are carefully preheated and cooled shortly after the welding operation. Most manufacturers of high-silicon irons can supply special alloy welding-rods for the purpose.

The Duriron Company of Dayton, Ohio, make a high-silicon iron known commercially as " Duriron," which contains approximately 14·5 per cent. silicon. The physical and mechanical properties of this alloy are as follows :—

Duriron (14·5 per cent. Si Iron)		
Weight		0·255 lbs./cu. in.
Melting point		2300° F.
Thermal conductivity (Ag = 1)	0° C.	0·125
Coefficient of expansion	32–212° F.	0·0000036″
	32–392° F.	0·00000470″
Tensile strength on ½-in. dia. bar		16,000 lbs./sq. in.

For handling hydrochloric acid, the Duriron Company manufactures a high-silicon iron known as Durichlor.

Haughton's Metallic Manufacturing Company of London manufacture a high-silicon iron known as " Ironac " and corrosion tests of this material are given in Table 17.

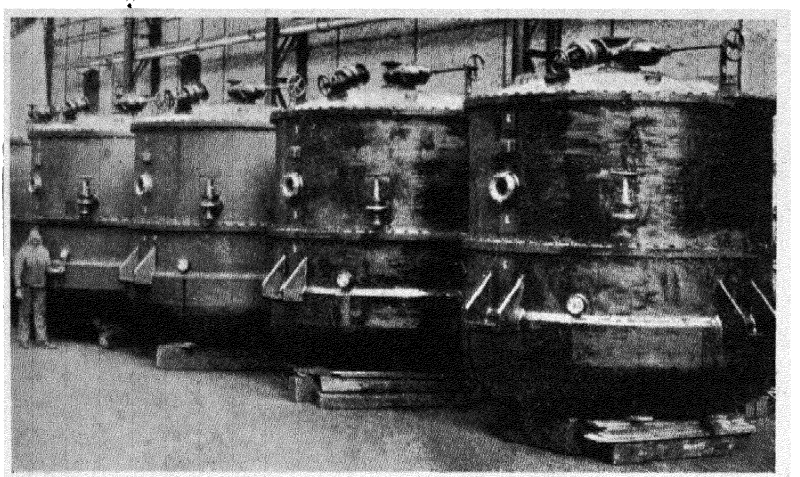


FIG. 32.

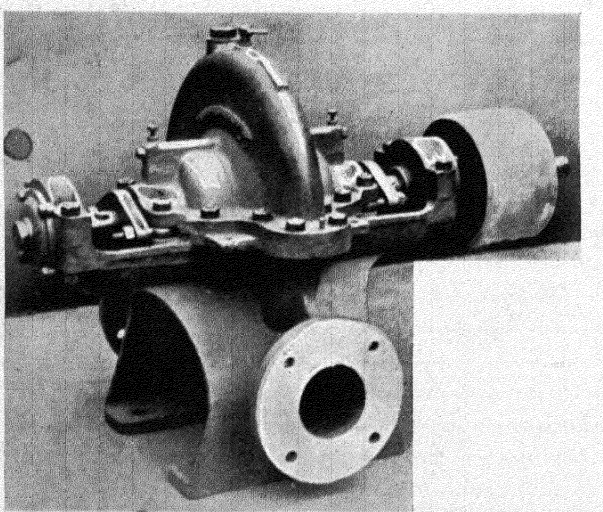


FIG. 33.

[*To face page* 89.

TABLE 17.

CORROSION TESTS ON "IRONAC" ACID-RESISTING IRON.

Acid.	Initial Weight (gms.).	Loss after Boiling at 150° C. for :—		
		24 hrs.	48 hrs.	72 hrs.
Sulphuric acid 65 per cent.	112·648	Nil	Nil	Nil
Sulphuric acid 20 per cent.	115·207	Nil	Nil	Nil
Nitric acid 90 per cent. .	13·392	0·011	0·038	0·074
Nitric acid 30 per cent. .	116·629	0·013	0·016	0·016

Loss after boiling in mixed acids as follows :—

Mixed Acid.	—	Original Weight (gms.).	Loss in gms.
65 per cent. H_2SO_4	24 hrs. at 150° C.	(1) 303·0	Nil
2 per cent. HNO_3	—	(2) 385·59	Nil
33 per cent. water	—	(3) 15·903	Nil
	15 hrs. at 150° C.	(1) 302·9	0·1
		(2) 385·59	Nil
		(3) 15·903	Nil
	15·5 hrs. at 150° C.	(1) 302·6	0·3
		(2) 385·5	0·09
	12·5 hrs. at 150° C. to 260° C.	(1) 302·6	Nil
		(2) 385·5	Nil
		(3) 15·903	0·08

Nitrogen Hardened Cast Irons.—These special irons are finding an increasing use for cylinder liners of compressors, for valve and pump parts, etc., where high hardness combined with adequate mechanical strength is required. A typical alloy cast iron of this type is "*Nitricastiron*." particulars of which are as follows :—

It is an alloy susceptible to heat treatment with a composition of the order of total carbon 2·65, silicon 2·5, manganese 0·6, sulphur 0·07, phosphorus 0·10, chromium 1·65, aluminium 1·40. To harden the articles they are placed within a furnace in a gas-tight box fitted with inlet and outlet branches for the circulation of ammonia gas. The ammonia undergoes dissociation and the nitrogen combines with the outer layer or skin of the iron to form a very hard casing. (*Note.*—Parts not required to be hardened can readily be protected against the action of the ammonia gas.) The best results as regards hardness and depth of penetration are obtained on castings with finely machined or ground surfaces. The usual depth of penetration

is of the order of 0·015 in. Typical tests on nitricastiron are as follows :—

Condition.	Nitricastiron.	
	Mod. of Elas. Lbs./sq. ins. × 10^6.	Diamond Hardness.
As cast	19·5–22·5	340–418
Annealed—slow cooled from 950°	19·7–22·5	269–300
Hardened : stabilised oil quenched from 870°. Reheated to 600°. Cooled slowly	19·2–22·7	300–307
Nitrogen hardened 90 hours at 510°	20·1–24·8	904–962

Figs 32, 33, 34, 35 show chemical equipment made from these alloy cast irons. Fig. 32 shows vacuum concentration pans (by the Maschinen Fabrik Sangerhausen A.G.) for use with caustic alkalis. The lower part of each container is in 2 per cent. nickel cast iron. Fig. 33 shows a centrifugal pump—Austenitic cast iron by Gwynne Pumps Ltd., and Fig. 34 shows coke crusher segments in Ni. Hard. A large crusher plant frame in Ni. Tensyl is seen in Fig. 35.

Vitreous Enamelled Cast Iron.

Considerable use is made in the chemical industry of vitreous enamelled cast iron ware in the form of stills, condensers, pans and the like. Such enamel ware is of particular use in cases where high purity of product is essential. Care is necessary with such plant to avoid chipping of the enamel coating, but with care enamal ware will last for long periods.

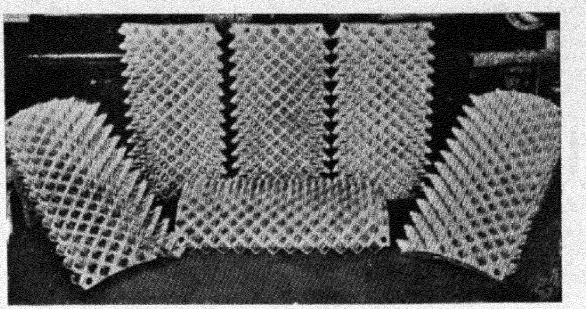


FIG. 34.

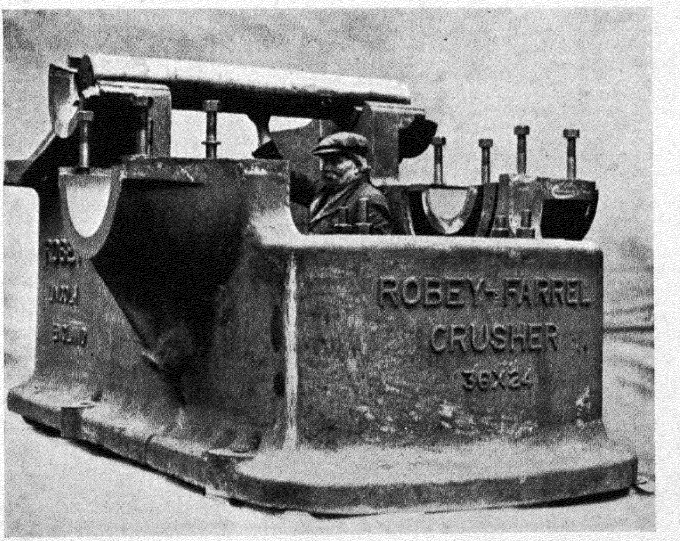


FIG. 35.

[*To face page* 90.

CHAPTER III.

STEELS AND ALLOY STEELS.

THE term "steel" is used in a general sense to describe those alloys of iron and carbon in which the carbon is present entirely, or almost entirely in the combined condition and in which the carbon content is below about 2 per cent. In addition, the term "steel" has of recent years been applied to alloys of iron and carbon with other elements (such as nickel, chromium, copper molybdenum) which are usually in excess of the carbon content and the presence of which considerably modifies the resulting material. These alloys are generally described as alloy steels.

Steels may be classified as follows :—

(1) Plain carbon steels.
(2) Low-alloy steels of the structural type.
(3) Corrosion-resisting steels.
(4) Heat-resisting steels.

The properties and application of the various classes of steels will now be discussed in detail.

1. *Plain Carbon Steels.*

Carbon in steel in sufficient amounts renders it susceptible to hardening; below 0·15 per cent., however, carbon steels show no appreciable hardening effect when rapidly cooled. As the percentage of carbon in plain carbon steels rises, so does the tensile strength and hardness with a corresponding reduction in the ductility of the material.

Plain Carbon Steels are usually classified according to the carbon content, which may vary from 0·05 per cent. to 1·0 per cent.

A large number of authorities (the British Standards Institution, Boiler Insurance Companies, the Board of Trade, Lloyds Register of Shipping, the A.S.M.E. Boiler Construction Code) issue detailed specifications for all classes of carbon steel for plates, forgings and castings, and one or other of these specifications should preferably be used when designing and fabricating equipment such as pressure vessels, tubes, valve and other castings, etc., from steels and alloys thereof.

Many chemical processes of to-day demand qualities not obtainable in plain carbon steels, and hence recourse must be had to either

structural alloy steels, which are used when corrosive conditions do not apply, or the more highly alloyed corrosion- and heat-resisting steels.

Before describing in detail the various classes of alloy steels now available, the heat treatment of steel will be discussed owing to its important bearing upon the usefulness and correct application of alloy steels.

Heat Treatment of Steels.

The fact that steel is capable of being heat-treated is dependent on the existence of two forms of iron, one capable of dissolving carbon up to 0·9 per cent., the other of dissolving it only to a very limited extent. The second form, known as Alpha iron, is stable at ordinary temperatures and, in the presence of carbon only, changes on heating into the former (Gamma iron), at a temperature of about 730° C. The reverse change takes place on slow cooling, at a slightly lower temperature. In steels containing approximately 0·9 per cent. carbon, this is the only temperature at which a change occurs, but for lower carbon contents, there is an "upper" change point, indicating the minimum temperature to be exceeded before grain refinement can be accomplished. The temperature of the upper change point varies inversely with the carbon content of the steel, falling from about 900° C. for 0·1 per cent. carbon to about 730° C. for 0·9 per cent.

The properties of steel vary with, and are dependent upon, the rate of cooling through the change points. In a medium carbon steel a slow rate of cooling gives a soft and ductile product, while small and medium-size sections cooled rapidly are hard and brittle. The rate of cooling necessary to produce the hard, or fully hardened, condition will depend on the analysis of the steel and the mass of the section being cooled. Reheating the rapidly cooled or quenched steel results in a lowering of the hardness, accompanied by an increase in the ductility. The best combination of mechanical properties results from an effective quenching (hardening) followed by suitable reheating (tempering)

In medium carbon steels, thin strip section will develop full hardness by quenching in oil, but for thicker parts over $\frac{1}{2}$ in., water quenching is necessary to induce complete hardening, and such drastic quenching often induces considerable distortion accompanied by risk of cracking.

The addition to steel of alloy elements lowers the rate of cooling necessary to obtain an efficient quench, and the effect of the quenching in inducing complete hardening will penetrate to the centre of a larger mass. The presence of alloy elements in the steel makes it possible to use oil instead of water as quenching medium, thus reducing

the risk of serious distortion and cracking and, at the same time, enables higher tensile strength to be obtained in larger masses. If sufficient content of alloy element or elements are present, complete hardening may be induced in fairly large masses, even by cooling in still air.

Hardening.—The hardening temperature varies according to the composition, from about 780° to 880° C., the best hardening temperature being usually about 20–30° C. above the upper change point of the steel. Cooling from the hardening temperature should be rapid and uniform. If oil or air hardening gives sufficient surface hardness and depth of penetration, they are preferable to water hardening, as less strains are thereby set up in the material.

Tempering.—Tempering consists of reheating the hardened steel to any temperature below the carbon change point—about 650° C.—the actual temperature varying slightly with the composition of the steel.

A fully hardened steel, on account of its brittleness and state of stress, has very limited application in spite of its great hardness. By reheating the steel, the internal strains can be relieved primarily without great loss of hardness, but the steel remains comparatively brittle. If the tempering temperature is progressively raised, the hardness rapidly drops while the toughness simultaneously increases.

Steel should be tempered as soon as possible after hardening, in order to minimise the risk of cracking. The tempering may be followed by rapid or slow (except in the case of steels susceptible to temper-brittleness, dealt with later) cooling without materially affecting the properties.

Normalising.—Considerable improvement in the mechanical properties of carbon steel and steels of low alloy content may result from cooling in still air from a temperature slightly above the upper change point. This method of treatment is termed normalising. In the case of certain applications of steel, where the best properties are not called for or price is of primary importance, the parts are subjected to a normalising treatment. Practically similar results are obtained by careful control of the finishing temperature of rolling, the steel being cooled in still air from the rolls.

If, however, the final hot working temperatures are too high, an excessively coarse structure is produced, while, if the temperatures are too low, excessive strains may exist in the product. Such deleterious effects are removed in steels of suitable composition by normalising, provided the analyses of the steels are such that air cooling is not sufficiently rapid to produce any marked increase in hardness.

Annealing.—In order to produce the softest possible condition, steel is subjected to an annealing process. In the case of carbon

steels and steels of low alloy content, the treatment consists of heating to about 750° C., and cooling very slowly. Annealing, whilst resulting in a softer condition than normalising, does not produce a steel of satisfactory mechanical properties.

Many alloy steels will respond to this annealing treatment at 750° C., but, with steels of high-alloy contents, sufficient softness is not usually induced by treatment at this temperature, and in such cases the softest condition may be produced by a prolonged tempering treatment, a suitable temperature for most alloy steels being 640° C.

Case Hardening.—For certain working parts it is desirable to have a steel with an extremely hard surface to resist wear, and a very tough interior to withstand shock. These diverse requirements are embodied in a case-hardened steel of suitable composition. By the case-hardening process soft steel is given a high carbon content (up to about 1 per cent.) at and near the surface. When such a steel is suitably heat-treated the surface is rendered very hard, while the low carbon core remains soft and ductile.

Case hardening is carried out on machined parts by packing in some suitable material rich in carbon, and heating to a temperature of about 900° C. At this temperature the steel absorbs carbon, the time and temperature being regulated according to the carbon content and the depth of case required, but in no instance should the carbon content greatly exceed 0·90 per cent.

The heat treatment of case-hardened parts presents quite a different problem from that offered by steels considered in the preceding section, as here there are two steels of different composition to be heat-treated together to give totally different properties. The carbonised steel has undergone a prolonged heating at a temperature which gives rise to an excessive grain growth in the core. This structure is refined by heating to just over the upper critical change point, between 830 and 900° C., depending on the composition of the steel, soaking thoroughly and then quenching in water or oil. The core is now too hard and brittle and the case will still retain an overheated structure ; the steel is therefore reheated to the refining temperature usually employed for a 0·9 per cent. carbon steel, i.e. 750–770° C., and again quenched. The case is now fully hardened, and the core made ductile. The best results, as far as the core is concerned, are obtained when the parts are quickly brought up from about 600° C. to the final heat and then quenched out. It is advisable to carry out a final low-temperature tempering at 150–200° C., in order to relieve hardening strains in the case.

The properties of case-hardening steels can be greatly improved by the addition of alloying elements.

The Effect of Various Elements on Mechanical Properties of Structural Steels.

It is impossible, within the scope of the space available in this book, to deal fully with the properties of the various structural alloy steels, but an attempt will be made to indicate broadly the inherent effects of the various alloy elements on steel, firstly upon the structural engineering steels.

As engineering development has proceeded, the tendency has been to demand higher and higher tensile strength, accompanied by adequate ductility for steel structural parts. The demand was met to a limited extent in carbon steels by increasing the carbon content, but a limit was soon reached, in that the increase in tensile strength was invariably accompanied by a rapid fall in ductility, amounting ultimately to decided brittleness. Another limitation to the use of carbon steel soon became evident, in that, for sections in general use, it was not possible to obtain a fully hardened and tempered condition throughout the mass. It is for this reason, apart from the general improved properties, that alloy steels have been so widely adopted.

Manganese.—All carbon structural steels contain appreciable quantities of manganese, varying usually from 0·4 to 0·8 per cent. There has been a decided tendency lately towards increasing the manganese content of carbon steels. It has been found that increased tensile strength can be obtained in this manner without appreciable loss of ductility while, by substituting manganese for part of the carbon content to give equal tensile strength, greatly improved properties are obtained (see Table) both in the normal and heat-treated steels.

NORMALISED $1\frac{1}{8}$-IN. DIA. BAR.

C	Mn	Max. Stress (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent. on 2 ins.).	Reduction of Area (per cent.).	Average Izod (ft.-lbs.).
0·38	0·70	41·9	27·2	24·5	46	38
0·36	1·34	41·8	27·0	30·0	64	61

The best combination of properties can only be obtained by careful adjustment of the carbon and manganese contents.

In the case of normalising steels, or steels for use in the " as rolled " condition, excessive manganese content will induce air hardening, resulting in considerable increase in hardness but accompanied by a lowering of the yield point, elongation, reduction of area and impact figure. The effect may, of course, be avoided by cooling more slowly, but the use in place of mild steel of a steel which may air harden is very inadvisable if the steel is to be used in the same condition as mild

steel, i.e. as rolled or normalised. (If properly heat-treated by hardening and tempering it would be satisfactory.) The permissible high limit of manganese must, therefore, be adjusted to suit the carbon content. To avoid air hardening, the manganese should be decreased from about 1·8 per cent. with 0·2 per cent. carbon to 1·4 per cent. with 0·35 per cent. carbon.

For certain applications where it is necessary to dispense with a quenching treatment, improved properties may be obtained by increasing the manganese content or adding a small percentage of another element such as nickel, chromium or molybdenum (the resulting steel thus becoming slightly air hardened), and subjecting the steel after air cooling to tempering at a suitable temperature.

After oil hardening and tempering all the mechanical properties of a medium carbon steel (0·4 per cent. C.) are improved by the presence of manganese up to about 2 per cent. Additional manganese gives little further improvement, and may introduce difficulties in forging.

Another development involving higher manganese content has resulted from endeavours to reduce the cost of certain alloy steels. Substitution of part of the nickel in steel by manganese can be carried out without detriment to the properties, while the combination of nickel and manganese is quite effective in reducing the deleterious effect of mass. A particularly effective combination is that of manganese and molybdenum.

The effect on the change points of manganese contents of the order under consideration is very slight, though lower hardening temperatures can usually be employed advantageously in the presence of high manganese.

Nickel.—Nickel was probably one of the first alloy elements used in the endeavour to obtain increased strength and toughness over those obtained in the ordinary rolled structural steel. The development and possibilities of heat treatment have greatly enhanced the value of nickel as an alloying element in steel. Nickel lowers the temperature of the change points. The lower change point is depressed by about 10° C. for each 1 per cent. of nickel present, and, consequently, the maximum temperature allowable for tempering is lowered by a corresponding amount.

Generally, for commercial treatment, a 3 per cent. nickel steel should not be tempered above 640° C. It is also possible, and advisable, to employ lower hardening temperatures for nickel steels as compared with carbon steels, though the deleterious effect of overheating is considerably lessened by the presence of nickel.

Nickel has a general strengthening effect on steel and produces a refinement in the general structure, while it inhibits grain growth at high temperatures. Thus, even for small sections, considerably enhanced strength, accompanied by increased ductility, will be ob-

tained by the addition of nickel to a carbon steel; for larger sections, the effect becomes still more pronounced. It may be stated that, compared with carbon steels, nickel steels show greater toughness for the same tensile strength, or greater tensile strength combined with greater ductility, both in the normal and heat-treated condition. In this connection, the improved notched bar figures are particularly noticeable.

The beneficial effect of additions of nickel on the mechanical properties are clearly illustrated in the figures which follow :—

OIL-HARDENED AND TEMPERED 1⅛-IN. DIAMETER BARS.

C	Mn	Ni	Max. Stress (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent. on 2 ins.).	Reduction of Area (per cent.).	Average Izod (ft.-lbs.).
0·45	0·69	- -	46·0	30·6	23·5	52	47
0·38	0·73	0·91	53·7	37·6	23·5	53	48
0·31	0·62	3·08	56·2	47·8	23·5	62	64

The refining and toughening action of nickel finds increasing application in the manufacture of large steel parts which can only be given the simplest of treatments. Rolled sections and large forgings in nickel steel containing up to 3·25 per cent. nickel give greatly improved properties after a simple normalising treatment consisting of cooling in air from about 840° C.

With higher carbon or nickel contents, the rate of cooling in air, as in the case of steels containing high manganese, is sufficiently rapid to induce a certain amount of hardening, accompanied by a marked loss in ductility but, here again, a simple tempering treatment may be applied. However, it is in the fully heat-treated condition that the presence of nickel in steel exerts its greatest value. To take full advantage of the various properties in nickel steel, a fairly wide range of analyses are used, some analyses being better suited for one purpose than another.

After oil hardening and tempering, all the properties of a medium carbon steel are improved by the addition of nickel up to probably 6 per cent., the strength, yield point and impact figures being raised without a corresponding loss in ductility.

Chromium.—Chromium is another element which has a hardening effect on steel, and it is an important constituent of many alloy steels. It is used alone or in combination with one or more of the other usual alloy elements, and particularly with nickel. The nickel-chromium steels constitute the most important group of heat-treated high-tensile alloy steels.

Chromium raises the temperature of the change point in steel by

about 25° C. for each 1 per cent. of chromium present, and this makes it advisable to modify the temperatures of treatment as applied to carbon steels. In particular, the tempering treatments of the higher chromium steels may safely be carried out at temperatures considerably higher than those permissible for carbon steels or steels containing nickel.

After oil hardening and tempering, all the mechanical properties of a 0·4 per cent. carbon steel are improved by the presence of chromium up to about 2 per cent., and even up to 3 per cent. some improvement in impact figure is obtained after tempering at a high temperature. Chromium has a marked effect in increasing the penetration of the quenching effect during hardening. The higher carbon-chromium steels find application where extreme hardness and resistance to wear is desired.

With higher chromium contents of the order of 12 per cent. and over, very marked characteristics are developed in the steel, in so far as increased resistance to general corrosion is concerned.

Nickel Chromium. The presence of both nickel and chromium in steel ensures considerable hardening, with a rate of cooling through the change point slower than that permissible in the case of steels with a similar content of either element alone, and, therefore, sections of still larger mass can be treated to give high tensile strength and uniformly good properties throughout the section. Nickel-chromium steels give remarkably high tensile strength and yield ratio, accompanied, when suitably heat-treated, by a high notched bar figure.

The improvement in properties obtained by the addition of 0·75 per cent. chromium to a 3½ per cent. nickel steel of the same carbon content is illustrated in the following tests :—

Section (ins.).	Max. Stress (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent. on 2 ins.).	Reduction of Area (per cent.).	Izod Value (ft.-lbs.).
3½ PER CENT. NICKEL STEEL. OIL HARDENED AND TEMPERED.					
1⅛	52·9	45·5	24·5	59	60
2¼	48·0	37·5	26·5	59	75
4½	48·0	35·1	25·5	55	65
3½ PER CENT. NICKEL, 0·75 PER CENT. CHROME STEEL.					
1⅛	61·6	56·6	21·5	62	60
2¼	61·1	56·1	21·0	61	58
4½	54·6	47·9	20·5	58	63

When sufficient nickel and chromium are present, the steel may be efficiently hardened by cooling in air.

Temper-Brittleness.

Some nickel-chromium steels are subject to temper-brittleness, which makes itself evident when tempering is carried out in the range 450–550° C., when the steel is cooled slowly through this range after tempering. Nickel-chromium steels treated in this manner give very low notched bar figures.

In medium-sized sections, air cooling after tempering is not sufficiently rapid to prevent an appreciable drop in the impact figure. The rate of cooling after tempering has no effect on the ductility of the steel as measured by the elongation and reduction of area.

When rapid cooling from the tempering temperature is impracticable, or the tensile properties required cannot be obtained by tempering outside this temper-brittle range, the susceptibility to temper-brittleness can be overcome by the addition of molybdenum.

Molybdenum.—During recent years, the use of molybdenum in steel has been very much developed.

Molybdenum has a pronounced effect, particularly in the presence of another alloy element, in improving the properties of heat-treated steel. It is most marked on the yield ratio and in eliminating the effects of mass and temper-brittleness. In steels developing temper-brittleness, the addition of about 0·3 per cent. of molybdenum eliminates this tendency; such steels are able to retain a high impact figure irrespective of the rate of cooling after tempering.

Test figures showing the effect of adding molybdenum to counter temper-brittleness:

Cooling Rate after Tempering.	Max. Stress (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent. on 2 ins.).	Reduction of Area (per cent.).	Izod Value (ft.-lbs.).
NICKEL-CHROMIUM STEEL.					
Oil	57·6	50·4	22·5	60	64
Furnace (slowly)	56·6	50·0	22·0	60	20
NICKEL-CHROMIUM STEEL WITH 0·45 PER CENT. MO. (Ni AND Cr CONTENTS AS FOR NiCr STEEL.)					
Oil	59·0	55·0	22·0	62	70
Furnace (slowly)	58·4	55·1	22·0	61	68

The addition of molybdenum to chromium steels results in marked improvements in physical properties, whilst the steels possess the property of being readily machinable, even when hardened and tempered to give high tensile strength. Molybdenum has a more powerful effect than nickel or chromium in reducing liability to incomplete hardening when the rate of cooling is comparatively slow.

Molybdenum also reduces the softening effect of tempering. Heat-treated alloy steels containing molybdenum can, therefore, be produced by choice of suitable composition to give high tensile strength in which, by long tempering at a high temperature, all quenching stresses are relieved without softening the steel beyond the desired strength. The advantage of prolonged tempering is reflected in the remarkably high notched bar figures obtained after such treatment.

Of all alloy steels, nickel-chromium-molybdenum steels reveal the best all-round combination of properties, particularly where high tensile strength, combined with good ductility, is desired in large masses.

The capability of nickel-chromium-molybdenum steels of complete hardening is shown by the relative absence of mass effect (as compared with nickel-chromium steels) revealed by the uniformity of properties throughout the thickness of comparatively large masses.

Vanadium.—Vanadium, in the same manner as other alloy elements, has a beneficial effect on the mechanical properties of heat-treated steels, this being most evident in the presence of another alloy element. Plain vanadium steels are used only to a limited extent, but chromium-vanadium steels, containing about 0·15 per cent. vanadium, have found a wide field of application for small and medium-sized sections. The mechanical properties resemble those of nickel-chromium steels, but usually show an advantage as regards reduction of area and limit of proportionality. Chromium-vanadium steels of the usual composition are, however, considerably more susceptible to mass effect than the corresponding nickel-chromium steels.

Copper.—The use of copper as an addition element to mild steel has been known for at least a century. There are numerous references to samples of mild steel in various forms which have withstood atmospheric corrosion to a marked degree, and which, on being analysed, have been found to contain a small quantity of copper. It is only in comparatively recent years, however, that detailed investigations in this country and abroad have proved that the addition of copper to steel greatly increases its resistance to atmospheric corrosion. As a result, the employment of copper steels for constructional purposes has reached considerable proportions: for example, the output of "copper-bearing" steel in U.S.A. in 1929 was estimated at over 800,000 tons.

The amount of copper necessary to confer corrosion-resistance to steel is quite small and the hot working, welding and general fabrication of these steels are not different from those of mild steel. The required copper content is considered to be 0·25 per cent. to 0·5 per cent.

Reduction of Atmospheric Corrosion of Steel by Alloying with Copper.—It is found that the addition of copper increases considerably the resistance of atmospheric corrosion of mild steel under the vast majority of conditions. Hitherto the most exhaustive tests on the atmospheric

corrosion of iron and steel with and without copper additions had been carried out by the American Society for Testing Materials (Committee A 5), the results of which have been published from time to time in the Transactions of that society.

Interesting results are obtained by a comparison of the life of similar steels with and without 0·25 per cent. of copper. An analysis of the A.S.T.M. corrosion tests has been made by Kendall and Taylerson (*A.S.T.M.*, 1929, Vol. XXIX, Part 2, pp. 204–19), and from the curves which they publish, an approximate generalisation may be made that, for the conditions of the tests, the addition of 0·25 per cent. Cu to steel increases its life to nearly four times that of copper-free material. With iron the life is approximately doubled.

This reduced corrosion is attributed by various authorities to the protective nature of the rust on copper-steel, which tends to form an adherent skin and minimises further attack. The initiation of corrosion and the rate of rusting during the initial periods of exposure may be nearly as rapid with copper steels as with plain carbon steels ; it is only when the steels have been exposed for some time that their greatly superior resistance to atmospheric corrosion is apparent.

Mechanical Properties of Copper Steels.—The addition of 0·25 per cent. to 0·50 per cent. of copper raises the tensile strength and yield point of mild steel slightly with little effect on the ductility and working qualities, so that the net effect on the mechanical properties of the steel is slightly beneficial.

The following are average comparative mechanical properties for 0·25 per cent. carbon steels with and without copper in the form of hot rolled sheet $\frac{3}{8}$ in. thick (as used for the tests of the Corrosion Committee of the Iron and Steel Industrial Research Council, First Report, p. 136).

Copper Content (per cent.).	Maximum Stress (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent.).
0·015	30·8	16·6	30·5
0·2	31·5	18·4	29·75
0·45	32·4	19·9	27·4

Corrosion-resisting copper steels of higher carbon content, giving upwards of 90 tons per sq. in. tensile strength when drawn into wire, are used for wire ropes, etc.

The effect of certain additional elements on steel is enhanced when copper is also present. For example, a mild steel containing 0·25 per cent. molybdenum with 0·25 per cent. copper has considerably higher creep limit at temperatures of the order of 450° C. than a normal mild steel, while retaining similar working qualities ; such a steel is suitable for steam-pipes, etc.

Steel containing 0·25 per cent. to 0·50 per cent. copper with 1 per cent. chromium is used as a high-tensile, corrosion resistant, structural steel, and has approximately 40 tons per sq. in. tensile strength with 20 per cent. elongation.

Welding Qualities of Copper Steels.—A summary of the evidence about the welding properties of copper steels may be found in a paper by K. G. Lewis (*Iron and Steel Inst. Carnegie Schol. Memoirs*, 1932, Vol. 21). The steels reported on in this paper contained up to 0·75 per cent. copper, and all welded easily. Lewis also quoted a number of other authorities as to the weldability of copper steels. Opinion is agreed that the steels at present under consideration, which have 0·25 per cent. to 0·50 per cent. copper content, can be welded without difficulty.

Low-Carbon Nickel Steel to Replace Wrought Iron (DuNic).

An interesting development, which emphasises the excellent ductility derived from the introduction of nickel into steel, is a low-carbon nickel steel which has been designed to replace the better grades of wrought iron, and I am indebted to Messrs. Samuel Fox & Co. for the following information in this respect :—

The following tests show that, whilst the elongation and reduction of area called for by I.R.S. Specification M1/29 (Best Yorkshire Iron) are easily met, a slight increase in tensile is shown with a very considerable increase in yield, the average yield ratio, even on the higher tensile, being over 70 per cent., as against 56 per cent. called for by the specification :—

	Max. Stress (tons per sq. in.).	Yield Ratio (per cent.).	Elongation (per cent. on 8 × D).	Reduction of Area (per cent.).
I.R.S. Specification M1/29 .	21/23½	56 min.	29 min.	53 min.
Low CNi steel tested in full section of 1 1/16″ Bar	26·58	75	33·7	66·6
	Izod 103, 107, 107 Av. 105·7 ft.-lbs.			
	Cold Bend : 180° without fracture.			
	Nicked fracture : Fibrous.			
	(Steel supplied in the "as rolled" condition.)			

If tested in the Izod machine, most wrought-iron samples give very variable Izod figures, mostly between 40 and 60 ft.-lbs. A minimum of 80 ft.-lbs. can easily be guaranteed on every bar of low-carbon nickel steel of this type.

In addition, despite the increased tensile, the steel meets conditions very satisfactorily as regards welding. The steel stands up well under abuse, and does not harden appreciably when cut with an oxy-acetylene flame.

Being made in fairly large casts, the steel can be depended on to give regular results. It was initially developed for locomotive staybolts and is being used by many railways, including the C.P.R. and New Zealand Government. The steel is now replacing wrought iron generally, and has been adopted by the Bengal Nagpur, East Indian and other Indian Railways.

Nitrogen Hardened Steels—" Nitralloy."—The hardening of the case of steels by exposure to ammonia at elevated temperature is based on the fact that steels of certain compositions will absorb nitrogen under these conditions. These steels undergo a eulectoid transformation at 580° C., and this enables an extremely hard *non*-brittle surface to be produced. A typical analysis of a " nitralloy " steel is : carbon 0·36 per cent., manganese 0·51, silicon 0·27, aluminium 1·23, chromium 1·49, sulphur 0·01, phosphorus 0·013, molybdenum 0·15. The nitriding process is carried out in a furnace the temperature of which must be closely controlled about 950° F. The parts to be hardened are placed in a gas-tight box provided with inlet and outlet connections for the circulation of ammonia gas. The process takes up to 90 hours, depending upon the desired depth of penetration of the hardened skin. The hardness of this case may be as high as 1066 (Diamond Hardness), whereas the core by suitable heat treatment may be rendered tough and shock resistant.

Corrosion-Resisting Steels.

Corrosion-resisting (or stainless) steels may be divided into two groups—the *martensitic* and the *austenitic*. The martensitic steels consist chiefly of the plain chromium steels containing 12–14 per cent. chromium, and a higher-chromium steel containing 18 per cent. chromium, with an addition of 2 per cent. of nickel.

All these martensitic steels are air hardening, and give a useful range of physical properties, the following being obtainable in the air-hardened and tempered condition, which is the best condition from a corrosion point of view.

C	Cr	Ni	Max. Stress (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent.).	Reduction of Area (per cent.).	Izod (ft.-lbs.).
0·10	12/14	—	70/40	60/30	12/40	40/70	20/100
0·16	12/14	—	95/45	90/40	10/30	12/70	40/120
0·22	12/14	—	100/50	95/45	10/30	12/65	15/70
0·35	12/14	—	110/50	100/45	4/30	4/50	5/30
0·10	18	2	65/45	50/30	20/30	55/60	60/80

The austenitic steels contain a higher percentage of chromium with

an addition of nickel and, in certain cases, smaller proportions of other alloying elements are added to enhance the resistance to corrosion.

The alloying elements usually added are tungsten, titanium, molybdenum and copper. The type which is in most general use is the well-known 18–8 chromium nickel.

All the steels in the austenitic group are very similar to each other as regards mechanical properties. They cannot be hardened by heat treatment and are put into their best corrosion-resisting condition by quenching from a temperature usually exceeding 1000° C., and in this state they give comparatively low tensile strength.

Max. Stress (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent.).	Reduction of Area (per cent.).	Izod (ft.-lbs.).
40/60	10/18	60	60	100

The properties of the martensitic and austenitic corrosion-resisting steels will now be discussed in detail, and the following notes are taken from W. H. Hatfield's interesting paper on the subject before the Chemical Engineering Congress, London, 1936.

Referring to Table 18, it will be noted that the first four steels differ essentially in carbon content. The object of this difference is to obtain various mechanical properties and to vary the form in which the material can be produced. For example, solid drawn tubes and large plates can only be made in the low carbon types, whereas for high hardness and wear resistance the higher carbon types are necessary.

No. 5 steel has been developed to provide improved corrosion-resistance as compared with 1–4, and also to retain the mechanical properties associated with the hardening steels. No. 6 provides superior corrosion-resistance.

No. 6 provides superior corrosion-resistance to the plain chromium steels 1–4, together with great ductility, rendering it particularly suitable for cold-working operations such as deep pressing. The standard high corrosion-resisting material for chemical work is, however, based upon the 18–8 chromium-nickel composition, the addition of 0·5–1·0 per cent. tungsten being made to give the steel an increased resistance to intercrystalline corrosion which is sufficient for many purposes. Complete immunity from this type of corrosion, even under the most drastic conditions of service and without any softening treatment after welding, is obtained by the addition of both titanium and tungsten together, as with the third steel in this group.

Steels 6 and 7 are fully austenitic. They cannot be hardened by heat-treatment and are most often used in the fully softened condition. Where greater hardness is required with these materials, resort must be had to cold working.

The addition of molybdenum to the 18–8 chromium-nickel steel confers special acid-resisting properties (e.g. to acetic acid and sulphuric acid). Such steels have an essentially austenitic structure, but are modified by the introduction of a new phase resulting from presence of the molybdenum.

Steel No. 13 was made to provide a material having a corrosion-resistance comparable with that of the ordinary 18–8 chromium-nickel steels, but having in addition a high yield point. It thus provides a material of special value for turbine blading where high steam temperatures and pressures have to be met.

Where the highest possible acid-resistance is required, it is sometimes necessary to employ more complex materials, and of these the most interesting is a steel containing approximately 14 per cent. chromium and 18 per cent. nickel, with 4 per cent. each of molybdenum and copper. This steel offers a particularly high resistance to sulphuric acid.

Application of the Corrosion-Resisting Steels.

Sulphuric, Hydrochloric and Nitric Acids.—In the manufacture of sulphuric and hydrochloric acids there is little scope for the use of special steels, but in nitric acid manufacture, steels 1–4 and 6–13 find one of their most important applications. Literally hundreds of tons of these steels, particularly the 18–8 chromium-nickel class of steel, have been used during the last ten years in the construction of plant for the manufacture and storage of this acid. The items of plant include oxidiser coolers, heat interchangers, towers, storage tanks, pumps, pipe-lines, valves and cocks, transport drums and tank wagons.

Resistance of 18–8 *Chromium-Nickel Type of Steel for Nitric Acid.*—Experience confirms that, bearing in mind the question of fabrication, the most suitable material for this work is the 18–8 chromium-nickel steel with suitable small additions of special elements to ensure freedom from intercrystalline corrosion. Such steel is practically unaffected by any strength of nitric acid in the cold, and it is only with the higher concentrations at temperatures approaching boiling point that some attack becomes apparent; in the very highest concentrations, e.g. 98 per cent. acid, its use is not recommended much above normal temperature.

Phosphoric Acid.—Phosphoric acid has become of considerable importance and in its manufacture there is a limited field of application for the special steels 6–13. Since small amounts of other acids, such as sulphuric, hydrochloric and hydrofluoric, are frequently present, it becomes necessary to know the details of any particular case before it is possible to give details of limiting concentrations and temperatures.

TABLE 18.

CORROSION-RESISTING STEELS.

No.	Typical Analysis. C	Cr	Ni	W	Ti	Mo	Cu	Si	Condition.	Mechanical Properties. Yield Point (tons per sq. in.).	Max. Stress (tons per sq. in.).	Elongation (per cent. on 2 ins.).	Reduction of Area (per cent.).	Brinell Hardness.	Young's Modulus of Elasticity (tons per sq. in.).	Physical Properties. Specific Gravity.	Coefficient of Thermal Expansion 20–100°	Thermal Conductivity (C.G.S. units).	Electrical Resistivity (Microhms per cm.³).	Maximum Permeability (C.G.S. units).
1	0·10 max.	12·0–15·0	—	—	—	—	—	—	Hardened and fully tempered or annealed	15–25	30–40	30–40	50–60	140–180	13,400	7·73	0·0000107	0·046	52–57	500
2	0·15 max.	12·0–15·0	—	—	—	—	—	—												
3	0·20–0·35	12·0–14·0	—	—	—	—	—	—	Hardened and fully tempered	25–35	40–50	20–30	50–60	200–240	13,700	7·75	0·0000107	0·050	50–55	650
									Hardened and lightly tempered	—	—	—	—	450–550	—	7·74	—		65–70	75
4	0·40–0·50	12·0–14·0	—	—	—	—	—	—	Hardened and lightly tempered	—	—	—	—	550	—	7·74	—	—	—	—
5	0·15	16·0–20·0	1·5–2·5	—	—	—	—	—	Hardened and tempered	35–50	50–60	15–25	40–60	240–280	13,500	7·70	0·0000104	0·040	72	210
6	0·10	12·5	12·5	—	—	—	—	—	Fully softened	13–17	35–40	40–60	40–60	130–150	12,900	8·01	0·0000181	0·030–0·035	70	1·005–1·03
7	0·15 max.	18·0	8·0	0·5–1·0	—	—	—	—	Fully softened	15–18	37–45	40–60	40–60	160–180	12,900	7·93	0·0000170	0·030–0·035	73	1·005–1·03
8	0·15 max.	18·0	8·0	0·5–1·0	0·5–1·0	—	—	—	Fully softened	16–20	40–50	35–50	40–50	160–200	13,000	7·90	0·0000168	0·030–0·035	73	1·5–1·03
9	0·07 max.	18·0	8·0	—	—	2·5–4·0	—	—	Fully softened	15–18	35–45	40–60	40–60	150–180	13,200	7·96	—	—	—	1·005–1·03
10	0·07 max.	18·0	10·0	—	—	1·0–1·5	—	—	Fully softened	15–18	35–45	40–60	40–60	150–180	13,200	7·96	0·0000170	0·030–0·035	73	—
11	0·15 max.	15–16	10·0–11·0	—	—	—	—	—	Fully softened	14–17	35–45	40–60	40–60	130–150	12,900	7·98	0·0000175	0·030–0·035	72	1·005–1·03
12	0·20–0·30	10–14	35·0–37·0	—	—	—	—	—	Fully softened	22–26	40–50	25–40	40–60	160–200	13,000	8·10	0·0000136	0·020–0·025	98	Slightly Magnetic BH = 3·500 for 150
13	0·25	20·0	9·0	—	1·3	—	—	—	Fully softened	26	45	30	55	230	13,000	7·88	0·0000150	0·030–0·035	82	4–10

Resistance of 18–8–2·5 Chromium-Nickel-Molybdenum Steel to Phosphoric Acid.—The addition of molybdenum to the 18–8 chromium-nickel steel offers some advantage, and in the case of such a steel containing 2·5 per cent. of this element, the following results were obtained in pure phosphoric acid solutions at boiling point :—

Concentration.	Loss in gr./sq. cm. /24 hrs.	Corresponding Loss in Thickness in mm. per year.
Conc. (S.G. 1·75)	0·5635	—
80 per cent.	0·0326	—
65 „ „	0·0112	5
50 „ „	0·0026	1
35 „ „	0·0003	0·1
20 „ „	0·0000	negligible
10 „ „	0·0000	„

At 80° C. the attack was in no case greater than 0·0002, i.e. less than 0·1 mm. per year.

Acetic Acid.—Turning to the organic acids, acetic acid is one of the most important, occurring not only as the pure acid but also in the form of vinegar. The excellent resistance of 18–8 chromium-nickel steels containing about 3 per cent. of molybdenum to acetic acid, and the fact that, unlike copper, this resistance is not seriously impaired by the presence of air, makes this material of great service in the preparation of this acid. For the less onerous conditions, the addition of molybdenum is not essential. The most drastic conditions appear to be boiling acid of strengths just below 100 per cent., and for these conditions the presence of molybdenum is essential, and even with molybdenum present there may be a very slight attack under these conditions.

Formic Acid.—The lowest member of the aliphatic series, formic acid, is considerably more corrosive than acetic. For this acid, only the 18–8 steel with molybdenum should be considered, and its usefulness is more limited than for acetic acid.

Stearic and Oleic Acids.—The corrosiveness of the acids of this series falls off with increasing molecular weight. For example, with stearic acid the plain 18–8 chromium-nickel steel withstands attack,

even with the boiling acid and vapour. This is also true with oleic acid.

Citric Acid.—In the later stages of the manufacture of citric acid, the conditions are complicated by the presence of relatively small amounts of sulphuric acid, and since it is in these stages that the use of special steels is desirable, it becomes necessary to allow for this factor. The 18–8 chromium-nickel steel without molybdenum offers a considerable degree of resistance to many conditions, but it is probably safer to rely upon the greater resistance of the 18–8 steel containing molybdenum. This steel shows a high resistance, even in concentration solutions, at high temperatures.

Lactic Acid. Lactic acid is usually encountered as a constituent of certain food products, such as cheese, milk, etc., and under these conditions is perfectly resisted by steels 6–13. If hot solutions of pure lactic acid are in question, the 18–8 steel with 3 per cent. molybdenum should be used, and even this material will not withstand the stronger solutions at boiling point under ordinary pressure.

Alkalis.—Alkaline solutions are much less corrosive than acid solutions to most materials, and there is not much call for special steels to meet alkaline conditions. In certain processes in which alkaline solutions are used in the presence of other substances, the superior resistance of the steels 6–13 has made them of service, but in the actual manufacture of alkalis they have not been applied to any extent. To solutions of ammonia and the alkali carbonates, of course, all the corrosion-resisting special steels are completely resistant at temperatures up to and including boiling point. With regard to caustic soda and caustic potash, although steels in Group 6–13 are resistant in all concentrations at normal temperature, they are attacked by hot strong solutions of these alkalis, and in such solutions offer little or no improvement over mild steel.

Fertilisers.—For ammonium sulphate, produced either as a by-product of the gas-works or from synthetic ammonia, the application of special steels of 6–13 is found in the final stages, for evaporators and centrifugal dryer baskets. The usefulness of these steels is determined by the free acidity (sulphuric) and the temperature involved, and since both these vary within fairly wide limits each case must be considered on its merits.

Nitrates.—These steels can be used with success for the production of nitrate fertilisers. The 18–8 chromium-nickel variety would normally be preferred.

Superphosphates.—The production of phosphate fertilisers usually involves the treatment of phosphatic materials with sulphuric acid and this limits the use of the special steels, although their resistance to phosphoric acid has rendered the 18–8 type of steel of service in certain particular cases. For other fertilisers, such as basic slag,

guanos, fish manures, and Chili nitrates, there does not appear to be a call for these special steels.

Fuel Production : *Corrosion-Resisting Steels for Oil Cracking.*—In oil cracking the presence of sulphur compounds has tended to confine the application of the special steels to the plain chromium material (steels 1–4) because nickel is not resistant to sulphurous gases at elevated temperatures. On the other hand, there are advantages in fabrication in the use of the 18–8 chromium-nickel type of steel, and the amount of nickel in this steel is not sufficient to modify appreciably the resistance conferred by the chromium, so that there would appear to be no reason why steels 6–13 should not be used with success.

Cellulose and Cellulose Products.

Cellulose Extraction—Sulphite Process.—There are two main methods of extraction of cellulose, one involving the digestion of wood-pulp with caustic alkali, and the other the treatment of the pulp with sulphite liquors. It is for the latter process that the special steels are used, the 18–8 chromium-nickel type having given satisfactory service. It is considered in some quarters that the addition of 3 per cent. of molybdenum gives improved resistance in the conditions obtaining in certain plants, and good resistance is also reported from manufacturers with austenitic chromium nickel steel of still higher alloy content.

Papermaking.—The first stage in producing paper from cellulose pulp, known as refining, involves the addition of size, and in this process beater bars, refiner bars, bed plates and retaining rings, made from the 18–8 chromium-nickel types of steel, have all given excellent and improved service, both in resistance to abrasion and to corrosion, as compared with phosphor bronze. Such items of equipment as trays for the pulp liquor and pumps and pipe-lines for the waste products have also been successfully used. In the strainers, pipe strays have been used and the same steel has been employed in the form of doctor blades for cleaning the drying and glazing cylinders.

Artificial Silk.—There are three important methods by which artificial silk can be manufactured, viz. the viscose process, the cellulose acetate process and cuprammonium process. For the viscose process, any of the steels 1–13 should be satisfactory for dealing with the cold caustic soda solutions or for use in the carbon disulphide treatment, but the spinning bath usually contains about 10 per cent. free sulphuric acid and the conditions here are such that it is not often possible to recommend any of the special steels.

Cellulose Acetate Process.—For the acetylation of cellulose use has been made of the 18–8 chromium-nickel steel, with or without the addition of molybdenum, depending upon concentrations and temperatures involved. For the spinning of the acetone solution of cellulose acetate any of the steels 1–13 should be satisfactory for resist-

ance to corrosion, although it would probably be preferable to adhere as far as possible to steels 5–13.

Cuprammonium Process.—For resistance to the dissolving and spinning solutions used in the cuprammonium process, the 18–8 type of steel is quite satisfactory; this material can also be used for the sulphuric acid bath employed for removing the copper from the product, providing a small addition of copper sulphate is made to this bath before use, since the presence of this salt renders the steel immune from attack, which would otherwise occur in sulphuric acid solutions.

Nitro-Cellulose Process. In the nitro-cellulose process the cellulose is nitrated by means of a nitro-sulphuric acid mixture. As with the preparation of explosives, the 18–8 chromium-nickel steel resists a wide range of concentrations of such solutions.

Celluloid and Nitro-Cellulose Explosives.—Both in the manufacture of nitro-cellulose explosives and celluloid, nitration of the cellulose is carried out in mixed nitro-sulphuric acid solutions. A wide variety of solutions is employed, ranging from hot concentrated nitrating solutions down to very dilute washing solutions. Whilst not entirely unaffected at all concentrations and temperatures, the 18–8 chromium-nickel steel, as indicated above, offers complete resistance over a very wide range and has been used with considerable success in a number of processes. This resistance results from the presence of the nitric acid and depends to some extent on the relative proportions of the two acids.

Paint, Lacquer and Varnish.

The chief application in this field of the corrosion-resisting steels is in the preparation of varnishes, since with these substances a very small amount of corrosion can spoil the transparency and colour of the varnish. The 18–8 chromium-nickel type has been used with great success for varnish boilers, since not only does it not affect the colour of the varnish, but also it offers improved resistance to wear as compared with, say, copper. Since fairly high temperatures are reached in these pots, it is of course essential to use a type of steel which is not susceptible to intercrystalline corrosion.

Rubber.

The coagulation of the latex at the plantations usually involves addition of acetic acid, and successful use has been made of the 18–8 chromium-nickel steel for vessels to contain such mixtures. The usefulness of this type of steel in the later stages of production involving vulcanisation depends upon the particular conditions involved. For certain work good service is being obtained, but it is a field in which work's testing is desirable before installing large-scale plant.

Tanning.

The 18–8 chromium-nickel type of steel is particularly resistant to the tanning liquors, this steel being more resistant than bronze and aluminium alloys.

Soap Industry.

The excellent resistance of steels 6–13 to stearic and similar fatty acids has already been referred to. In soap-making, it is the salts of those acids which are involved, and use has been made of this group of steels for soap-making vessels, where the corroding influence is that of the sodium chloride used in the salting out of the soap. Use has also been made of steel 5 to make soap moulds, and considerable quantities of steels 1–13 are used as press-plates.

Foodstuffs.

With foodstuffs, the question of metallic contamination is of vital importance. For example, a few parts per million of copper in butter are capable of producing considerable rancidity and " off-flavour " in a relatively short time.

The steels 6–13 not only offer very high resistance to corrosion by most food products, but also have the great advantage that they are readily produced with a polished surface, which can very easily be kept in a thoroughly clean and hygienic condition. The strongest alkaline cleansers can be employed without any danger of attack on the steel.

Dairy Products.—There has, during the past two or three years, been a large and increasing use of steels of the 18–8 chromium-nickel type for such items of plant as milk-transport tanks (road and rail), milk-treatment machines, separators, coolers, pasteurisers, pipe-lines, condensing plant, milk dryers, cheese vats, butter-conditioning pans and general small utensils.

Beer, Wines, Spirits and Cider.—The corrosion-resistance and ease of cleansing possessed by steels 6–13 makes them particularly suitable for certain parts in the production of beers, wines and spirits.

Vinegar, Sauces, Salad Creams and Pickles.—Steels 6–13 have been employed successfully for vinegar distillation. In particular the 18–8 chromium-nickel steel containing 3 per cent. molybdenum offers high resistance to corrosion under such conditions.

Preserves.—The absence of metallic contamination is of great importance for preserves, as it bears upon the colour and clarity of the product, and here also the steels 6–13 are successfully employed.

Welding of Corrosion-Resisting Steels.

Welding.—Generally speaking, it is not advisable to weld the martensitic steels owing to their air-hardening tendencies, and even

with those steels which, on account of their low carbon-content, do not materially air-harden, there is a tendency towards large grain size after welding which cannot be removed by heat-treatment.

The austenitic steels can be welded by all methods except that of the smith's hearth. The electric resistance processes—flash, butt, spot and seam—offer no particular difficulties. Flash welding is to be preferred to butt welding, particularly for the larger areas.

When arc-welding these steels the electrodes should preferably be of the same composition as the material being welded. The arc should be kept as short as possible. A long arc usually results in improper fusion and lack of penetration, and is liable to be unsound.

When welding by the oxy-acetylene process two main factors must be observed, (1) the maintenance of the correct flame, and (2) the use of the correct flame in the correct manner. The flame must be strictly neutral, as if too much oxygen is present the weld will be unsound, whilst if too much acetylene is present the characteristics of the weld may be seriously affected. Excess acetylene causes decreased ductility and may adversely affect the corrosion-resisting properties of the weld. Moreover, if a polished finish is desired, it will be found that a high-carbon weld will not have the same clear appearance as the parent metal, but will be milky or cloudy.

The second important factor is to ensure that during welding the tip of the welding cone is kept in contact with the molten metal, thus ensuring the maintenance of a clear pool. The feed wire should be of the same composition as the steel being welded. The use of a flux is not really necessary if the foregoing principles are adopted, except with those steels containing titanium. If difficulty is experienced in obtaining penetration, a flux may be used on the under-side of the joint to prevent oxidation during welding and so facilitate the smooth blending of the edges on the under-side of the joint. For the titanium-bearing steels the use of a flux is desirable. A suitable flux consists of approximately equal portions of silica and borax.

When welding the austenitic steels it should be remembered that their thermal expansion is approximately 50 per cent. greater than that of mild steel, and allowances should be made accordingly. It should also be remembered that the thermal conductivity of these steels is less than that of ordinary mild steels, and the heat applied by the blowpipe, therefore, is not dissipated through the surrounding metal so rapidly as in the case of mild steel. A smaller size of blowpipe jet can, therefore, generally be used. It is suggested that thicknesses greater than 14 Ga. (0·08 in.) be welded by the arc process, where possible.

Heat-Treatment of Corrosion-Resisting Steels.

A wide range of mechanical properties is available in the series of steels under discussion. The lower carbon plain-chromium steels (1–4)

are generally used in the hardened and fully tempered condition or in the annealed condition. The hardening consists of oil-quenching the steels from 950 to 1000° C. and the full tempering is carried out at 750° C., giving the properties stated in the table.

The higher-carbon plain-chromium steels (1–4) may be used in the hardened and lightly tempered condition with a Brinell hardness of 450 to 550, or they may be hardened and variously tempered to give a tensile strength between 45 and 100 tons per sq. in. The hardening in either case is done by quenching in oil from 950° to 1000° C. For light tempering a temperature of 180° C. is used, whilst a full tempering from 750° C. gives the mechanical properties reproduced in Table 18.

Steel No. 5 may be annealed by air cooling from a temperature of 600–650° C. Hardening may be effected by cooling in air or oil from 950° C., and the tempering temperature usually employed is in the region of 500–600° C.

The austenitic steels 6–13 do not harden by quenching from a high temperature, and heat treatment is only employed to soften them or to obtain the best condition for resistance to corrosion. All the steels in this group may be softened by heating to a temperature of about 1050–1100° C., followed by quick cooling. With the 12·5-chromium 12·5-nickel, a somewhat lower softening temperature of 950–1000° C. may be used.

Soft and Hard Soldering and Brazing of Corrosion-Resisting Steels.

Soft Soldering.—All the steels under review can be soft soldered, provided that a suitable flux is used. As in the soft soldering of ordinary metals, cleanliness of the parts to be soldered is essential. The corrosion-resisting steels (which are the steels primarily in question where soft soldering is concerned) are almost invariably supplied in the descaled or polished condition, and it therefore generally only remains to remove the dirt and grease which may have been introduced during the working of the steel by the fabricator. This can generally be done by means of emery cloth or other suitable medium. Where scale or oxide is present on the surface of the steel due to heating operations, recourse must be made to a descaling operation (see later). The most suitable flux consists of a saturated solution of zinc chloride salt in a 50 per cent. solution of hydrochloric acid. A good alternative flux is a 50 per cent. solution of orthophosphoric acid. With the aid of either of these fluxes, tinning and soldering can proceed in the normal way using the ordinary soldering bit. Attention is particularly drawn to the desirability of washing away with clean water, after soldering, all traces of flux, especially in the case of the first-mentioned flux.

Hard Soldering and Brazing.—All the austenitic steels may be hard or silver soldered and brazed, but with the martensitic steels some care

must be exercised to choose a solder with a sufficiently low melting point to enable soldering to be carried out at a temperature below that at which air-hardening of the steel would occur.

Cleanliness of the parts to be jointed is as necessary as with soft soldering, and similar methods of ensuring this cleanliness may be used.

The most suitable flux for silver soldering is one containing approximately equal quantities of potassium fluoride and boric acid. This flux may be used dry or mixed with water to form a thin paste. The heat, which should be applied gently, should be only just sufficient to cause the solder to flow freely. Experience has shown that, given the correct flux, failure to obtain good silver-soldered joints has been due to (1) inefficient application of the flux during heating, (2) overheating of the joint, thus causing excessive oxidation. For brazing, either ground borax glass or Sifbronze flux should be used.

It is a good practice, when hard soldering and brazing by the hot-dipping method, to float a layer of borax on the top of the soldering or brazing metal of sufficient depth to allow the part being dipped to be preheated in the borax before being lowered into the metal.

Removal of the flux after hard soldering or brazing operations can be effected by immersing the soldered parts in a boiling solution of 5 per cent. caustic soda.

Examples of equipment in stainless steels are seen in Figs. 36 and 37. Fig. 36 shows a large stainless steel digester jacketed with mild steel for use in nitric acid plant. It was fabricated by Thompson Bros., of Bilston, Staffs., from 18·8 Staybrite steel. A large casting in 18·8 Staybrite steel by Firth Vickers Ltd. is seen in Fig. 37.

Stainless Clad Steel.

Stainless clad steel was developed to retain the corrosion-resisting advantages of solid stainless steel, but at a reduced cost. It is a ply material having a thin surface of true stainless steel on a foundation of soft or mild steel. It is made by a number of manufacturers including, for example, the Ingersoll Steel and Disc Division of the Borg-Warner Corporation, whose product is known as "IngAclad." The following description of IngAclad has kindly been supplied by the makers.

It is evident that if a sheet or plate has but a thin surface of the costly stainless steel, and the bulk of that sheet or plate is ordinary steel, the cost of the stainless clad product will be much lower than if the material were entirely composed of solid stainless steel. It is on this basis that IngAclad has found acceptance in so many applications where the corrosion-resistance of stainless steel was desired, but where the economy of the clad steel dictated its use.

IngAclad may be produced with a variety of stainless steel surfaces, and a stainless cladding varying from a very thin layer to a thickness

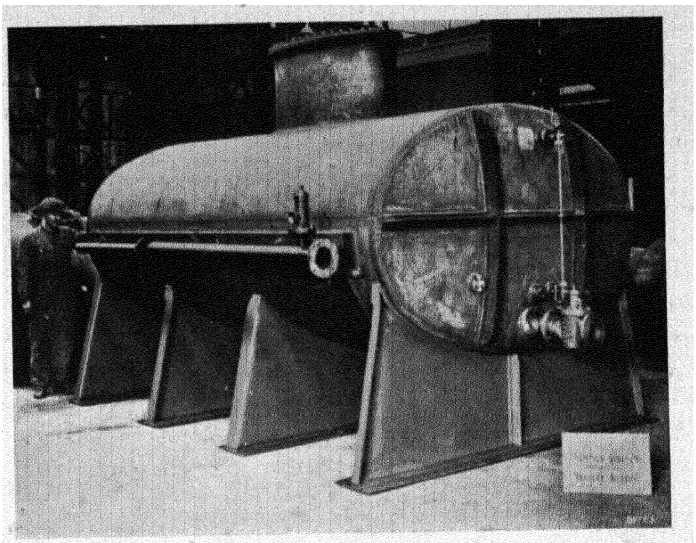


FIG. 36.

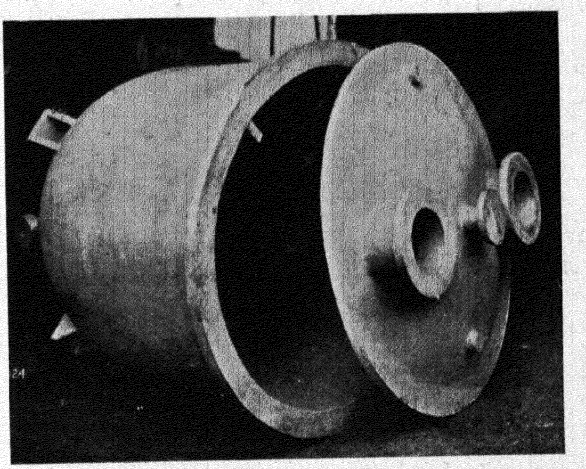


FIG. 37.

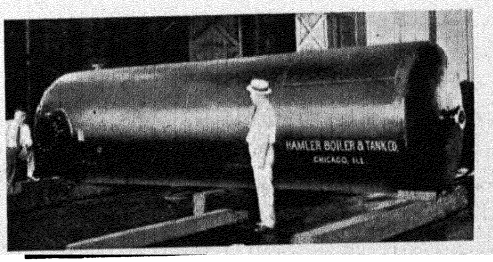


FIG. 38.

[*To face page* 114.

comprising 30 per cent. or more of the total sheet or plate thickness. It has been found, however, that the 18–8 stainless steel cladding, comprising 20 per cent. of the total sheet or plate thickness, satisfies most commercial requirements. For this reason the company has standardised on this cladding, except in special cases where tonnage requirements justify a variation from this specification.

The physical properties of stainless clad steel are a combination of the physical properties of the two metals– mild steel and stainless steel—which form the combined sheet or plate. Thus the tensile strength of the stainless surface is identical with the tensile strength of a similar sheet or plate of solid stainless steel. Likewise the strength of the mild steel is not affected by being in combination in the clad material. The user is assured that the tensile strength of the clad material is as high, or higher, than the combined strength of the two materials.

IngAclad may be used wherever the use of a corrosion resistant metal is desirable or practical, within certain limitations. In many applications, such as tank work, pressure vessels, etc., it has definitely established itself as one of the most economical forms of stainless material available, due to the initial economy of the clad steel.

Stainless clad steel is eliminated from such applications as perforated sheets or plates in which the underlying mild steel side of the clad material might be subject to corrosive attack. Likewise IngAclad is excluded from those uses where corrosive attack occurs on both sides of the metal, except where plating or a protective coating can be economically used on the mild steel side. Again, it should not be used for heat applications in which the mild steel side would be adversely affected due to oxidising and other factors which may affect the mild steel at elevated temperatures. Because of this, the heat limit for stainless clad steel applications is about 800° F. With these exceptions, IngAclad is recommended for application in which a corrosion-resistant or stainless material is desirable.

In designing any vessel where the vessel, its fittings or its parts, are to be in contact with liquids, it is the best practice to have all fittings and parts of the same material as the vessel itself. This prevents any electrolytic or galvanic action which would corrode the different metals or alloys employed.

Stainless clad steel may be manipulated by any of the usual processes used for fabricating steel, but naturally special precautions must be taken, particularly in welding. An example of IngAclad vessels is seen in Fig. 38.

The Manufacture of IngAclad.

The process of making IngAclad consists essentially of two major operations. First, the production of stainless steel plates, and

secondly, the process of making the ply-steel. The stainless steel, usually of the type designated as 18–8, is made up of a major portion of virgin metals poured into ingot moulds and rolled into plates. After rolling, the plates are cleaned and ground and cut into inserts which are used in making clad steel.

After proper preparation one face of each stainless plate is coated with an insulating material. The coated plates are then placed face to face and the four edges are sealed by arc welding. These two plates, thus joined, are known as an insert.

An insert of stainless steel as described above is then placed in a mould. Mild steel of a special analysis is then poured in the mould, completely covering the stainless steel insert, producing a composite ingot. The ingots so produced are rolled into sheets or plates of desired gauge. After finish rolling all sheets are annealed to produce the austenitic structure desired. The four edges are then sheared back to the point where the stainless steel begins, thus producing two stainless clad sheets from each ingot.

All clad steel sheets are then pickled and passivated to bring out the maximum corrosion-resisting qualities of the stainless steel.

It is apparent that with this cast-in-the-ingot method the stainless steel surface of the clad sheet or plate is not subject to roll marks, scaling, or oxidation because the stainless surfaces are completely surrounded by an envelope of soft steel during the heating, rolling and annealing operations.

This patented method of producing IngAclad from a composite ingot insures a bond between the stainless surface and the mild steel.

CHAPTER IV.

PROPERTIES OF METALS AT HIGH AND LOW TEMPERATURES.

UNTIL comparatively recently the maximum working temperature of steam and pressure plant was within the temperature range in which the properties of materials of construction are not materially different from those at ordinary temperature, and consequently the tensile (shear or compression) strength of materials of construction as found by tests at ordinary temperature was a principal factor in determining the scantlings of the vessels concerned.

During the past twenty years there has been a marked development in the use of considerably higher temperatures in both steam and chemical plants, and these higher temperatures have been accompanied by a corresponding increase in working pressure and rate of heat transmission. These severe operating conditions soon demonstrated that the properties of materials at ordinary temperature are by no means a satisfactory basis upon which to design stressed parts of high temperature plant above certain critical temperatures. It was discovered that above a certain temperature (peculiar to each material) the breaking strength is not properly disclosed by the ordinary tensile test procedure, even if this is carried out at the temperature at which the material will operate in service.

A stress less than (often much less than) that which is required to cause failure of a tensile test specimen pulled at the ordinary rate may cause fracture if the time during which the stress is applied is sufficiently long. The physical process which brings about this slow failure is called " creep." Creep may continue for weeks (even months) under certain conditions as will be seen from Fig. 39, which gives the creep curve of a 0·4 per cent. carbon cast steel stressed to 4·47 tons per sq. in. at 425° C. (Kanter and Spring, *Proc. Am. Soc. Test Mat.*, 1928, **28**, 2–80).

Naturally there has been a great deal of research of late years into the properties of structural materials at high temperatures. The creep of metals is usually determined by stressing a form of tensile test specimen at a given temperature, and measuring the extension produced between gauge points in given times. This work necessitates great care in design of the apparatus and particularly so in respect of the method of measurement of the creep.

Owing to the lack of a standard test method for determining creep there is some difficulty in comparing the results of different investigators. There are, however, many aspects of creep upon which there is general agreement; in so far as steels are concerned these are as follows :—

Within the creep region of temperature, if a metal is subjected to a steady load at a uniform temperature and strain measurements are taken it has been found that :—

(*a*) The metal elongates rapidly during the first few hours, after the application of the maximum stress. (See Fig. 39.)

(*b*) This initial elongation is followed, if the applied stress is not too great, by a period in which the rate of creep is markedly less than in the initial period; it decreases uniformly and the rate of strain becomes fairly constant.

(*c*) If the applied stress reaches a certain critical figure there will be a sharp increase in the rate of creep and fracture will take place.

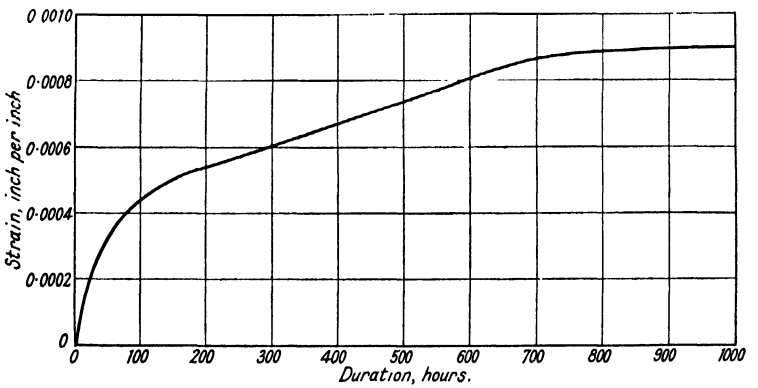


FIG. 39.—Creep curve for a 0·40 per cent. C. Cast Steel at 425° C. under a stress of 4·47 tons/sq. in.

It is clear, therefore, that the working stress for any design must be less than the figure which would cause an excessively high continuous creep, and since under many conditions of high-temperature service " creep " must be accepted as inevitable, the designer must so arrange the working conditions that this creep will not cause excessive deformation within the life of the vessel concerned. Naturally the allowable creep will vary widely with the type and nature of the problem under review. For example, Baumann (*Proc. Inst. Mech. Eng.*, 1930, 1039) suggests the following as permissible creep of parts of a steam power plant :—

	Strain.
(1) Turbine discs pressed on shaft . . .	10^{-9} per hr.
(2) Bolted flanges of turbine cylinder . .	10^{-8} „ „
(3) Steam piping—boiler tubes	10^{-7} „ „
(4) Superheater tubes	10^{-6} „ „

Influence of Composition of Steels upon Creep.

In resisting stress at elevated temperatures, chemical composition is as important a factor as at ordinary temperatures. An alloy more nearly approaches a rigid body than does a pure metal, and this property is preserved at elevated temperatures. Generally, small additions of strengthening elements are more effective proportionally than large additions, and small additions of several elements are more effective than an equal number of a single element. The heat treatment of steel and alloys has a pronounced effect upon resistance to creep, and frequently such treatment has an influence equally as great as change of chemical composition. The effect of the various elements used in alloying steel for high-temperature service will now be discussed, followed by extended references to typical compositions and results now being obtained in practice.

Carbon.—There is as yet no agreement upon the effect of varying amounts of carbon in plain carbon steels subjected to stress at high temperature. Earlier researches upon the resistance to creep of various carbon steels appeared to show that, within limits, an increased carbon content led to a greater resistance to creep or an increase in tensile strength at high temperatures. Recently an important paper published by the British Electrical and Allied Research Association (Report J/T101 of 1936) shows that under certain test conditions a higher carbon content gives a structure less resistant to creep than a lower carbon content, i.e. the reverse of the properties of these steels at ordinary temperatures. For example, this report gives particulars of tests upon thirteen carbon steels of varying carbon content, and in particular in the wrought condition a 0·4 per cent. carbon steel had a lower strength at 450° C. than a 0·15 per cent. carbon steel, each under a stress of 8 tons per sq. in. The report also emphasises the importance of heat treatment of steels for high-temperature service, e.g. a heat treatment causing spheroidisation of the cementite lowers the resistance to creep, whereas coarsening of the ferrite grain increases it, especially in the case of a 0·4 per cent. carbon steel.

Molybdenum.—The addition of small percentages of molybdenum greatly increases the creep strength of carbon steels between 400–600° C. Thus the addition of about 0·35 per cent. of molybdenum to an ordinary mild steel improves the creep strength in the range 450–550° C. by about 100 per cent. Molybdenum also in conjunction with chromium produces an alloy markedly resistant to creep within the range 450–550° C. For example, a steel of the following analysis :— C 0·25, Mn 0·95, Si 0·20, Cr 0·62, Mo 0·20, has a creep rate of about 0·2 per cent. in 1000 hours at 480° C. and a stress of 25,000 lbs. per sq. in. ; and for 700 hours at a stress of 20,000 lbs. per sq. in. at the same temperature no extension exceeding one fifty-thousandth of an

inch was noted (J. L. Cox, *Am. Inst. Chem. Eng.*, 1933, XXIX, 43). Molybdenum is used as an alloying element in most of the structural steels for pressure vessel construction at high temperatures, and details of actual service experience will be given later.

Nickel alone in moderate proportions has little effect upon "creep" value of steel. For example—Tapsell and Johnson and Clenshaw ("Properties of Materials at High Temperatures: No. 6—The Strength at High Temperatures of Six Steels and Three Non-ferrous Metals," *Dept. Sci. Ind. Res. (Brit.) Sp. Rep.*, No. 18 [1932]) found a 3·43 per cent. nickel steel no better than plain 0·50 carbon steel at 400° C., and above. The addition of 0·24 per cent. chromium did not improve it, nor was C 0·35, Mn 0·66, Cr 1·18, V 0·25 per cent. equal to the nickel and carbon steels at 500° C. Bailey, Dickenson and others ("The Trend of Progress in Great Britain on the Engineering Use of Metals at Elevated Temperatures. Symposium on Effect of Temperature on Properties of Metals," *Am. Soc. Mech. Engrs. and Am. Soc. Testing Materials* [1931], pp. 218–36) found 3–3½ per cent. nickel with about 1 per cent. chromium little, if any, superior to a good mild steel at temperatures between 400° and 500° C., and doubted if nickel was of any advantage in improving the load-carrying ability of this type of steel at elevated temperatures.

Chromium is very active in raising creep strength. It is the basis of most heat-resisting alloys, increasing strength and decreasing oxidation. At about 5 per cent. combined with ½ per cent. of molybdenum in a low carbon steel, it has over twice the creep strength of carbon steel at 540° C., and offers fair resistance to oxidation and corrosion. Stainless iron, carrying about 0·10 per cent. carbon and 15 per cent. chromium, has somewhat over twice the creep strength of a plain 0·11 per cent. carbon steel from 400° to 500° C., and fair strength above that range, besides a good degree of resistance to oxidation, but it has a high initial elongation.

The straight chromium steels with high chromium possess greater creep strength and greater resistance to oxidation, but have very low impact strength and are liable to great coarsening of the grain on long exposure to heat. A small addition of nickel helps to restrain this growth.

Combined with *nickel* in varying proportions, *chromium* produces some of the best commercial refractory ferrous alloys available in quantity to-day. They can be further strengthened by small additions of molybdenum, tungsten, titanium, etc. The well-known alloy "18 and 8," having 18–20 per cent. chromium and 8–10 per cent. nickel, has excellent creep properties. It belongs to the class of austenitic alloys, having a face-centred cubic lattice, whereas ordinary steels are body-centred. Although the austenitic alloys are comparatively soft at atmospheric temperature, they are much more slowly softened by heat

than is the other type, and are far stronger at high temperatures. For use at medium high temperatures the 18–8 alloys should have a very low carbon, and should not be given the usual high quench if it is to be used in the range of about 510–700° C., in which it may otherwise become embrittled and suffer intergranular weakening. At higher temperatures the carbides precipitated in this dangerous temperature range, which are the cause of the trouble, are in solid solution, permitting the use of higher carbon and a cheaper raw material. Titanium in small amounts is reported largely to correct this intergranular weakening.

For severe conditions even higher chromium-nickel ferrous alloys are used as in the following table :—

PERCENTAGE OF ALLOYING ELEMENTS.

Cr	Ni	W
25	10	—
25	20	—
30	30	—
20	35	—
20	8	4
12	60	2·5

All these are well-known compositions. The last two are Hadfield's HR—1 and Commentry-Fourchambault and Decazeville's BTG metal, the latter being the alloy used for catalyst tubes in the Claude process for synthetic ammonia, operating at a temperature of about 565° C., and at a pressure of about 1000 atms.

In considering the type of steel or alloy to use for a particular high temperature problem, the following points must be borne in mind :—

(1) The steel chosen must possess suitable mechanical properties at the working temperature, with a sufficient margin to allow for unavoidable temperature variations above the desired normal working temperature.

(2) It must retain its original properties during the desired life of the plant, and it must not be susceptible to deterioration by heating and cooling cycles.

(3) The steel must possess sufficient resistance to corroding, or disintegrating media involved in service conditions.

(4) It should not present any serious manufacturing difficulties in order to fabricate it into the form desired.

(5) The cost should not be economically prohibitive.

In general, the steel selected will be that which shows superiority

in the more important of the above points, since rarely is a steel available which will completely satisfy all requirements.

There are three main types of steel available for high-temperature service—namely, carbon steels; low-alloy steels, chiefly of the pearlitic type; and third, the more highly alloyed steels of the high nickel-high chromium type. The relative strength of these steels will be seen from Table 19 (Bailey, Dickenson, Inglis and Pearson, "Symposium or Effect of Temperature on Metals," loc. cit. page 220).

TABLE 19.

Material.	Composition (per cent.).							Stress to give a Creep of 0·000001 in. per in. per day lbs./sq. in.			
	C.	Ni.	Cr.	Mo.	Va.	Si.	W.	660° F.	840° F.	1020° F.	1110° F.
Nickel Chrome Steel.	0·30	3·8	0·95	—	—	—	—	31,000	9,000	1000	—
Ni Cr Mo Steel . .	0·28	3·5	0·87	0·24	—	—	—	56,000	33,500	2000	—
Cr Va Steel . . .	0·35	—	1·13	—	0·15	—	—	85,000	22,500	2000	—
Cr Si Steel . . .	0·61	—	8·32	—	—	2·62	—	53,500	25,500	4500	—
Martensitic Stainless	0·27	—	14·0	—	—	—	—	49,000	27,000	4500	—
Austenitic Stainless	0·16	8·0	18·0	—	—	—	0·6	—	14,500	6500	4500

For manufacturing reasons, for large pressure vessels in the chemical industry, selection must be made from the low alloy steels, and the following discussion relates to steels of this class.

Steels Resistant to Creep at Moderate Temperature, and the Use of Creep Data in Design of Pressure Vessels.

In Great Britain many designers of high-temperature pressure vessels now include in the specification a clause specifying a so-called "proof stress" as an acceptance test. This term is used to define the *minimum* stress required to produce a permanent change of dimensions of the standard tensile test specimen at a particular temperature.

The basis usually adopted for the purpose of carrying out the proof-stress test is the load required to produce not more than 0·05 per cent. permanent set at the specified testing temperature. Usually *half* the proof stress is taken as a safe working stress for pressure vessel work, and Fig. 40 gives 0·05 per cent. proof-stress values for three typical carbon steels, such as are used for high-pressure boiler drums and similar vessels (H. H. Burton, W. H. Hatfield and T. M. Service, *Trans. Chem. Eng. Congress London*, 1936, I Paper A 1).

It is important to note that after long periods under stress at elevated temperature the physical condition of many steels may change considerably, and hence, this aspect should be borne in mind in selecting otherwise suitable materials. For example, it is now well established that many alloy steels become dangerously brittle under such condition, and many failures of pipe flange bolts have been traced

to this cause. Secondly, many chemical processes at elevated temperatures are of a corrosive nature, and gases such as hydrogen have an embrittling effect on many steels at high temperature.

I am indebted to Dr. W. H. Hatfield of the Brown Firth Research Laboratories for the following notes in regard to forgings for high-pressure and elevated-temperature service.

The problems encountered in the design of boiler drums, where the fluid enclosed consists of steam, become still more complicated when the plant is designed to handle fluids which either in themselves, or through products produced during chemical reactions, can have a deleterious influence upon the materials used in the construction of the plant. Outstanding examples of this type are the plants for the synthesis of ammonia, for oil distillation, and for the more recent

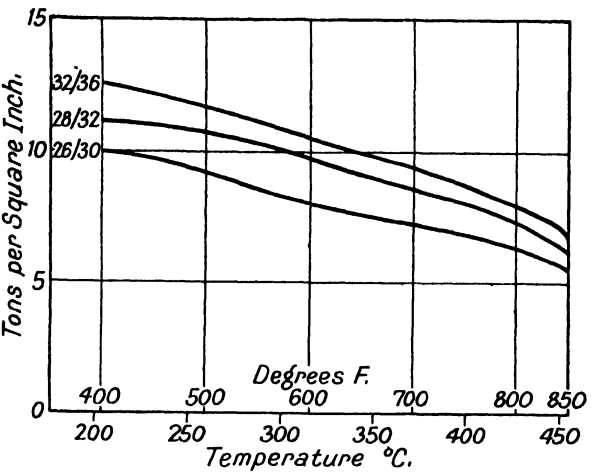


FIG. 40.— 0·05 per cent. proof values for carbon steel forgings.

coal-hydrogenation processes. In some of these plants the working temperatures and pressures are higher than those employed in steam generation, and in addition the fluids handled are liable to attack the reaction vessel or vessels in which they are contained. The leading steel-makers have been developing, for some years past, the manufacture of specialised steels for these purposes, and large forgings in highly alloyed steel have been produced from ingots weighing as much as 150–200 tons.

When the manufacture of forgings for these chemical processes was commenced, the first material employed was plain carbon steel of a type not unlike that generally employed for boiler drums, but the design of these vessels was necessarily uneconomical on account of the limitations of the properties of the steel employed, and in all the more recent plants some form of alloy steel has been used, with a consequent

economy in the dimensions of the vessels required for a given output. Owing to the fact that by suitable heat treatment large alloy steel forgings can be manufactured with much better and more uniform properties than can be obtained with carbon steel, it has also been possible in certain instances to increase the size of individual units, and to work with a higher combination of temperature and pressure. One of the most difficult problems which has arisen is that of resistance to hydrogen attack, and much research has been required to produce the steel for this purpose.

An immense amount of investigation has been made on the deterioration of steel structures when subjected to attack by gases containing hydrogen, but unfortunately the results of many of the earlier investigators are of little practical value, because they were carried out under conditions quite dissimilar from those encountered in some of the actual processes. Thus the most varied conclusions have been drawn regarding the effect of hydrogen upon the various types of steel, since some investigators have worked at temperatures far above those involved in actual chemical manufacture, whilst others have studied the question of the effect of temperature without taking into account the very important factor of pressure.

One of the most complete investigations of the attack by hydrogen at high pressures and temperatures was that of Inglis and Andrews,* who worked under pressures up to 250 atms. and at temperatures up to 500° C. They concluded that at high pressures hydrogen will attack steel at much lower temperatures than those causing attack at normal pressures ; that a number of the alloy steels generally used for engineering purposes, such as nickel-chromium, nickel-chromium-molybdenum, chromium-vanadium and chromium-molybdenum steels have a resistance to hydrogen attack much superior to that of ordinary carbon steels ; and also that the structural condition of the steel had an important influence on the rate of attack, so that fully heat-treated steels were, in general, more resistant.

The chief materials studied in this investigation had already been employed in the manufacture of chemical plant working at high pressures and temperatures, and some data regarding the properties of these steels will now be given. For the synthesis of ammonia the steel which has been most generally employed for the high-pressure vessels is a nickel-chromium-molybdenum steel of the following approximate composition :—

Carbon	0·25–0·30 per cent.
Nickel	2·3–2·8 „ „
Chromium	0·50–0·80 „ „
Molybdenum	0·30–0·50 „ „

* *J. Iron and Steel Inst.*, 1933, No. 1, 383–97.

Some of the vessels manufactured from this steel have necessitated an ingot weighing over 150 tons, and the manufacture of alloy steel in such masses naturally presents a number of difficult problems. Vessels of this type have now been in use for a number of years with satisfactory results.

Typical mechanical properties of a large forging made from such nickel-chromium-molybdenum steels in the manner just described are given below.

Yield point	35–40 tons per sq. in.
Maximum stress	45–50 „ „ „
Elongation	25–18 per cent.
Izod	60–40 ft.-lbs.

A more recent development, which has resulted from a study of the behaviour of various alloy steels under the influence of hydrogen attack, is the use of steels of the chromium-molybdenum type containing little or no nickel. In the paper referred to by Inglis and Andrews, it was shown that steel containing 3 per cent. of chromium was resistant to attack by hydrogen at 250 atms. up to about 400° C., whilst a steel containing 6 per cent. chromium was found to be resistant up to at least 500° C., at the same pressure.

Cox (*Trans. Am. Inst. Chem. Eng.*, 1933, **29**, 43) reports that an alloy of the following composition, C 0·06, Mn. 0·30, P and S 0·02, max., Si 0·40, Cr 5·00, Al 0·75, V 0·05, Mo 0·40, was immune from hydrogen attack at 450° C., in a hydrogen-nitrogen mixture at 300 atms. for 630 hours ; as also was a steel containing C 0·10, Cr 6·00 Mo 0·50.

A study of the properties of the chromium-molybdenum steels seems to indicate that the creep-resistance characteristics decrease, to some extent, with increasing chromium content, and consequently a compromise has to be effected between the resistance of the steel to chemical attack and the corresponding mechanical properties obtainable from a given composition. In the accompanying data some particulars are given of the mechanical properties at normal and high temperatures of three chromium-molybdenum steels containing varying amounts of chromium. It will be seen from Fig. 41 that the stress required to produce a given rate of creep is highest in steel " A " containing less than 1 per cent. of chromium. The analyses of the three steels referred to were :—

	A (per cent.).	B (per cent.).	C (per cent.).
Carbon	0·23	0·195	0·22
Manganese	0·56	0·45	0·49
Chromium	0·62	3·19	5·88
Molybdenum	0·51	0·38	0·5

A most interesting problem which arises in the manufacture of reaction vessels in chromium-molybdenum steel is whether, in order to obtain the longest service without deterioration of the material under conditions of high temperature and stress, the steels should be fully heat-treated in the sense of being hardened and tempered, or should be subjected to normalising and tempering or even to a full annealing treatment, which, according to the views of some users, results in a more stable condition, although the mechanical properties of the annealed steel, as determined by ordinary mechanical tests, are inferior to those obtained from the fully heat-treated steel.

Judging by the results of extensive experiments conducted in Sheffield at the Brown Firth Research Laboratories during the past few years, the answer to this question of the respective merits of the

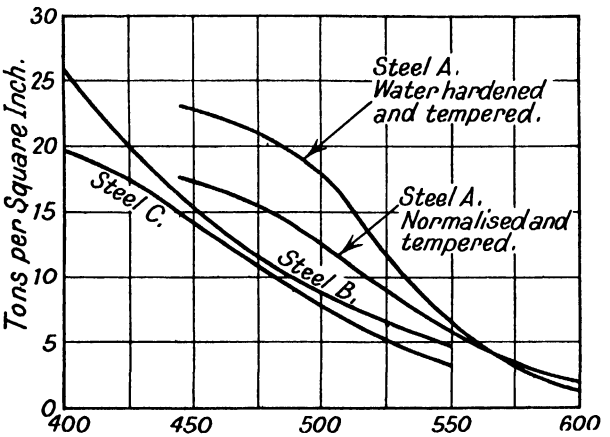


FIG. 41.—Stress giving rate of creep of 10^{-6} /in./in./hr. at 60 days.

different types of heat treatment is that the choice should be governed by the working temperature of the vessel or vessels in question. Thus, with a vessel working at, say, 400° C., the properties of an alloy steel which has been hardened and tempered are often distinctly superior to those of a similar steel in the normalised and tempered or annealed condition, whether the comparison is made at the working temperature or at normal air temperature. As the testing temperature increases, however, the advantages of the hardened and tempered material gradually decrease, and at a certain temperature, which varies according to the composition of the steel in question, the original order of merit may be actually reversed. This is strikingly illustrated by the two curves for the low chromium-molybdenum steel in Fig. 41, which shows that the " creep " properties of the hardened and tempered material are distinctly higher than those of the normalised material

tempered up to 500° C., but that at 550° C. the difference has almost disappeared, whilst at 600° C. the order has changed, the normalised and tempered steel being now the better of the two.

It has already been mentioned that many steels deteriorate when subjected to a combination of high temperature and stress, and this may not always be accompanied by chemical attack. It must never be overlooked in selecting a steel for a particular type of high-temperature service that the original properties of the material as indicated by tests taken at normal and elevated temperatures, may undergo considerable changes during the life of the plant under service conditions. In many cases a decrease in the toughness, or to put the matter in the opposite way, an increase in the brittleness of the steel after a long period of service, may be of minor importance, especially where the structure or vessel considered is not subject to any type of shock loading, or to any very rapid fluctuations in pressure, but there are instances where this "embrittlement" after long exposure to high temperatures and stress may become a serious problem.

The term "embrittlement" * is now almost universally employed to denote the gradual change in the resistance of material to the notched bar impact test after exposure to the service conditions just mentioned. Though it is perhaps not quite the same thing, as it is brought about through service conditions and not through the form of heat treatment, there is considerable resemblance between this so-called "embrittlement" and the familiar "notched bar temper-brittleness," which formerly gave rise to difficulties with nickel-chromium and other alloy steels.

In the following tables some impact figures are given for three chromium-molybdenum steels immediately after heat treatment and after subsequent heating to various temperatures for periods up to 2400 hours.

EMBRITTLEMENT AT 450° C.

	Time Soaking (hrs.).	Izod Value Before (ft.-lbs.).	Izod Value After (ft.-lbs.).
Steel A (Water quenched and tempered) .	2400	68	70
Steel B (Oil hardened and tempered) .	480	90	91
Steel C (Air hardened and tempered) .	480	114	114

* The only means at present available for judging this "brittleness" is the notched bar impact test. Certain service experience has been claimed to give confirmation.

EFFECT OF TEMPERATURE ON IZOD IMPACT VALUES TIME AT TEMPERATURE 1400 HOURS.

	Steel A (W.H. & T.).		Steel B (O.H. & T.).		Steel C (A.H. & T.).	
	Before.	After.	Before.	After.	Before.	After.
400° C.	---	—	74	72	111	105
450° C.	72	72	74	74	111	112
500° C.	72	72	74	24 .	111	113
550° C.	72	69	74	39	111	115

TENSILE STRENGTH AT 20° C. OF MATERIALS USED IN ABOVE TESTS.

	Yield Point (tons per sq. in.).	Maximum Stress (tons per sq. in.).	Elongation (per cent.).	Reduction of Area (per cent.).
Steel A	47·2	54·7	21·0	64·4
Steel B	37·8	47·3	24·0	71·2
Steel C	34·9	46·8	27·7	73·3

It will be seen that all three steels are practically unaffected by prolonged heating up to 450° C., but that above this temperature the 3 per cent. chromium-molybdenum steel shows some reduction in impact value. The remarkable stability or freedom from notched bar embrittlement of the low chromium-molybdenum type of steel is evident, because, after heating to 450° C. for 2400 hrs., the only noticeable change is a slight increase in the notched bar impact value.

Whilst discussing the question of notch embrittlement, reference may be made to the behaviour in this respect of nickel-chromium and nickel-chromium-molybdenum steels. The well-known phenomenon of temper-brittleness of ordinary nickel-chromium steels when slowly cooled through, or exposed at, temperatures between 450–500° C., has been generally considered to be avoided by introducing about 0·5 per cent. of molybdenum into the steel, but recent work tends to indicate that this is only a partial cure and that the molybdenum only retards the production of notch embrittlement. As a result, there is a tendency to blame the presence of nickel for the effect produced.

There is, however, evidence that certain nickel-chromium-molybdenum steels have withstood long periods of service at 450–500° C. without deterioration and, further, that other steels containing nickel have actually recovered notched impact value after long exposure at such temperatures in spite of a temporary decrease. The whole

question demands further enquiry, as factors other than composition, i.e. the steel-making process, heat treatment, etc., are known to have an influence.

In conclusion, it must be noted that some lightly alloyed steels offer distinct advantages over plain carbon steels in respect of permanence of properties and dimensions at high temperatures and stresses. Research work carried out over all the world indicates that in attempting to improve the creep-resisting properties of a steel, the addition of a comparatively small percentage of molybdenum brings about the desired result more effectively than any other alloying element. Plain molybdenum steels, however, though excellent for their resistance to creep, do not show a very marked advantage over plain carbon steels for the lower range of temperatures when compared on the basis of the 0·05 per cent. proof stress, which has been shown to be an important factor in the design of vessels which have to be made as light as possible, and at the same time retain permanence of dimensions under working conditions. These steels are intermediate in character, and owing to their superior creep-resistance are suitable for slightly higher temperatures. On the other hand, it is possible, by the use of certain other alloying elements, to increase the 0·05 per cent. proof-stress value without materially improving the creep properties of the steel. A notable example of this type is a steel containing about 1·5 per cent. of manganese, which could be used up to 450° C., in many applications where a plain carbon steel would not suit, as boilers, drums and similar forgings made in such a steel could be quite safely made with thinner walls than would be permissible with drums made in plain carbon steel working under the same conditions. For slightly higher stresses, but within the same temperature range, a similar 1·5 per cent. manganese steel, but with the addition of about 0·3 per cent. molybdenum, offers distinct possibilities, and this steel has the added advantage of slightly superior creep properties. For still higher temperatures, a low chromium-molybdenum steel seems to be one of the best materials so far studied, since it exhibits a resistance to creep superior to that of a plain carbon-molybdenum steel, and the addition of the chromium has the effect of increasing the 0·05 per cent. proof-stress value, so that permanence of dimensions can be relied upon under working conditions. It seems almost inevitable that one or more of the types of steel just mentioned will be employed in the near future in the place of plain carbon steel. Always, however, before adopting these modified steels the whole of the working properties should be determined and considered in the light of fabrication requirements.

Additional difficulties arise in considering forgings for handling fluids which have a definitely deleterious influence upon the steel, but evidence is accumulating that several steels containing chromium and molybdenum can be developed to fill the gap which formerly existed

between what may be properly called the stainless steels and the more ordinary carbon and alloy steels. Until quite recently the manufacture of, for example, the 3 per cent. chromium-molybdenum steel was very difficult when the mass of the forging was such that the necessary ingot could not be made from the electric furnace, but a suitable melting technique has now been evolved by the leading open-hearth steel-makers, and 6 per cent. chromium-molybdenum steel is now available in very large masses, produced by either process.

W. H. Hatfield (*Journ. Inst. Fuel*, 1938, XI, 245) gives the following particulars of the result of long-time creep tests on many types of steels and alloys. The figures given should prove of real service in assisting to determine working stresses in the temperature region in which the tests were carried out (see opposite page).

Hatfield gives also some valuable information about the resistance of many steels to oxidation at elevated temperatures, and the paper is concluded by a most complete bibliography of the more important papers and publications relating to the employment of steels and alloys at elevated temperatures.

Fig. 44 shows in graphical form the various types of steels suitable for different temperature ranges.

The following is a short abstract of a recent paper by Dr. W. H. Hatfield, "Heat Resisting Steels, etc." (*Proc. Chem. Eng. Congress*, London, 1936).

Heat-Resisting Steels of the Highly Alloyed Type

Such heat-resisting steels may be conveniently divided into four groups :—

(1) Plain chromium steels (12–30 per cent. chromium).
(2) Silicon-chromium steels.
(3) Austenitic chromium-nickel steels, chromium and nickel each up to 30 per cent. with or without additions of tungsten and titanium.
(4) Higher nickel-chromium alloys, e.g. 60 per cent. nickel, 20 per cent. chromium.

Referring to the heat-resisting steels in Table 21, steel No. 1 possesses excellent resistance to oxidation up to a temperature of about 900° C., but has no great mechanical strength at high temperatures. This steel is essentially used for internal-combustion engine valves.

Steel No. 2 is very good for resisting oxidation up to about 700–750° C., but again possesses no special strength at high temperatures, although better than mild steel in this respect.

Steel No. 3 is excellent for resistance to oxidation up to about

TABLE 20.

Analysis.							Particulars of Condition and Results of Long-time Creep Tests.
C	Si	Mn	Ni	Cr	Mo	W	
0·25	0·18	0·48	0·10	0·04	—	—	Normalised. Stress of 5¼ tons/sq. in. at 400° C. gave total movement of 0·05 per cent. in 500 hrs. Final creep rate $1·0 \times 10^{-7}$ hr. decreasing
0·28	0·22	0·53	0·66	0·16	0·11	—	Annealed 650° C. 6 tons/sq. in. at 500° C. gave total movement of 0·025 per cent. in 500 hrs. Final rate $2·0 \times 10^{-7}$/hr. decreasing
0·36	0·26	0·12	0·30	14·66	—	—	Oil hardened 975° C. Temp. 600° C. 4¼ tons/sq. in. at 500° C. gave total movement of 0·02 per cent. in 500 hrs. Final rate $1·5 \times 10^{-7}$/hr. dcg.
0·13	0·50	0·33	8·22	18·65	Ti 0·61	0·63	Air cooled 1150° C. 8 tons/sq. ins. at 500° C. gave total movement of 0·015 per cent. in 500 hrs. Final rate $1·0 \times 10^{-7}$/hr. decreasing
0·40	0·97	0·41	10·31	13·65	—	3·53	Air cooled 950° C. 6 tons/sq. ins. at 500° C. gave total movement of 0·01 per cent. in 500 hrs. Final rate $1·0 \times 10^{-7}$/hr. decreasing
0·23	1·65	0·41	11·85	23·20	—	2·98	Air cooled 1050° C. 4·0 tons/sq. ins. at 600° C. gave a total movement of 0·025 per cent. in 500 hrs. Final rate $3·0 \times 10^{-7}$/hr. decreasing
0·40	2·15	1·25	27·65	14·85	—	3·85	Air cooled 1050° C. 7 tons/sq. ins. at 500° C. gave a total movement of 0·02 per cent. in 500 hrs. Final rate $1·2 \times 10^{-7}$/hr. decreasing
0·14	1·36	0·29	21·5	24·35	—	—	Air cooled 1050° C. 10 tons/sq. ins. at 500° C. gave a total movement of 0·06 per cent. in 500 hrs. Final rate $4·5 \times 10^{-7}$/hr. decreasing
0·22	0·69	0·56	0·26	30·4	—	—	O.Q. 1050° C. T. 700° C. 10 tons/sq. ins. at 500° C. gave total movement of 0·02 per cent. in 500 hrs. Final rate $1·0 \times 10^{-7}$/hr. decreasing
0·10	0·45	1·40	62·0	13·0	—	—	Air cooled 1050° C. 12 tons/sq. ins. at 500° C. gave a total movement of 0·04 per cent. in 500 hrs. Final rate $1·5 \times 10^{-7}$/hr. decreasing
0·07	0·27	0·21	78·55	13·44	—	—	Air cooled 1050° C. 4 tons/sq. ins. at 600° C. gave a total movement of 0·04 per cent. in 500 hrs. Final rate $3·0 \times 10^{-7}$/hr. decreasing

TABLE 21.

HEAT-RESISTING STEELS.

Typical Analysis.								Mechanical Properties.					Physical Properties.			
No.	C	Cr	Ni	W	Ti	Si	Condition.	Yield Point (tons per sq. in.).	Max. Stress (tons per sq. in.).	Elongation (per cent. on 2 ins.).	Reduction of Area (per cent.).	Brinell Hardness.	Specific Gravity.	Coefficient of Thermal Expansion 20–100°.	Thermal Conductivity (C.G.S. Units.).	Electrical Resistivity (microhms per cm.³).
1	0·4–0·5	6·0–10·0	—	—	—	3·0–4·0	Hardened and tempered	45–50	65–70	15–20	35–45	250–285	7·60	0·0000130	0·030	75–85
2	0·1–0·5	12·0–14·0	—	—	—	—	Hardened and tempered	15–40	30–60	20–40	40–60	140–280	7·74	0·0000106	0·045	52–65
3	0·10–0·20	25–30	0–5·0	—	—	1·0–2·0	Softened	20–35	30–45	15–25	30–50	150–225	7·50–7·90	0·0000104	0·030	80–86
4	0·5 max.	10·0–15·0	10·0–15·0	2·0–3·0	—	1·0–2·0	Softened	30–45	50–65	20–35	30–50	220–290	8·00	0·0000169	0·033	78
5	0·5 max.	12·0–16·0	25·0–35·0	0–4·0	—	1·0–2·5	Softened	30–40	50–60	20–30	40–50	180–270	8·00	0·0000151	0·030	85
6	0·15 max.	18·0	8·0	0·5–1·0	0·5–1·0	—	Softened	16–20	40–50	35–50	40–50	160–200	7·90	0·0000168	0·030–0·035	73
7	0·2–0·4	19·0–26·0	7·0–13·0	0–4·0	—	1·0–2·0	Softened	22–35	45–60	20–35	35–55	190–260	7·80–7·90	0·0000155	0·030	85–87
8	0·40 max.	20·0–25·0	20·0–25·0	—	—	1·0–2·0	Softened	22–35	40–55	30–50	40–60	180–260	7·90	0·0000154	0·030	92
9	1·0 max.	15·0–25·0	60·0–80·0	0–4·0	—	1·0	Softened	35–45	50–60	15–25	25–35	180–250	8·10	0·0000121	0·020	105

(W. H. Hatfield, *Trans. Chemical Engineering Congress*, London, 1936).

1100° C. This steel has a tendency to be brittle at ordinary temperatures, although it is quite ductile at elevated temperatures. Again, this steel possesses no special mechanical strength at elevated temperatures.

All the steels (4–8) possess excellent ductility at ordinary temperatures, and, at elevated temperatures, all possess very appreciable mechanical strength, as compared with the previous steels. The first two steels in this group show good resistance to oxidation up to about 900° C., whilst the third steel is very good up to 800° C., and the fourth and fifth steels are very good up to about 1050–1100° C.

The nickel-chromium alloy (No. 9) exhibits good resistance to oxidation up to about 1150° C., combined with good mechanical properties at elevated temperatures.

Heat Treatment of Heat-Resisting Steels.

Heat-resisting steel No. 1 may be oil hardened from 950° C., and tempered from 650° to 700° C., to reproduce mechanical properties within the range quoted in the table.

The lower-chromium steels 2 and 3 are generally hardened by oil quenching from 950° to 1000° C., and tempered at 750° C. The higher-chromium steels of this group may be softened by air cooling from 750° C.

All the steels 4–8 are austenitic and are generally used in the softened condition. They can all be fully softened by air cooling from about 1050° C. A similar treatment applies to alloy No. 9.

As an indication of the commercial availability of these heat-resisting steels, Table 22, gives particulars of such materials as regularly manufactured by Hadfields Ltd., and the following notes are taken from "Heat-Resisting Steels," by Sir Robert Hadfield, a publication of the Bureau of Information on Nickel.

The servicerequirements of these highly alloyed heat-resisting steels are in general :—

(1) Resistance to scaling.
(2) Resistance to action of hot and often corrosive gases.
(3) Retention of good mechanical properties at high temperature.
(4) Stability against deterioration and structural modification resulting from cyclical or continuous temperature operation.
(5) Resistance to impact and/or wear at the working temperature.

(1) *Resistance to Scaling.*—The predominating element in resistance of alloy steels to scaling is chromium, and loss by oxidation is roughly inversely proportional to the chromium content. Silicon and aluminium have a favourable effect, but the latter may embrittle the steel. Fig. 42 gives particulars of resistance of steels in Table 21 to scaling at a temperature of 1100° C. (3A Steel is 3 Steel + 3·0 Si).

Table 23 gives details of tests carried out in industrial furnaces which, working intermittently, give rise to more severe conditions than steady temperatures.

(2) *Resistance to Corrosive Gases.*—Wide use is made of steels types 2–7 (Table 22) for components of sulphide roasting furnaces. No. 5 steel ("Hecla A.T.V.") is much used for turbine blading under conditions of high superheat.

(3) *Stability at High Temperature.*—These highly alloyed steels show good degree of freedom from embrittlement when subjected to high temperature, as will be seen from Table 24.

TABLE 22.

TYPICAL HEAT-RESISTING STEELS MANUFACTURED BY MESSRS. HADFIELDS LTD., SHEFFIELD.

Reference No.	Approximate Analysis.					Treatment.	Mechanical Properties.										Coeff. of Expansion 10^{-6} per ° C. at 20°.
							Room Temperature.						800° C.				
	C	Cr	Ni	W	Si		Yield Point (tons per sq. in.).	Max. Stress (tons per sq. in.).	Elongation (per cent.).	Reduction of Area (per cent.).	Brinell Hardness No.	Izod (ft.-lbs.).	Max. Stress (tons per sq. in.).	Elongation (per cent.).	Reduction of Area (per cent.).	Creep Stress 10^{-6} per hr. at 1000 hrs. (40 days).	
1	0·40	13·5	13·5	2·5	1·5	Forged	37	60	37	42	260	50	24	32	60	1·0	15·1
2	0·30	20	7	4·0	1·5	,,	38	61	34	41	260	35	25	36	60	1·2	13·3
3	0·25	20	7	—	1·5	,,	30	56	42	46	190	50	23	38	61	0·5	15·7
4	0·45	14	28	4·0	1·5	,,	32	50	30	45	200	35	21	32	43	0·55	14·1
5	0·43	10	37	—	0·25	,,	28	48	30	50	200	50	17	44	61	—	7·3
6	0·25	25	18	—	2·0	,,	33	50	29	46	195	50	20	33	48	0·5	14·3
7	0·50	30	—	—	1·5	,,	25	45	18	30	215	5	Same order as for carbon steel.			0·28	8·7
8	0·50	12	60	—	1·5		25	51	33	47	185	50	23	43	53	0·48	11·0

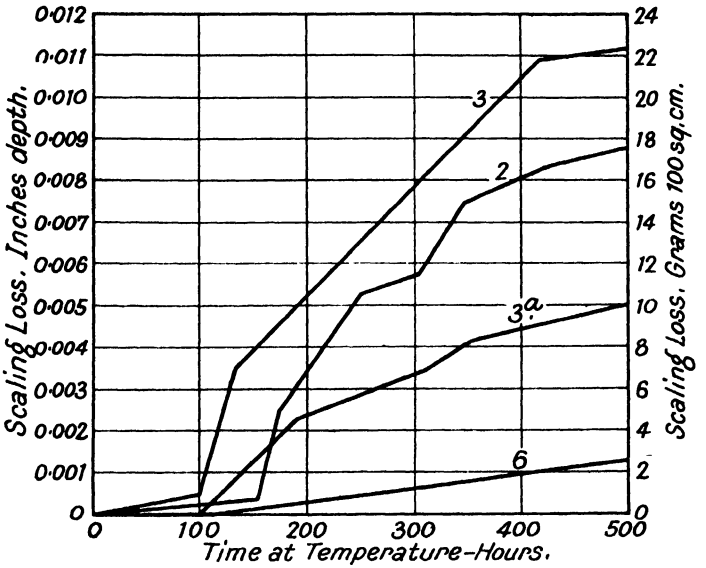


FIG. 42.

TABLE 23.

RESISTANCE TO SCALING IN INDUSTRIAL FURNACE ATMOSPHERES.

Temperature.	Time at Temperature Hrs.	Fuel Used.	Loss due to Scaling (ins. in depth).					Mild Steel.
			Type 2.	Type 3.	Type 6.	Type 7.	Type 8.	
950° C.	3000	oil	0·010	0·019	0·003	0·0055	—	0·18 *
1050° C.	1000	coal	—	—	0·038	0·044	0·093	0·135 †

* In 350 hrs. † In 50 hrs.

TABLE 24.

Steel.				Temperature.	Hrs.	Izod Impact Figure (ft.-lbs.).	
C	Si	Cr	Ni			Before Heating.	After Heating.
0·10	0·30	18	8	450° C.	240	120	120
0·13	1·25	25	18	450° C.	400	55	47
0·35	1·75	25	18	950° C.	200	46	31
0·45	1·50	14	28	850° C./900° C.	1000	30	24

Should corrosive conditions be present, however, it must be noted that intercrystalline embrittlement is liable to occur, particularly in

the case of the 18–8 CrNi types. The 25–18 CrNi is much more resistant in this respect.

(4) *Strength at High Temperatures.*—The creep particulars of these steels are given in Table 22, and Fig. 43 gives further information in this respect.

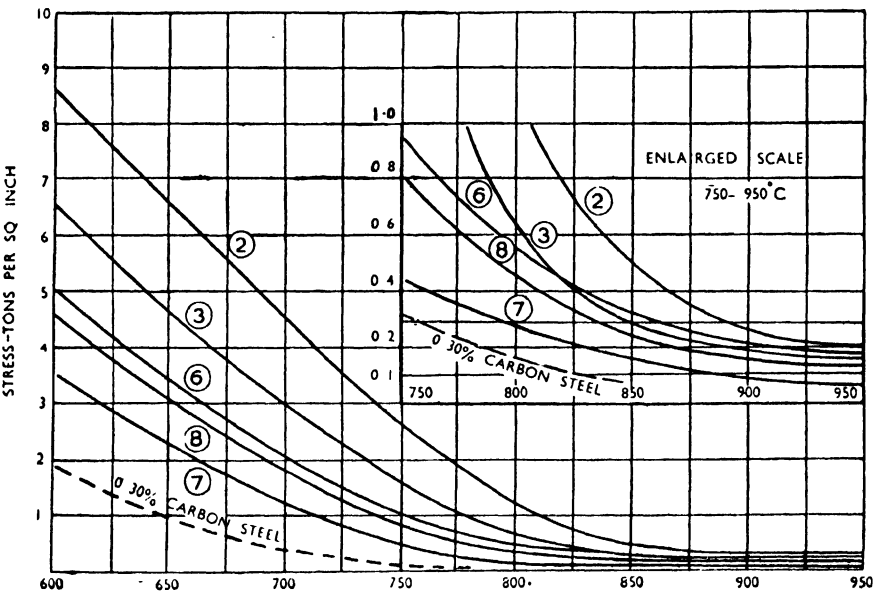


FIG. 43.—Stress temperature cures in a rate of creep of one-millionth (10^{-6}) per hour. Measured after 40 days of load.

(5) *Resistance to Wear and Impact.*—Often these heat-resisting steels must work under highly abrasive conditions as agitator fingers in gas producers, clinker shutes in cement kilns, skid rails in furnaces, scrapers in ore roasting furnaces. Fortunately these heat-resisting steels are highly resistant to such abrasive conditions.

The Properties of Non-Ferrous Materials at Elevated Temperatures.

Tapsell and Bradley (*J. Inst. Metals*, 1926, **35**, 75) found that the limiting creep stress of Ni 68·7, Cu 28·2, Fe 0·56, Mn 2·35, a nickel-copper alloy rolled bar, was 24·0 tons per sq. in. at 400° C., and that at higher temperatures, 500° C., failure occurred not on account of creep, but primarily because of severe intercrystalline cracking. A nickel-chrome alloy (Ni 79·7, Cr 19·0, Fe 0·88), again in rolled bar form, has a limiting creep stress of 24·0 tons per sq. in. at 500° C., but at higher temperatures failure under stress is due to intercrystalline cracking.

Cournot and Pages (*Rev. de Met.*, 1926, **23**, 701) found that annealed

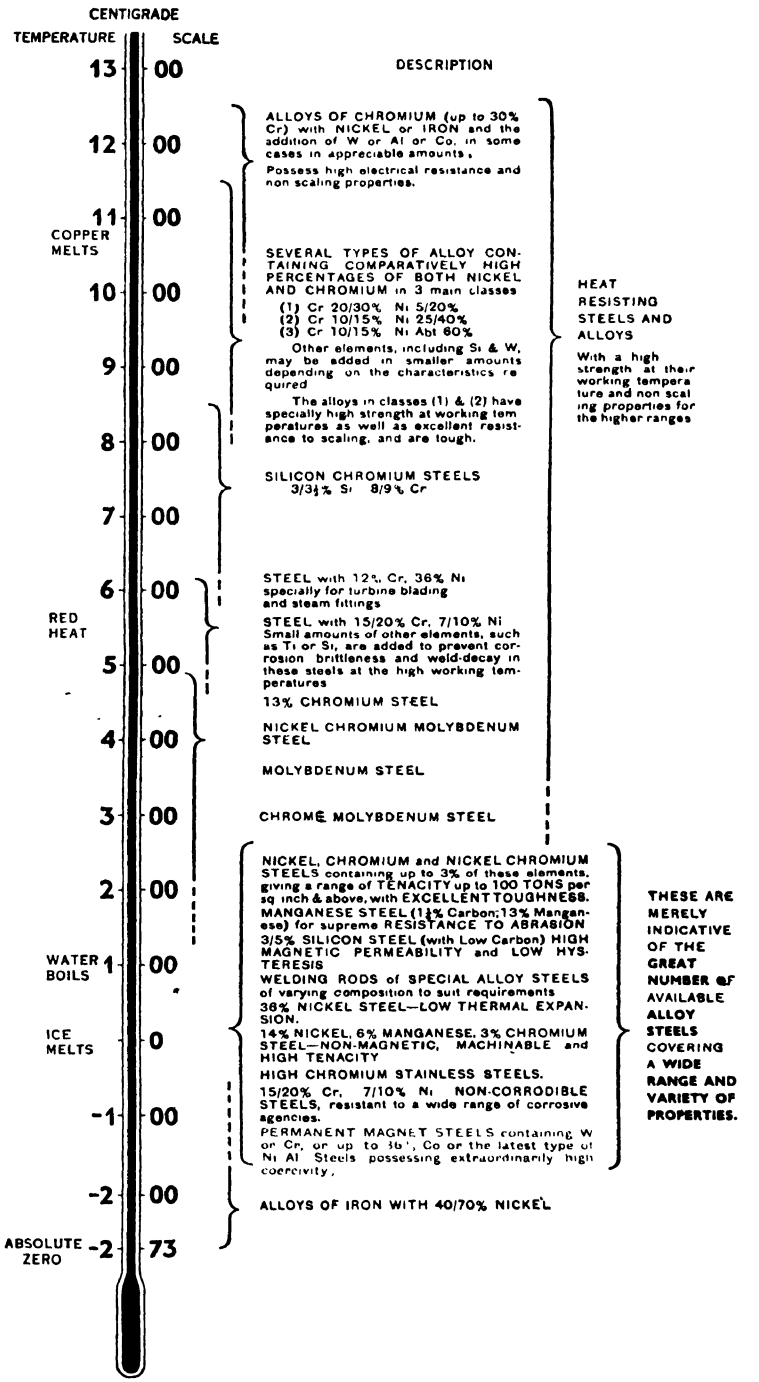


FIG. 44.—Chart showing the steels suitable for various ranges of temperature.

copper begins to lose strength at 100° C., and that the strength at 250° C. is half that at ordinary temperature. At 400° C. this material is entirely plastic under very low stress. National Physical Laboratory tests on rolled brass bar (Cu 59·8, Zn 38·6, Pb 0·99, Sn 0·34) show that this material has a limiting creep stress of 0·4 tons per sq. in. at 250° C., and that a rolled phosphor bronze bar (Cu 94·26, Sn 5·49, P 0·24) has a limiting creep stress of 4·4 tons per sq. in. at 250° C., and 1·0 tons per sq. in. at 350° C. Further particulars of the properties of useful non-ferrous alloys are given in Table 25.

The following notes (F. Hudson, *Metallurgia*, Dec. 1937) are of interest in the application of non-ferrous metals in high-temperature service :—

In modern engineering practice, non-ferrous alloys are extensively employed under conditions of elevated temperatures such as is obtained, for example, in steam valves and fittings, chemical plant. Table 26 gives the results of short-time tensile tests of non-ferrous metals. It is interesting to observe that alloys having similar room temperature properties do not necessarily maintain their strength to the same degree at elevated temperatures. Composition plays a very important part in this direction and nickel additions are most advantageous in stabilising the alloy, resistance to softening at high temperatures being increased in proportion to the increase in nickel content. This is clearly shown by comparison of the results given in Table 26, which has been compiled from data published by various investigators during the past few years. For example, an ordinary 11 per cent. tin bronze has a tensile strength at 800° F. (427° C.) of around 9 tons per sq. in., which is increased to 11 tons per sq. in., with the addition of 3·5 per cent. nickel and up to 30 tons with 50 per cent. nickel. Similar comparisons can be made from Table 26 in connection with 70/30 brass versus nickel silver and the aluminium bronzes with and without nickel additions. This effect of nickel in stabilising the properties of non-ferrous alloys is used to great advantage in modern engineering for steam valve faces and seats, etc., where a high measure of strength and hardness must be maintained at operating temperatures to ensure satisfactory service. The reason for nickel acting in this manner is not yet clear, but it quite possibly hinges upon temper-hardening characteristics mentioned in a previous article by Hudson (*Metallurgia*, Oct.–Nov. 1937).

In view of non-ferrous alloys having to work in conjunction with steel for high temperature applications the question of coefficient of expansion is of some importance. In the past it has been considered that some of the high nickel tin bronzes (30 to 50 per cent. nickel) as used for steam control purposes have coefficients of expansion similar to steel, but this is not correct as actual tests indicate that the value for such alloys is between 0·000017 and 0·000018 and more represen-

TABLE 25.

The Properties of Some Non-Ferrous Alloys at Elevated Temperatures.

In modern engineering practice non-ferrous alloys are extensively employed under conditions of elevated temperatures such as arise in steam valves and fittings, chemical plant, bearings, etc., and it is universally recognised that this causes an alteration in the mechanical properties normal to room temperature. When metals become heated the tensile strength drops and ductility, as measured by percentage elongation, varies considerably according to the composition of the alloy and the temperature. Some knowledge of the extent of these alterations in mechanical properties is highly important and the graphs below give the results of short-time tensile tests, together with other data in connection with the subject.

Properties of Certain Alloys at Four Temperatures.

A = Room Temperature. C = 315° C. (600° F.).
B = 205° C. (400° F.). D = 427° C. (800° F.)

The values given here are taken from various published sources and do not necessarily represent absolute values. They show the general trend of the properties of the materials.

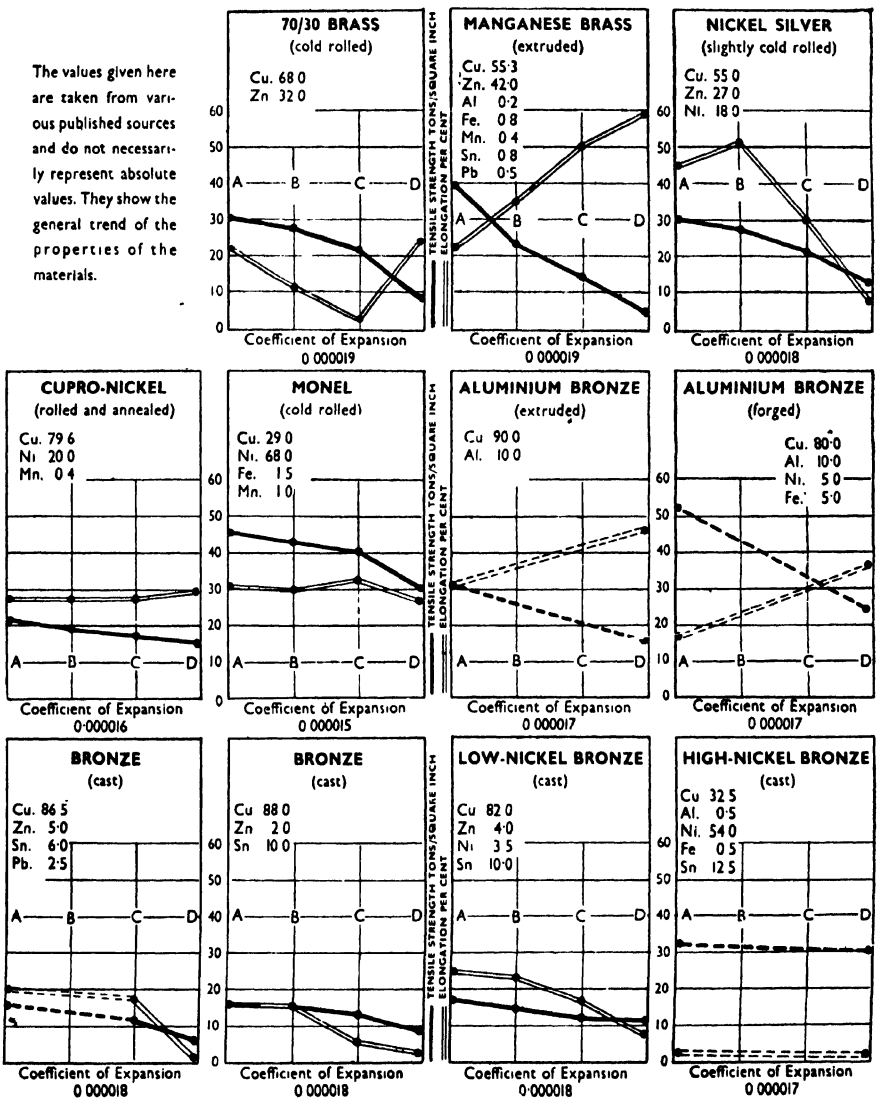


TABLE 26.

Properties of Brasses and Bronzes at Elevated Temperature.

Alloy.	Composition.									Room Temp.		205° C. (400° F.).		315° C. (600° F.).		427° C. (800° F.).	
	Cu.	Zn	Al.	Ni.	Fe.	Mn.	Sn.	Pb.	Be.	Max. Stress (tons/ sq. in.).	Elong. (per cent.).	Max. Stress (tons/ sq. in.).	Elong. (per cent.).	Max. Stress (tons/ sq. in.).	Elong. (per cent.).	Max. Stress (tons/ sq. in.).	Elong (per cent.).
70 30 brass (cold rolled) .	68·0	31·98	—	—	0·02	—	—	trace	—	31	24	29	12	23	4	9	26
60/40 brass, Muntz (hot rolled)	60	40	—	—	—	—	—	—	—	25	51	21	50	11	40	4	18
Manganese brass (extruded)	55·1	41·89	0·07	0·28	0·84	0·36	0·77	0·52	—	40	21	24	35	15	50	5	60
Brass (cast)	57·14	40·11	0·44	—	1·72	—	0·10	0·49	—	29	21	21	51	13	74	4	102
Nickel silver (rolled) . .	55·0	27·0	—	18·0	—	—	—	—	—	30	45	27	52	22	30	13	8
80/20 Cupro-nickel (hot rolled)	79·6	—	—	20·0	—	0·4	—	—	—	21	26	19	26	17	26	15	28
Monel (rolled)	29·0	—	—	68·0	1·5	1·0	—	—	—	47	31	43	30	40	33	30	28
Aluminium bronze (extruded)	90·0	—	10·0	—	—	—	—	—	—	32	31	—	—	—	—	16	47
Aluminium bronze (rolled).	80·0	—	10·0	5·0	5·0	—	—	—	—	53	16	—	—	—	—	24	37
Common gunmetal (cast) .	86·28	5·10	—	0·23	0·06	—	5·99	2·33	—	15	20	—	—	11	16	6	2
Bronze (cast)	86·52	1·29	—	0·09	0·01	—	11·86	0·17	—	19	17	18	15	13	4	9	2
Low nickel bronze (cast) .	82·0	4·0	—	3·5	—	—	10·0	—	—	16	25	14	23	12	15	11	8
High nickel bronze (cast) .	32·55	—	0·32	53·8	0·48	—	12·72	—	—	32	2	—	—	—	—	30	2

tative of ordinary bronze than otherwise. In the author's opinion the question of difference in expansion is in many cases not so vital as it is made out to be and very often the design of the structure effects this factor to a greater degree than the use of dissimilar metals. For example, in a steam valve a slightly greater coefficient of expansion in seat materials over that used for the body tends to keep the faces tight and prevents them working loose. If a coefficient of expansion approximately equal to steel is essential it becomes necessary to use an alloy having a nickel content of 70 to 90 per cent. with preferably a ferrous base, or alternatively, either Monel or one of the higher-class stainless steels.

Hydrogen Attack of Non-Ferrous Metals.

Cox (*Trans. Am. Inst. Chem. Eng.*, 1933, **29**, 43) states that in a private communication from Krupp that hydrogen penetration tests made in an atmosphere of hydrogen-nitrogen, at a temperature of 450° C. and a pressure of 300 atms. for 630 hrs., Monel metal broke in the hand, and copper was seriously affected both in strength and ductility.

The Properties of Metals at Low Temperatures.

Colbeck, McGillivray and Manning (*Proc. Inst. Chem. Eng.*, 1933, **11**, 89) describe some interesting research in this field, and the results may be briefly summarised as follows :—

Table 27 shows the chemical analysis of the materials tested, and their source. The Armco iron, low-carbon steel, and nickel-chrome-molybdenum steel were included for control, and purposes of comparison.

The tests carried out were ordinary tensile and impact tests. In the latter case, the standard Avery 120 ft.-lbs. machine was used, and specimens were quickly transferred from the cooling bath to the vice grips of the machine to avoid sensible temperature rise. The whole operation did not take more than seven seconds, and the authors found that in such circumstances the error was negligible.

The tensile tests were carried out in a simple hydraulic testing machine, and a cryostat surrounded the test specimen. A special extensometer of the tilting-mirror type was fitted.

The tensile test results are given in Table 27.

The Izod impact test results are given in Table 27A.

Regarding the results, the following are especially worthy of note :—

(1) Tensile Tests.

(*a*) The very high tensile strength obtained with some of the special steels at − 180° C.

(*b*) The very low yield point obtained with the austenitic steels over the whole range of temperature.

TABLE 27.

TENSILE RESULTS.

* denotes average of two tests.

Material.	Diameter of Test-Piece (in ins.).	Temperature of Test (° C.).	Ultimate Strength (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent. on 2 ins.).	Reduction of Area (per cent.).	Fracture.	Analysis (per cent.).	
Nickel-chrome-molybdenum steel: Oil hardened 850° C. Tempered 640° C.	0·25	Room	68·0	61·5	14·0	65·0	Fibrous, radial ridges		
	0·25	— 21	69·0	62·9	15·6	64·0	Fibrous		
	0·25	— 60	73·2	64·0	14·0	63·0	Jagged edges	Carbon	0·33
	0·25	— 67	72·8	65·0	15·6	62·0	Very jagged edges, radial ridges	Nickel	2·45
	0·25	— 96	76·1	66·6	16·4	61·0	Jagged edges, longitudinal split	Chromium	0·67
	0·25	—180	90·0	82·0	17·0	63·0	Jagged edges	Molybdenum	0·64
	0·504	Room	72·6	66·2	19·0	61·0	Fibrous, radial ridges		
	0·504	—180	93·0	88·5	20·0	50·0	Broke in four pieces		
Armco iron as received	0·25	Room	20·4	N.O.	27·9	73·2	Fibrous, silky		
	0·25	— 20	24·0	13·7	42·0	75·0	Fibrous		
	0·25	— 50	26·5	18·8	43·0	74·0	Fibrous		
	0·25	— 70	27·5	19·4	37·5	72·0	Fibrous		
	0·25	—100	29·8	25·5	26·5	70·0	Fibrous		
	0·25	—120	34·4	29·8	17·0	68·0	Crystalline, fibrous core		
	0·25	—180	50·0	N.O.	Nil	Nil	Coarsely crystalline		
	0·504	Room	20·8	10·0	43·0	72·0	Fibrous, part cup and cone		
	0·504	—180	49·7	N.O.	Nil	Nil	Coarsely crystalline		
Low-carbon steel as received—fine grain size, pearlite and ferrite structure	0·25	Room	29·6	24·4	29·7	71·8	Cup and cone		
	0·25	— 65	36·0	30·2	33·6	70·3	Part cup and cone	Carbon	0·13
	0·25	—180	54·2	N.O.	26·5	55·0	Crystalline	Manganese	0·68
	0·504	Room	29·6	25·0	37·5	69·0	Fibrous, silky		
	0·504	—180	54·2	50·7	27·0	32·5	Crystalline		

X 98. Water quenched 1100° C.	0·25	Room	45·0	14·0	51·6	71·0	Jagged edges	Carbon	0·11
	0·25	− 20·5	64·4	17·2	44·5	75·0	¾ cup and cone	Nickel	10·0
	0·25	− 61·5	80·0	21·0	37·5	66·0	Part cup and cone, jagged edges	Chromium	14·7
	0·25	−101	86·3	15·8	25·5	63·0	½ cup and cone		
	0·25	−125	93·8	18·0	30·5	62·0	½ cup and cone		
	0·25	−180	114·0	22·2	23·5	50·0	¾ cup and cone		
	0·504	Room	45·0	16·7	58·5	72·3	45° shear, central cup and cone		
	0·504	−180	109·5	29·4	28·0	49·0	Complete cup and cone		
X 99. Water quenched 1100° C.	0·25	Room	41·4	16·5	54·0	74·0	Jagged	Carbon	0·11
	0·25	− 20	51·0	19·0	62·5	73·0	45° shear, fibrous	Nickel	10·05
	0·25	− 60	61·1	22·2	61·0	74·0	½ cup and cone	Chromium	18·3
	0·25	− 96	69·0	24·0	46·1	70·0	½ cup and cone		
	0·25	−116	80·0	32·5	48·5	63·0	¾ cup and cone		
	0·25	−180	99·5	33·3	45·7	55·0	Part cup and cone		
	0·504	Room	39·8	21·4	58·5	73·0	45° shear, small central cup and cone		
	0·504	−180	87·0	43·7	42·0	61·0	Almost complete cup and cone		
X 100. Water quenched 1100° C.	0·25	Room	37·0	15·2	58·0	77·0	½ cup and cone	Carbon	0·11
	0·25	− 21	47·3	15·0	64·0	76·0	Jagged edges	Nickel	12·0
	0·25	− 59·5	59·3	24·0	50·0	72·0	¾ cup and cone	Chromium	12·7
	0·25	− 98	74·5	15·0	43·0	67·0	Complete cup and cone		
	0·25	−120·5	81·2	19·4	38·0	64·0	Complete cup and cone		
	0·25	−180	105·0	28·2	36·0	50·0	Almost complete cup and cone		
	0·504	Room	34·0	14·9	62·5	78·0	45° shear, small central cup and cone, jagged edges		
	0·504	−180	101·9	35·8	37·0	53·0	Complete cup and cone		
X 101. Water quenched 1100° C.	0·25	Room	38·8	11·0	50·0	74·0	Two 45° shears, V-notch	Carbon	0·11
	0·25	− 22	46·0	20·0	61·5	79·0	Cup and cone, jagged edges	Nickel	12·0
	0·25	− 61	56·1	24·0	61·0	76·0	½ cup and cone	Chromium	14·7
	0·25	−100	66·5	25·0	48·5	70·0	Complete cup and cone		
	0·25	−121	74·0	28·2	46·1	70·0	½ cup and cone, jagged edges		
	0·25	−180	97·0	32·5	44·0	55·0	½ cup and cone		
	0·504	Room	35·4	10·0	60·0	75·0	45° shear, small central cup and cone		
	0·504	−180	94·7	35·75	45·5	55·0	Part cup and cone		

TABLE 27 (*continued*).

Material.	Diameter of Test-Piece (in ins.).	Temperature of Test (° C.).	Ultimate Strength (tons per sq. in.).	Yield Point (tons per sq. in.).	Elongation (per cent on 2 ins.).	Reduction of Area (per cent.).	Fracture.	Analysis (per cent).	
X 102. Water quenched 1100° C.	0·25	Room	38·0	12·1	51·5	76·0	45° shear		
	0·25	— 20	42·0	15·0	67·0	80·0	½ cup and cone, jagged edges		
	0·25	— 62	47·5	20·8	60·0	78·0	Part cup and cone	Carbon	0·11
	0·25	—100	59·5	22·0	56·0	75·0	¾ cup and cone	Nickel	13·8
	0·25	—177	94·5	32·0	44·5	58·0	Complete cup and cone	Chromium	12·2
	0·25	—121	69·0	24·0	50·0	71·0	½ cup and cone		
	0·504	Room	34·7	14·65	57·0	75·0	Part cup and cone, central core		
	0·504	—180	92·3	36·6	47·5	59·0	Complete cup and cone		
X 103. Water quenched 1100° C.	0·25	Room	38·5	15·3	51·0	76·0	Fibrous, jagged edges		
	0·25	— 20	43·5	18·5	62·0	79·0	45° tear, central cup		
	0·25	— 61·0	50·0	19·4	70·3	76·0	45° tear, central cup	Carbon	0·11
	0·25	—100	54·9	24·4	54·7	73·0	½ cup and cone	Nickel	14·0
	0·25	—121	62·0	26·8	56·0	72·0	Part cup and cone	Chromium	14·15
	0·25	—180	86·4	32·5	51·5	60·0	¾ cup and cone		
	0·504	Room	35·6	15·0	52·3	75·0	½ cup and cone, central core		
	0·504	—180	84·05	43·30	53·0	58·0	Part cup and cone		
X 104. Water quenched 1100° C.	0·25	Room	37·2	14·5	44·5	78·0	45° tear, central cup		
	0·25	— 20·5	40·0	16·2	61·0	79·0	45° tear, central cup		
	0·25	— 62·0	45·0	17·2	61·5	77·0	45° tear, very small central cup	Carbon	0·11
	0·25	—102	51·8	21·5	66·5	74·0	45° tear, central cup	Nickel	15·92
	0·25	—121	55·5	24·5	69·0	73·0	¾ cup and cone	Chromium	12·25
	0·25	—180	79·0	32·0	58·1	65·0	Part cup and cone		
	0·504	Room	34·4	16·5	56·0	75·0	½ cup and cone, central core		
	0·504	—180	77·20	37·2	64·0	67·0	Nearly complete cup and cone		

X 95. Water quenched 1100° C.	0·25	Room	41·8	20·0	47·8	51·7	Fibrous, jagged edges	Carbon	0·11
	0·25	−180	98·0	52·5	54·7	75·2	—	Nickel	11·5
	0·504	− 70	57·3	34·6	65·0	75·0	½ cup and cone	Chromium	16·2
	0·504	−180	94·0	50·0	50·0	64·0	Complete cup and cone		
X 96. Water quenched 1100° C.	0·504	Room	35·9	17·2	59·5	75·5	45° shear, central cup and cone	Carbon	0·06
	0·504	−180	88·2	40·0	47·0	60·0	Part cup and cone	Nickel	10·05
								Chromium	13·45
								Manganese	4·07
X 92. Water quenched 1100° C.	0·504	Room	50·0	24·0	43·0	47·5	Fibrous	Carbon	0·45
		−180	76·9	63·8	14·0	14·0	Jagged-dusty	Nickel	10·2
								Chromium	13·8
								Manganese	3·65
X 91. Water quenched 1100° C.	0·504	−180	103·7	34·4	30·5	45·0	¾ cup and cone	Carbon	0·11
								Nickel	10·5
								Chromium	15·6
Brown Bayley's "Anka" (as received)	0·504	−180	109·3	37·5	38·0	52·0	Almost complete cup and cone. 3 longitudinal splits	Carbon	0·11
								Nickel	10·1
								Chromium	15·8

(*c*) The very small proportional alteration found in all the tensile properties of the martensitic nickel-chrome-molybdenum steel.

(*d*) The absence of ductility and the approach of the yield point to the ultimate strength in Armco iron at the lower temperatures.

(2) Impact Tests.

(*a*) Armco iron becomes quite brittle at temperatures of — 37° C.

(*b*) Low-carbon steel shows no reduction in impact value down to — 65° C., but at — 180° C. has no resistance to impact.

(*c*) The nickel-chrome-molybdenum steel (Vibrac) shows little alteration in impact value down to — 120° C., but this falls appreciably at temperatures of — 180° C.

(*d*) There appear to be three types of austenitic steel when classified in connection with the response to low temperature in so far as impact value is concerned.

Firstly, there is the class which show practically no change in impact value even after prolonged soaking in liquid air.

Secondly, those which show no immediate change when cooled to — 180° C., but show a falling off when held for a period at this low temperature.

Thirdly, those which show a reduced impact value at intermediate temperatures, some of which show a further deterioration when held for periods in liquid air.

Regarding the austenitic steels, the study of which was the primary object of these investigations, in all cases the tensile strength was progressively increased from room temperature down to — 180° C. At this low temperature the tensile strength and yield point were two or three times as great as at ordinary temperatures.

Tensile strengths as high as 110 tons per sq. in. were recorded at — 180° C.

The authors draw special attention to the powerful stabilising effect of manganese. For example, ingot X 96 is almost identical with ingot X 98, with the exception that the former contains 4 per cent. of manganese. This has been sufficient to ensure that ductility and resistance to impact have been preserved down to — 180° C.

Special attention is also drawn to the embrittling effect of carbon under low-temperature conditions, and the authors recommend the carbon content should be below the maximum solubility of carbon in austenite.

Non-Ferrous Metals at Low Temperature.

Colbeck and McGillivray have recently published results of mechanical tests on non-ferrous materials at low temperature (*Proc. Inst. Chem. Eng.*, 1933, **11**, 107). Their results for copper, aluminium, nickel and brass are given in Table 28.

TABLE 27A.

IZOD IMPACT TESTS.

Material.	Room Temp.	− 65° C.	− 120° C.	− 180° C.	Time of Soaking in Liquid Air. (hours.)	Impact after Soaking in Liquid Air.	After Warming up to Room Temperature.	Remarks.
Low carbon steel .	94·0*u*	99·0*u*	—	3·0*b*	—	—	91·0*u*	* After warming up under cold water tap from − 65° C.
B and B "Anka"	—	—	—	75·0*u*	20	64·0*b*	—	—
* Vibrac	57·5*b*	53*b*(− 74° C.)	50·0*b* 51·0*b*	22·0*b*	—	—	60·0*b*	—
Armco	78·0*b*	4*b*(− 74° C.)	—	1·5*b*	—	—	83·0*u*	—
X 91	113·0*u*	—	—	86·0*u*	350	70·0*u*	117·0*u*	Several other tests after soaking in liquid air are recorded for this steel.
X 95	118·0*u*	118·0*u*	—	117·5*u*	336	117·5*u*	108·0*u*	—
X 96	117·0*u*	117·5*u*	—	117·5*u*	336	117·0*u*	—	—
X 92	61·0*b*	—	—	14·0*b*	—	—	—	—
X 98	116·0*u*	99·0*u*	86·0*u*	79·5*b*	168	79·0*b*	118·0*u*	—
X 99	114·0*u*	117·5*u*	107·5*u*	100·0*u*	192	100·0*u*	117·0*u*	—
X 100	118·0*u*	117·5*u*	98·5*u*	102·0*u*	216	95·0*u*	107·5*u*	—
X 101	117·0*u*	117·5*u*	117·5*u*	98·0*u*	216	95·5*u*	109·0*u*	—
X 102	111·0*u*	117·5*u*	117·0*u*	102·0*u*	168	103·0*u*	99·0*u*	—
X 103	117·0*u*	117·5*u*	117·0*u*	116·0*u*	168	103·5*u*	110·5*u*	—
X 104	115·0*u*	117·25*u*	117·5*u*	117·5*u*	168	117·5*u*	100·0*u*	—

* This is a NiCrMo steel (0·25 C, 0·6 Cr, 2·5 Ni, 0·6 Mo).

b Indicates that the specimen was broken in the machine. *u* Indicates that the specimen remained unbroken.

TABLE 28.

Material.	Temperature (° C.).	Izod (ft.-lbs.).	Ult. Strength (tons per sq. in.).	Proof Stress (tons per sq. in.).
Copper	R.T.	43·0	14·0	3·82
	− 80	44·0	17·2	4·50
	− 180	50·0	22·7	5·12
Nickel	R.T.	89·0	29·25	10·98
	− 80	92·0	34·1	12·27
	− 180	98·5	43·7	12·47
Brass 70-30	R.T.	65·5	22·8	12·57
	− 80	69·0	25·5	12·17
	− 180	78·5	32·8	13·2
Aluminium	R.T.	19·0	4·38	1·98
	80	20·0	5·30	1·90
	− 180	27·0	9·30	2·03

Soft solder was found to have lost practically all its resistance to impact at − 180° C., but its tensile strength and yield point were markedly increased.

CHAPTER V.

NON-METALLIC MATERIALS OF CONSTRUCTION.

Chemical Stoneware.

CHEMICAL stoneware is one of the most important and durable of the ceramic materials available for chemical processes. It is extremely hard and dense, is a good insulator, and resists the action of all acids and corrosive materials with the exception of hydrofluoric acid and hot strong alkalis.

An average chemical composition of such stoneware is as follows (*Kingsbury Ind. Eng. Chem.*, 1927, **19**, 693) :—

	Per cent.
Silica (SiO_2)	73·23
Aluminium (Al_2O_3)	22·27
Iron (Fe_2O_3)	0·58
Lime (CaO)	0·58
Magnesia (MgO)	Trace
Potash (K_2O)	2·02
Soda (Na_2O)	1·42
Loss on ignition	0·06
	100·16

As will be noted, it is essentially an aluminium silicate. Physically stoneware is an aggregation of refractory particles of ceramic material in various stages of fusion, and bonded together by means of a vitrifying clay with the addition of a flux. There are two main types, the porous and coarse textured, and the other as fine and dense as the finest porcelain. The more porous types are used for plant involving quick temperature changes.

There has been marked development and improvement in mechanical properties in such stoneware during the last few years as will be noted from the following table :—

	1921.	1931.
Ultimate strength, tension (lbs./sq. in.)	1,650	7,500
Ultimate strength, compression (lbs./sq. in.)	82,800	116,800
Ultimate strength, bending (lbs./sq. in.)	5,900	13,950
Ultimate strength, torsion (lbs./sq. in.)	3,570	4,580
Modulus of elasticity (lbs./sq. in.)	$5{\cdot}95 \times 10^6$	$5{\cdot}95 \times 10^6$
Coefficient of thermal expansion (per 1° F.)	$2{\cdot}3 \times 10^{-6}$	$0{\cdot}083 \times 10^{-6}$
Thermal conductivity (B.Th.U./sq. ft./hr./1° F. diff. in temp. through 1 ft. thick)	0·9	2·64

Other important physical characteristics that have no absolute values are compared by empirical tests, the results of which are given below.

	1921.	1931.
Hardness (by ball pressure test similar to Brinell)	1044	1253
Resistance to fracture (by swinging hammer)	1·9	4·7
Abrasion (loss of weight under sand blast) .	3·0	1·8
Toughness (loss of weight in ball mill) . .	3·6	2·6

(*Kingsbury Journal Chem. Educ.*, 1932, 9, 797.)

Chemical stoneware is usually glazed to give it a smooth and attractive finish. The most important is salt glaze, which is formed by throwing common salt into the kiln as the maximum temperature (of the firing of the ware) is reached. The salt consequently volatilises and combines with the aluminium silicate of the ware, forming a sodium-aluminium silicate, and dense fumes of hydrochloric acid are evolved.

Stoneware has long enjoyed an important place in chemical engineering. For example, in the eighth century Geber produced nitric acid from nitre, copper, sulphate and alum in such vessels. In the fifteenth century, a stoneware still was used by Valentinus in the preparation of hydrochloric acid by distilling common salt with ferrous sulphate, and in the sixteenth century large stoneware vessels were employed for the preparation of sulphuric acid. To-day a comprehensive range is available of all types of vessels, pumps, agitators, pans, packed towers, valves and cocks, etc. etc., for use in many different types of chemical reactions, and particularly where freedom from contamination is imperative.

For example, for the storage of corrosive liquids, the arrangement shown in Fig. 45 is often used. The plant illustrated comprises twenty stoneware vessels each of 525 gals. capacity for handling muriatic acid, and a second unit for handling sodium hypochlorite with a capacity of 7900 gals. in fifteen similar vessels. Each of the units is coupled by pipework as seen in Fig. 46.

To put the plant into operation a small amount of water or of the liquid to be used is placed in each vessel, including the narrow cylindrical so-called siphon pot, A (Fig. 46). Suction is then applied at B, drawing the liquid up the stoneware pipes until it appears in the glass bulb C, which is then closed. If the liquid is now admitted into one or more of the storage vessels, it will automatically siphon over into all the others until the level is the same throughout the train. Similarly, when the faucet on the siphon pot is opened and the contents are discharged, there is immediately a considerable difference of level between the liquid in it and in the storage system. Consequently,

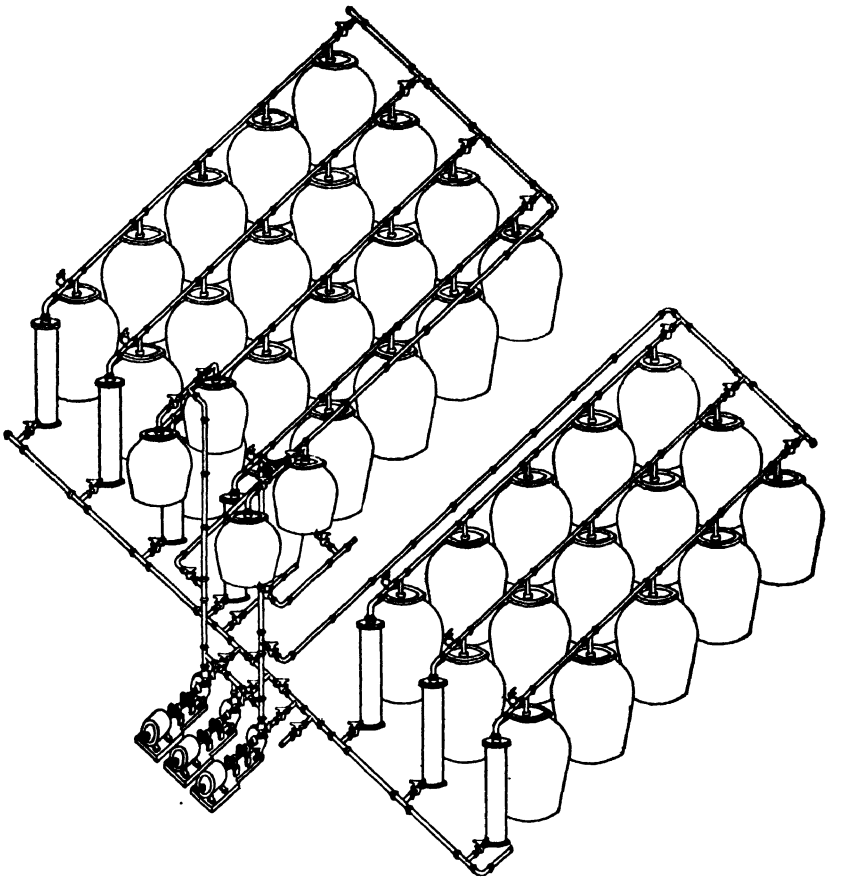


FIG. 45.—Acid Storage and distributing equipment in stoneware.

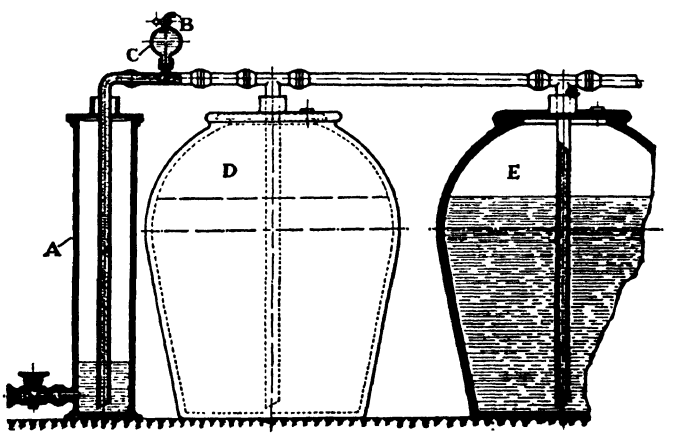


FIG. 46.—Stoneware pipes connecting units of above plant.

the liquid siphons over rapidly from the storage vessels D and E, and as the level gradually falls in these vessels they are replenished by siphoning over from the other vessels in the train. The whole system, in fact, operates just as if it were one large tank. Note, however, that there are no bottom outlets on the storage vessels, and all the connections are above the liquid level, where they are out of the way. Even if they should break, no damage is done, and the breakage can be quickly repaired at trifling expense. Experience has shown that the siphons will hold their prime for a considerable period, and they can be reset in a few moments when necessary. This plant is installed at the American Enka Corporation, Ashville, N.C., and was constructed by the General Ceramics Company of New York.

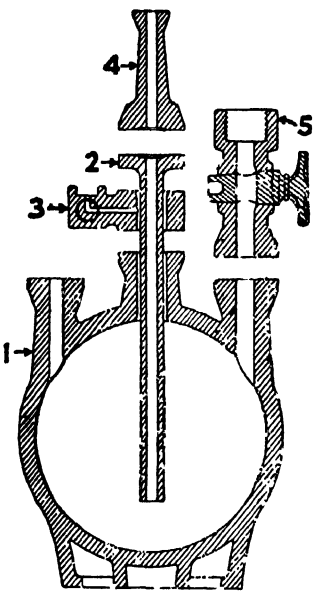


FIG. 50.—Sectional drawing of Acid Elevator.

Figs. 47-48 show sections of a typical stoneware vacuum filter and pressure filter respectively.

Fig. 49 is given to illustrate the large sizes in which stoneware coils are now obtainable. The illustration is of a coil 130 ft. long, 2½ ins. in diameter, and which weighs 825 lbs. (General Ceramics Co.)

Fig. 50 shows a stoneware acid elevator, the action of which is as follows :— the elevator is actuated by means of compressed air, and consists of a pressure vessel with connections for admission and discharge of liquid and of compressed air. It is operated by gravity and can therefore only be used when installed below a supply tank. When full, the acid inlet (5) and air outlet (3) are closed and compressed air admitted through (1). This ejects the contents through discharge pipe (4). When the vessel is empty it is recharged by shutting off compressed air inlet, and inlet (5) and air outlet (1) are opened and operation is repeated. These stoneware acid elevators are also supplied in automatic form to dispense with hand operation.

G. N. Hodson (*British Clayworker*, Feb. 1935) gives some interesting data on the practical use of chemical stoneware. For example, it is recommended that for high temperature service all sharp angles should be avoided in design, and varying thicknesses and abrupt changes in wall size are quite unsuitable in such circumstances.

Method of Heating Stoneware Vessels.—Direct-flame heating is unsuitable for all but the smaller sizes unless great care is exercised to apply the flame gradually and evenly. *Heating by hot gases* is used

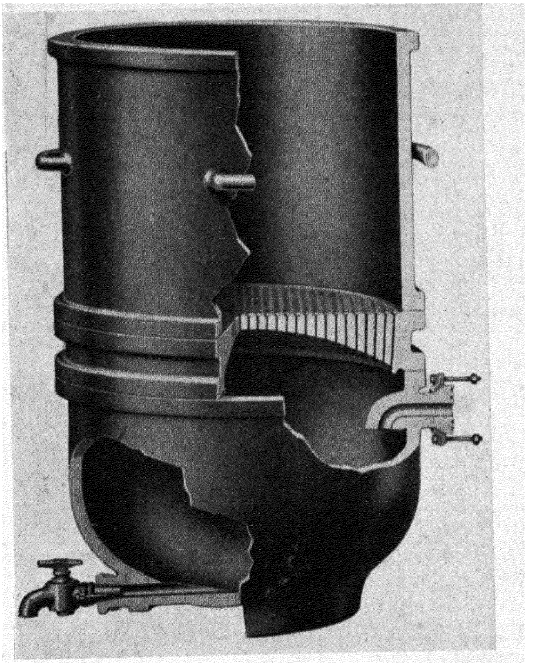


FIG. 47.—Stoneware vacuum filter.

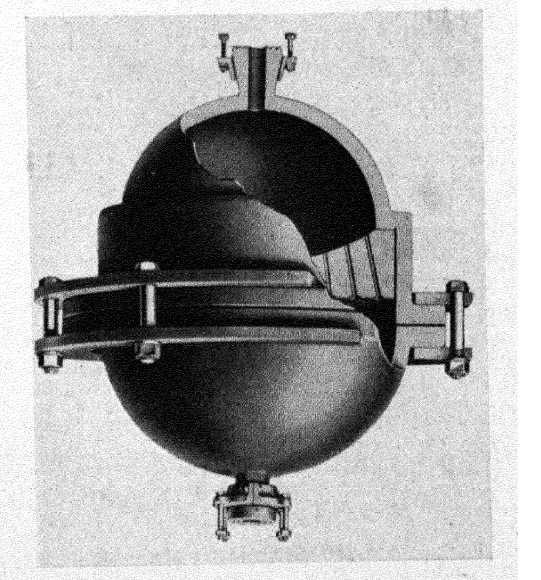


FIG. 48.—Stoneware pressure filter.

[*To face page* 152.

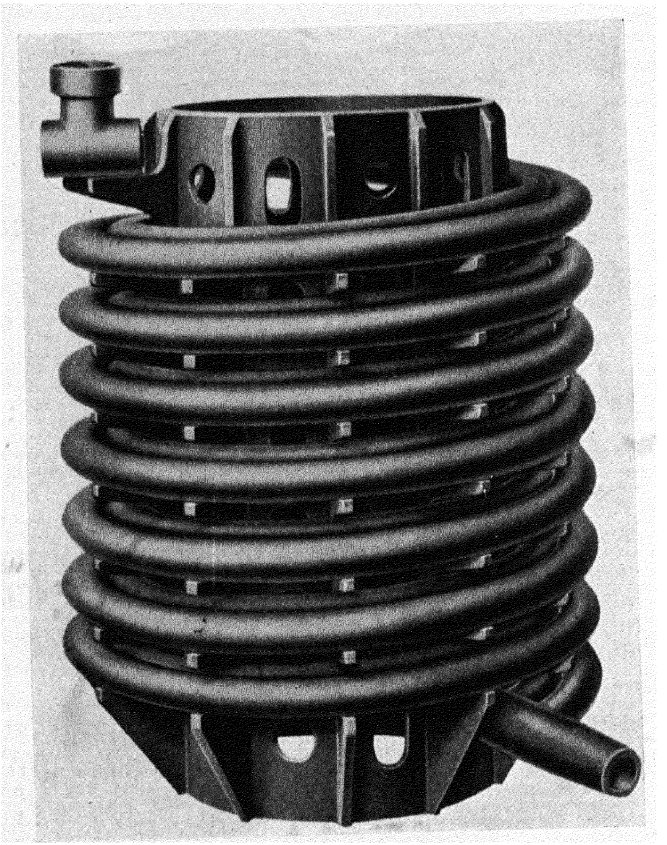


FIG. 49.—Large stoneware pipe coil.

[*To face page* 153.

for stills, and if care is taken to warm up slowly the method is satisfactory except in large vessels. *Heating in a sand bath or water bath* is frequently employed with good results. *Heating by coils* in the vessels is a good method, as is *heating by electric immersion* heaters enclosed in silica tubes.

Tile linings in chemical stoneware are often used, and the tiles are set in acid-proof cement, mastic asphalt or sodium silicate forming the base of most of these cements.

Flanged or spigot-socket pipework is available in quite large sizes, and armoured stoneware pipe (the armour being a cast-iron jacket) is employed for quite high pressures.

Industrial Chemical Glassware.

Recent developments in glassware permit of this material being used on the industrial scale in many chemical operations. Such industrial glasses are of the borosilicate type, which are notable for high resistance to heat, shock, and possess good mechanical properties.

"Pyrex" Borosilicate Glass.

Physical Characteristics.

Linear coefficient of expansion between 66° F.–660° F.	0·0000018″
Specific gravity	2·24
Specific heat	0·20
Modulus of elasticity	9×10^6 lbs./sq. in.

Flanged "Pyrex" Pipe.

Standard pipe hangers may be used for support, the bottom of the hanger being covered with a resilient sleeve to prevent scuffing or cutting during installation.

Pyrex piping expands with temperature change only one-third to one-quarter as much as metal pipe. The insertion of expansion or slip joints (Fig. 51) is dependent on the location of bends, elbows, valves and tanks, and thus is a function of each individual piping system. In general, however, they should be inserted in straight runs at intervals not exceeding 50 ft. for 1-in. and $1\frac{1}{2}$-in. pipe and 100 ft. for 2-in. and 3-in. pipe. They should always be inserted in runs for conveying hot liquids or gases and having fixed ends.

Joints are of the compression type shown in Fig. 52. Pipe-ends are conical flanges and are compressed to a gasket by metal flanges and clamping bolts. Gaskets are self-centring, held in place by the flange bolts.

In installation, pipe should be placed in hangers, malleable flanges loosely in place. Faces of abutting pipe-ends should be checked for parallelism and gaskets inserted between them. Assembly should proceed preferably from the fixed point of a system. Flanges should be

drawn together with faces parallel by a uniform tightening of nuts, in rotation and one-quarter to one-third turn at a time. Uniform compression of the gasket and a tight joint are thus assured. Tightening more than necessary for a firm gasket contact and lasting leak-proof joint should always be avoided.

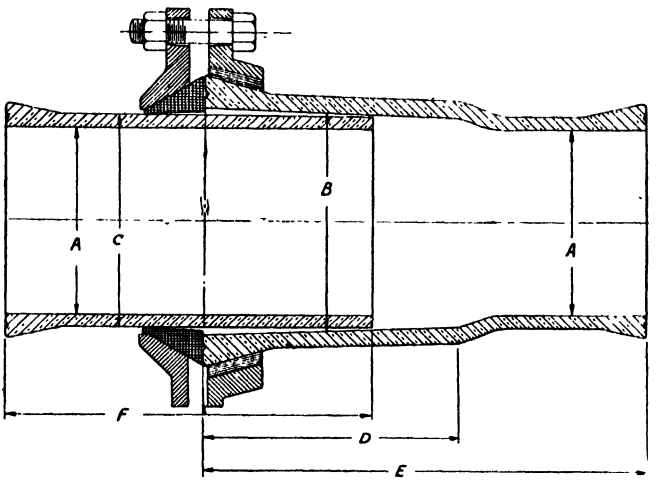


FIG. 51.—Expansion joints for glass pipework.

Heat Exchangers in Glass Pipework.

Heat exchangers of glass pipe are most generally of the jacketed type shown in Fig. 53. Lengths of light wall glass piping are enclosed in standard metal pipe, packed at the ends by means of suitable stuffing

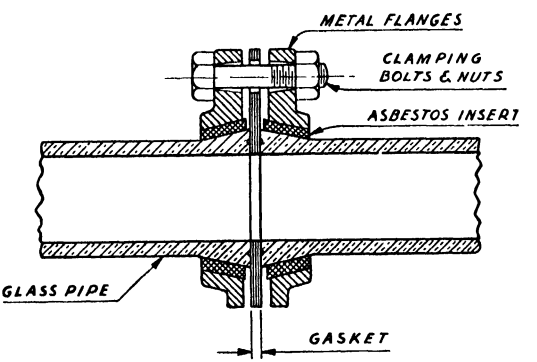


FIG. 52.—Connection for glass pipework.

boxes and connected in series by means of U-bends. Steam or heating or cooling water is circulated in the exterior jackets thus formed, heating or cooling the liquid or gas in the glass piping. The corrosion-resistance of Pyrex brand glass ensures a heat exchanger of long life, during which heat conduction is unchanged by scaling or surface pitting.

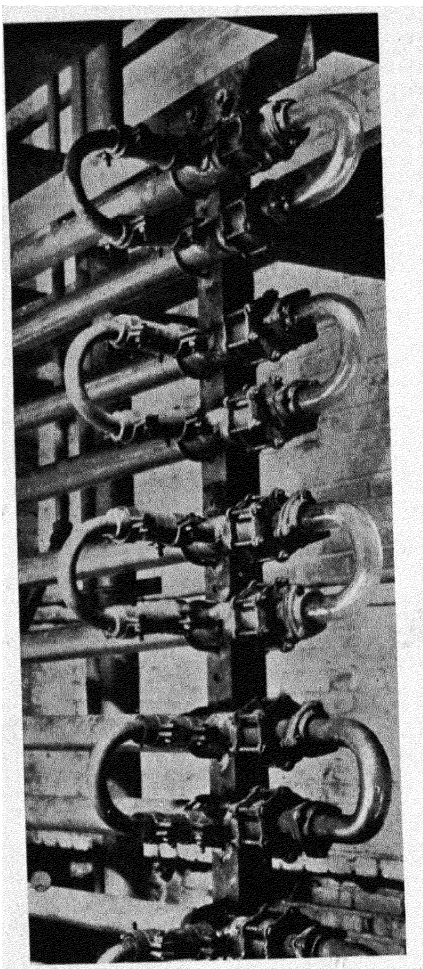


FIG. 53.—Glass heat exchanger.

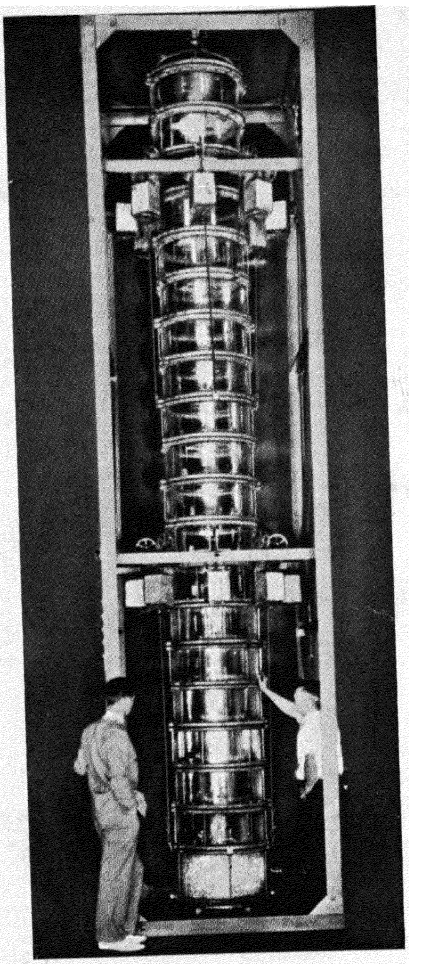


FIG. 54.—Glass fractionating column.

[*Facing page* 155.

Thus the theoretical heat conductivity of the glass is of lesser practical importance, and after a period of use glass heat exchangers compare very favourably with those constructed of metal tubes which may have initially a much greater theoretical conductivity.

A 20-ft. fractionating column by the Corning Glass Works of Corning, N.Y., is seen in Fig. 54, and glass bolts and nuts used in the assembly of this large column are shown in Fig. 55. The column weighs 2930 lbs., and the operating temperatures are 125° C. at the bottom and 95° C. at the top.

In addition to the above uses, glass-lined equipment such as pans, stills, etc., is becoming widely popular.

Fused Quartz or Silica Equipment.

Vitreous silica (perhaps better known by the trade name of Vitreosil, manufactured by the Thermal Syndicate of Wallsend-on-Tyne) consists of pure silica, fused by electric process into a homogeneous product containing 99·8 per cent. SiO_2.

In the early days of this material it was chiefly used for laboratory ware, but the process has been extended in a remarkable way, and many large chemical process plants are now made entirely from this material. It can be obtained in the translucent and transparent types.

Physical Properties of Fused Silica.

Density :	
Transparent	2·21 gms./c.c.
Translucent	2·07–2·15 gms./c.c.
Melting point	1700–1800° C.
Specific heat 0–900° C.	$(167+0{\cdot}189t-0{\cdot}000125t^2)\times 10^{-3}$
Coefficient of linear expansion, average 0–1000° C. α average	$0{\cdot}54 \times 10^{-6}$
Thermal conductivity :	
Transparent	0·0035 cal./sec./cm./cm.^{2} ° C.
Translucent	0·0025 cal./sec./cm./cm.^{2} ° C.

Mechanical Properties of Fused Silica.

Tensile strength :	
Transparent rods (0·25–0·6 ins.)	4000 lbs./sq. in.
Translucent rod (0·5 in. dia.)	400 lbs./sq. in.
Compressive strength :	
Transparent rod up to 0·75 in. dia.	163,500 lbs./sq. in.
Translucent rod up to 0·75 in. dia.	39,000 lbs./sq. in.
Ultimate Crushing stress :	
Translucent tubes 0·4 in. internal, 0·74 in. external dia.	2012 lbs./sq. in.
Transparent tubes 0·42 in. internal, 0·75 in. external dia.	6500 lbs./sq. in.

Chemical Resistance of Fused Silica.

It is unaffected by halogens and acids at all usual temperatures and concentrations, with the exception of fluoric, hydrofluoric and phosphoric acids. The last affects fused silica only at high temperatures, and it is therefore practicable to concentrate phosphoric acid successfully in fused silica vessels, and for all ordinary purposes this material can be used with this acid. Sulphuric, nitric and hydrochloric acids, or a mixture of these acids, have no action on fused silica even at very high temperatures.

Other materials which are unaffected by fused silica are :—acid gases (as described above), solutions of acid and neutral salts where elevated temperatures do not decompose them into alkaline residues, pure carbon, sulphur, and certain unfused acid and neutral salts.

Materials which have little or no effect upon fused silica, but react at temperatures above 100° C., are dilute and moderately concentrated solutions of basic salts, metallic oxides, and basic salts not in solution.

Strong alkalis react with fused silica, and by certain metallic oxides at high temperature.

Fused silica is practically unaffected by water and is therefore of great utility in delicate chemical operations where completely insoluble containers are required.

Fused silica is amongst the most refractory of materials, but when subjected for long periods to very high temperatures it tends to become brittle, as there is in these circumstances a reversion from the vitreous to the crystalline state.

Fused silica can, however, be used safely up to 1100° C. under ordinary working conditions, and it can be used indefinitely up to 1350° C., provided that the temperature is maintained above 300° C. This property enables it to be used for sighting tubes for furnaces which are in continuous operation, and for protection tubes for thermocouples, in which case for rapid readings it may be taken up to 1400° C.

Certain compounds, including potassium and lithium salts, sodium, tungstate, vanadic acid, ammonium fluoride, phosphates and radioactive substances, promote the devitrification of fused silica at lower temperatures.

Small muffle and electric furnaces are made in various types and sizes for either gas heating or by electric resistance winding around the exterior.

For industrial process work, fused silica components can be supplied in many varieties, such as basins for sulphuric acid concentration by the cascade system, or condensing coils, etc. Fig. 56 shows a "Vitreosil" silica coil 60 ft. long and 3 ins. diameter in supporting-frame.

A "Vitreosil" silica distillation apparatus for acids is seen in Fig. 57. All contact parts are of this material.

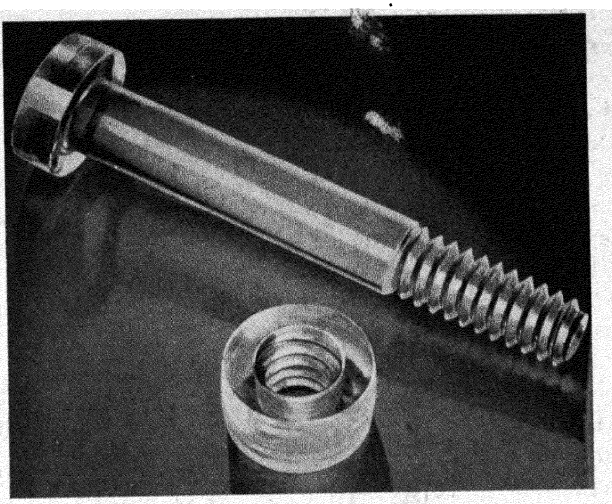


FIG. 55.—Glass bolts for glass fractionating column.

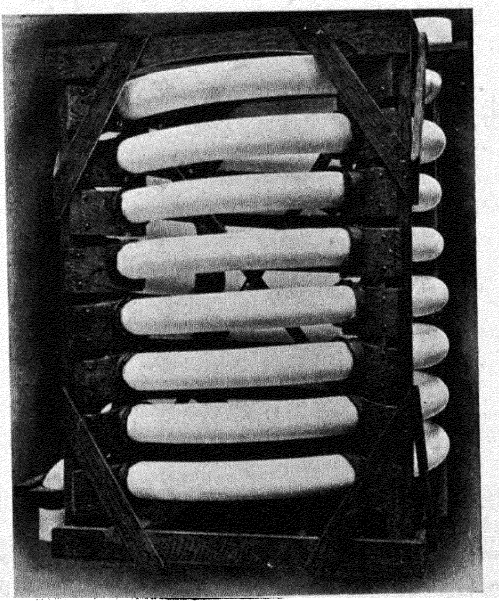


FIG. 56.—Large pipe coil in Vitreosil.

[*Facing page* 156.

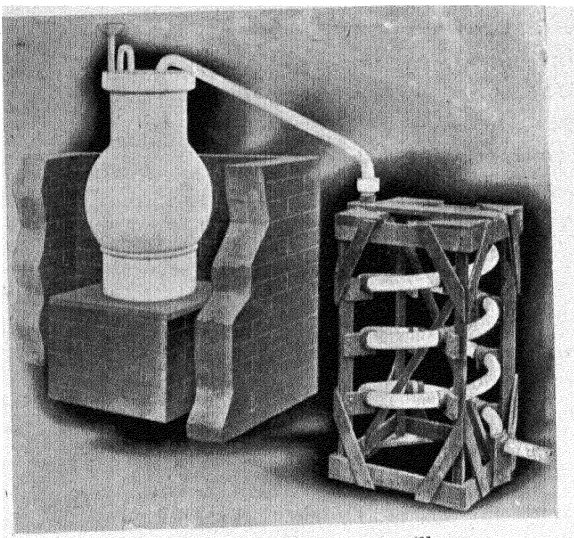


FIG. 57.—Vitreosil acid still.

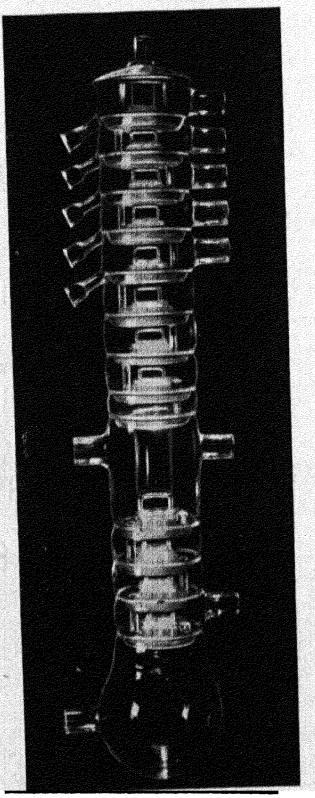


FIG. 58.—Vitreosil distillation column.

[*Facing page* 157.

An experimental transparent fused silica fractionating column, 20 ins. high, is seen in Fig. 58.

In the laboratory, fused silica has many applications. Examples are basins of all types, combustion tubes, beakers, crucibles and capsules for bomb calorimeter flasks, electric immersion heater casings, muffles, retorts and stills, and all sizes of tubes.

Rubber for Chemical Equipment.

RUBBER may be defined as a vegetable product formed by the coagulation or evaporation of a milky fluid or latex, obtained by making incisions in the bark of a variety of trees and shrubs. Rubber consists of an essential constituent—caoutchouc—together with varying amounts of resins, proteins and sugars. These latter materials confer remarkable stability upon the caoutchouc and also play an important part in the process of vulcanisation. Caoutchouc is regarded as a colloid or mixture of colloids possessing an empirical formula C_5H_8, and as might be expected from this constitution it exhibits the characteristics of an unsaturated hydrocarbon. It is readily attacked by bromine and chlorine and in the *pure* condition is rapidly oxidised by exposure to air. (Porritt, *Proc. Inst. Chem. Eng.*, 1927, **5**, 62).

Raw rubber finds but few industrial applications. In the first instance, it is susceptible to temperature ; in the cold it slowly becomes hard and tough, but when heated it tends to become permanently weaker and " sticky." When subjected to any appreciable degree of stretching it becomes permanently deformed, and in contact with hydrocarbon solvents it swells, becomes adhesive and finally dissolves.

The rubber industry as we know it to-day arose from the discovery of three processes whereby raw rubber could be converted into products with highly desirable properties. These processes were :—(1) milling or mastication, (2) compounding, (3) vulcanisation.

Milling represents the first preparatory process to which raw rubber is subjected in the manufacturing cycle. By mechanical treatment between steel rollers for a period of about thirty minutes, the rubber becomes plastic and adhesive. After being subjected to this mechanical treatment the rubber has largely lost its initial toughness and it can be readily fashioned either mechanically or by hand into any desired shape or form.

Regarding vulcanisation, the addition of an amount of sulphur to the milled rubber followed by a brief period of heating in the absence of air, the original strength and elasticity of the rubber is not only restored but greatly enhanced, while the product becomes insoluble in organic solvents and more resistant to temperature changes.

It is to be noted that, from the constructional aspect, the vulcanised rubber possesses no adhesive properties, and when firm attachment to

metals or other materials is desired, this must be effected prior to the treatment.

There are several methods for carrying out vulcanisation in practice. The rubber-sulphur mixture may be heated in moulds or between platens in an hydraulic press. In the presence of certain organic and inorganic compounds known as accelerators, which enhance the activity of the sulphur, vulcanisation may be effected by heating in air, but the process is restricted to products made of relatively thin materials.

In general, the vulcanised rubbers usually employed for chemical plant may be divided into two main groups, i.e. the soft vulcanised rubbers and the harder rubbers often described as ebonite or vulcanite.

Soft vulcanised rubbers may vary widely in their physical properties, and are usually defined by the amount of sulphur used in the compound. The amount of sulphur in soft vulcanised rubber may vary from 1 to 6 per cent. *Hard rubbers* of the ebonite class contain a much higher proportion of combined sulphur which in a fully vulcanised ebonite may rise as high as 30 per cent. In certain specialised types of rubber used for heat-resistance, however, no sulphur is used in the compound. The quantity necessary for vulcanisation is obtained from the accelerators of vulcanisation present, leading to a combined sulphur content often as low as 0·25 per cent.

TABLE 29.

TYPICAL RUBBERS USED IN CHEMICAL WORK.

Quality.	Specific Gravity.	Ash (per cent.).	Tensile Strength (lbs. per sq. in.).	Tensile Strength calculated on Area at Break (lbs. per sq. in.).	Ultimate Elongn. (per cent.).	Hardness. Pusey and Jones Plasto-meter.
Soft abrasion resisting	0·950	0·70	2,460	15,466	810	205°
Special soft resistant rubber	1·040	1·00	3,820	23,684	720	161
Standard	1·100	5·0	4,270	23,485	640	114
Special and conveyor cover	1·485	58·0	2,840	10,366	465	82
Special soft ant-cutting rubbers	1·005	4·83	2,230	14,495	750	205
Soft vulcanised rubber for chemical plant work	1·450	50·25	2,475	16,180	560	110
Pure ebonite	1·20	1·0	9,260	9,272	4·0	2·0
Flexible ebonite	1·31	22	2,930	3,030	17·5	2·0
Loaded ebonite	1·31	26	3,270	3,278	5·0	1·0

The above Table (*Trans. Chem. Eng. Congress*, 1936, **1**, 343) shows the properties of several types of rubber used in chemical plant con-

struction, from which it will be noted that although the percentage of combined sulphur may serve to distinguish a soft rubber from a rubber of the ebonite class, this percentage cannot be regarded as a guide to grading. The wide latitude obtained by methods of compounding enables the manufacturer to emphasise a particular characteristic desired by the user, by choice of properties of sulphur type and quantity of accelerator employed and the nature, quantity and treatment of the other compounds and ingredients employed.

For use in the lining of chemical equipment, rubbers of the soft vulcanised type are most suited for abrasive conditions, such as liquids containing crystals in suspension or when rapid and severe temperature changes are employed. Such soft rubbers are more resistant to mechanical shock, and since they are not thermo-plastic, they are suitable for high-temperature service. On the other hand, the soft rubbers are not so chemically resistant to strong liquor as the hard rubbers or ebonites, as under these conditions the soft rubbers swell owing to absorption of the liquid.

By contrast the ebonites have a decided advantage in respect of chemical resistance, and this quality, together with low absorption and freedom from staining, renders them desirable materials for lining of chemical equipment in many processes. Frequently, however, ebonite can be a rather brittle material, and if used in conjunction with metals, differences in thermal expansion may lead to cracking and distortion of the ebonite. It is hence desirable that the temperature of the ebonite lining, together with the surrounding metal, should be maintained as uniformly as possible.

It is to be noted in this connection that ebonite " creeps " at elevated temperatures, and it readily deforms at temperatures in excess of 70° C. The resistance to plastic flow can be increased by the addition of inert compounding ingredients, but only at the expense of elasticity.

Flexible ebonites have been recently developed by using a smaller proportion of sulphur than formerly, but whereas such ebonites show much improved flexibility, yet they tend to soften and creep at temperatures lower than the ordinary ebonites. Also the flexible ebonites are relatively unstable chemically and must be carefully and suitably compounded to give a reasonably long, useful life. In spite of these shortcomings, however, these flexible ebonites have many advantages and have been successfully used for covering rollers of dye-baths and bleach liquors and similar work.

[1] *Use of Rubber in Chemical Engineering.*

The general utility of rubber can be seen from the following table which gives the more important of the many industrial applications of the material :—

(1) Ebonite pipes, cocks, buckets and pipe fittings.

(2) Rubber-lined equipment, e.g. tanks, cylinders, ball mills, barrels, pumps, etc.
(3) Rubber-covered rollers.
(4) Hose and flexible pipework.
(5) Rubber-covered conveyors and rubber transmission belting.
(6) Washers, gaskets, valves, flooring.
(7) Clothing and gloves, aprons, respirators.

In the case of rubber-lined equipment, it is essential that the containing-vessel, whether of wood or metal, should be specifically designed to receive the rubber lining. Many of the troubles experienced in the use of rubber-lined plant are due to lack of care in the design of the containing-vessel. It is to be noted that the function of the rubber is to provide an anti-corrosive lining, and that of the metal shell or container to give rigidity, strength and support to the rubber lining. For example, the presence of rivet-heads is highly undesirable, and even in the case of flush-welded seams, great care is necessary to ensure that all irregularities are removed before the lining is applied. In addition, a porous weld often causes trouble because the special rubber solution which is applied is usually made with a volatile petroleum solvent, and there is a risk of a blister through the pressure of the vaporised solvent behind the lining when heat is applied for any subsequent purpose.

It is highly desirable that, in the fabrication of rubber-lined equipment, the manufacturer of the metal shell should work in close co-operation with the person who will subsequently supply and line the vessel with rubber, as in this way the best use will be made of this important material which often provides the only practicable solution to corrosive problems.

The following brief description of processes used in the rubber-lining of plant will be of interest in this respect.

In the case of metal tanks, containers, etc., which are to be rubber-lined, the first step is to eliminate all oil or grease by " sweating," which consists of putting the vessel or casting in a large steam-pan and subjecting it to a slight pressure of steam for a few hours. The inner surface to receive the lining is then sand-blasted to remove all loose scale and to render the surface suitable for the reception of the lining. The whole surface is then given a coat of a special solution of rubber compound, and when dry this is followed by several other coats until the desired thickness is obtained. The lining, in the form of sheets cut to convenient size and shape, is then applied, care being taken to remove all trapped air by rolling with specially hard rollers. Special care is taken at the seams, and the edges of the rubber are bevelled at the joints to facilitate closure at these points. Frequently an overlapped joint is made, but in certain cases it is considered preferable to arrange a butt joint covered with a butt strap.

After application of the complete lining, the whole area is examined

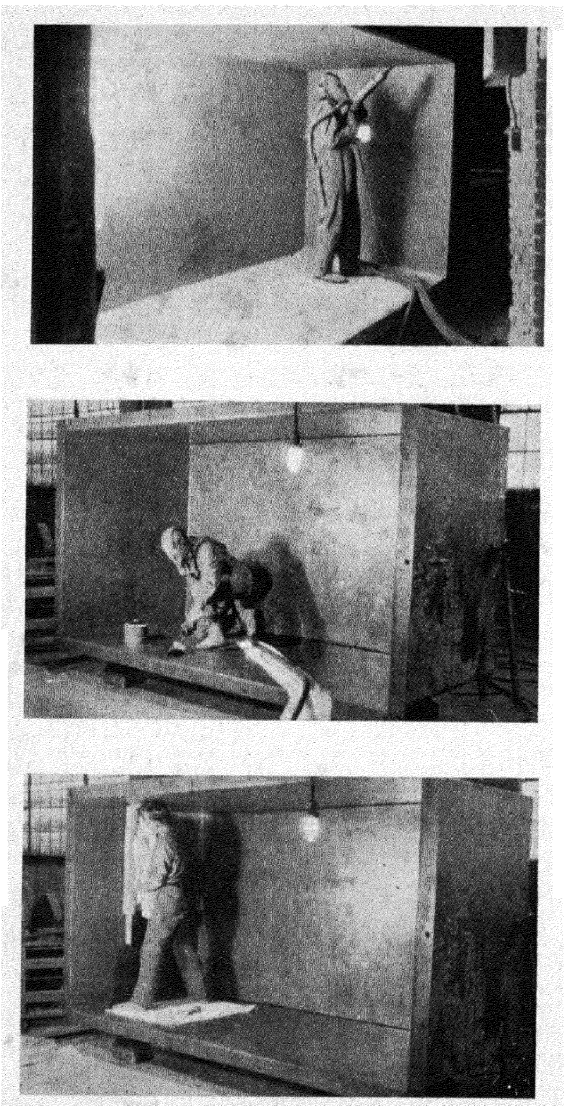


FIG. 59.—Rubber tank linings.

[*To face page* 161.

for pinholes and other defects by the application of an electrical brush discharge of several thousand volts. Any spot where direct access to the metal is possible is indicated by the immediate formation of a spark discharge, and the spot is marked for repair. During this time any small air blisters formed between the lining and metal are punched out. Before completing the vulcanisation of the rubber, the lined vessel is sometimes submitted to a short preliminary heat treatment in a steam-pan with the object of disclosing any further small blisters prior to complete vulcanisation, as their presence to any extent in the finished lining may mean the complete removal of the whole lining, often a matter of considerable difficulty and expense and a second attempt at the work. Fig. 59 shows these three principal steps in rubber tank-lining (*Rubber in Chemical Engineering*, Stevens & Donald, 1933, published by the Rubber Growers' Association).

The American Hard Rubber Company's patented method of rubber-lining metal tanks is one wherein the lining consists of a layer of hard rubber exposed to the solution overlaying and united with a layer of soft rubber which is bonded to the steel tank.

For the lining of steel pickling tanks the B. F. Goodrich Company have developed a method whereby a layer of hard rubber is fitted between two layers of resilient soft rubber. The three plies are vulcanised together.

Rubber linings can also be successfully applied under certain conditions to wooden vessels. A hard wood is necessary, free from resin or knots, and it is also essential that the wood should not have received any coating of paint or Stockholm tar preservatives.

During the past few years, special plastic compositions of latex and cement have been developed on the lining material itself where the liquor to be retained is only moderately corrosive, and such compositions have been successfully applied to storage vessels where the use of concrete alone has not been satisfactory.

Articles such as pipework, pumps, centrifuges, fans, etc., are covered by methods similar to those described for tanks. Special precautions must be taken in the use of rubber linings for ball and tube mills. Firstly the design of the mill should facilitate satisfactory anchorage of the rubber and also permit a sufficient thickness to be employed, and the temperature developed should not be allowed to exceed 130° F. When these conditions can be satisfied, the use of a rubber lining has proved highly satisfactory. The grinding of wet slurries is a notable example.

In addition to the foregoing examples, brief mention may be made of some of the other uses of rubber and rubber products in chemical engineering.

Hose, for example, can be obtained specifically designed for many purposes, e.g. for air hose is available up to 1½-in. diameter, and for

work in pressures as high as 300 lbs. per sq. in. Suction and discharge can be obtained up to 12-in. diameter and working pressures up to 200 lbs. per sq. in. Hydraulic hose is manufactured for pressures up to 3000 lbs. per sq. in. Hose can also be obtained with special linings or covers for resistance to oil or grease, whilst special heat-resisting rubbers are available for temperatures up to 260° F.

Rubber transmission belting has several advantages over leather belting, e.g. lower cost, it is less liable to stretch and the coefficient of friction is higher. If exposed to acid fumes such belts are provided with an acid-resisting protective layer.

Rubber Paints, Cements, etc.

While rubber sheeting as a protective layer has a wide application in the chemical industry, there are many cases where a type of paint or putty would be more suitable. Various methods have been devised for the use of rubber under these conditions, and it will be of interest therefore to consider the various alternatives and the conditions most favourable to their use so that the chemical engineer can make his own selection.

Rubber Varnishes.—Rubber has been used for a large number of years as an ingredient of varnishes in combination with either rosin, turpentine, or linseed oil.* It has the disadvantage of unduly increasing the viscosity of the varnish, so that only a very small proportion of rubber can be incorporated with the mix.

Rubber Cements (unvulcanised).—This is the name given to solutions of raw rubber in suitable organic solvents which are widely used for sticking together two rubber surfaces. It has been suggested † that they could be used for coating tanks against corrosion, but their viscosity is, in general, such as to make the resulting dry layer very thin and of a low rubber content. In general, the thickness of the deposited layer with two other coats would be insufficient to afford protection unless subsequently vulcanised, particularly as the freshly deposited raw rubber readily takes up moisture, swells and would soon come away.

Sulphonated Rubber.—The action of sulphuric acid or its homologues on rubber gives a sulphonated product which has remarkable adhesive properties. It is also chemically inert and has been used in solution for coating articles such as glass bottles to prevent the action of alkalis on the glass.‡

Chlorinated Rubber.—This is a compound which is gradually assuming a position as a very valuable commercial product. It is marketed as "Duroprene," "Tornesite," "Pergut," etc. The rubber

* Farbe u. Lack (1925), **1**, 363.
† German Patent, 427946.
‡ *Journ. Ind. and Eng. Chem.* (*Anal. Ed.*), 1929, **1**, 109.

hydrocarbon molecule contains unsaturated double bonds and will take up chlorine gas just in the same way as it will take up sulphur during vulcanisation. On further chlorination, the chlorine will continue to enter into the rubber molecule and in doing so displaces hydrogen in the form of hydrogen chloride. The chlorine content can be increased up to an amount corresponding to 68 per cent. of the weight of the chlorinated rubber.

One of the advantages of chlorinated rubber over raw rubber lies in the fact that very much greater proportions can be incorporated in the ordinary organic solvents without an excessive increase in viscosity. * If the chlorination † is carried out completely at the boiling point of carbon tetrachloride, the resulting product is very stable and, being a saturated molecule, has no tendency to be oxidised by air or react in any way.‡ Amines § may be added to counteract any tendency to form more hydrogen chloride and so develop further acidity, although it appears that improvements in manufacture may eliminate this possibility. The chlorinated rubber film is resistant to the attack of acids, even nitric acid of 1·4 specific gravity, hydrogen peroxide, alkalis, etc., and has a very tough and elastic surface, which can be still further improved, if necessary, by the use of plasticisers || such as tri-cresyl, phosphate, etc. It has been used for coating steel pipes against corrosion and, while retaining its elasticity, gives a harder finish than oil lacquers. Resistance to blows and cracking is obtained by adding finely divided quartz or carborundum.¶ Unlike nitrocellulose lacquers, it is not affected by sunlight, it is non-inflammable and can be applied in a moist atmosphere. It is a non-conductor of electricity, can be used in the manufacture of plastics and has been suggested as a suitable basis for fibres.**

Latex.††—The original rubber latex as it flows from the trees can be obtained in various stabilised and concentrated forms and, in combination with other substances, can be applied as a paint without inflammable vapours being given off as in the case of rubber cements. Another advantage of latex over rubber cement is that the rubber can be applied in a far greater concentration, resulting in a thicker film. In latex, the rubber exists as very minute particles in an aqueous medium and so it is essential that the film should dry or coagulate before there is any possibility of rain spoiling the coating when laid. The proper coagulation or gelling of the rubber particles into a homo-

* *Oil and Colour Trades Journ.*, 1920, **57**, 1250.
† B.P., 1894/15; U.S.P., 1544532; B.P., 328818.
‡ *Rubber Growers' Assn. Bull.*, 1932, **14**, 210.
§ U.S.P., 1695641. || U.S.P., 1750583. ¶ B.P., 355547.
** U.S.P., 1695643.
†† For the general properties and methods of utilising latex see *Rubber Latex*, published by the Rubber Growers' Association.

geneous whole is a process which may take some time unless artificially accelerated. Latex can be used for the following purposes :—

(1) Adhesives.
(2) Sealing compounds or putty.
(3) Coating articles by the dipping process.
(4) Coating articles by the electrophoretic process.
(5) In conjunction with rubber cement as a coating.

Latex has been employed for many years as an adhesive * for the boot and shoe industry, for making labels adhere to glass bottles and for general purposes of this type. As a sealing compound in conjunction with suitable fillers † (Darex and Gold Seal products) it is used to a very large extent for making the seams of tin cans airtight, especially in the food canning industry.

Two types are employed, one for food tins containing vegetables, fruits, etc., which have to be treated after filling and the other for oil and grease tins in which the filling is the last stage of the process. The compound used in the latter type will hold, in a properly made can, everything except ether. These compounds supersede those made of rubber solutions which have the usual disadvantages. It is said that it only requires the faintest trace of benzol taint to affect the whole contents of a can of foodstuff.

Latex putty ‡ is also available for repair work. In the case of articles such as wire netting, open mesh wire baskets, coke screens or any object having awkward re-entrant angles a deposit of rubber from a latex mixture forms a protective coat, particularly when vulcanised. This deposit may be produced by one or more dips in the latex mixture. It has, however, been found that the best method, in any case for large sheets of wire mesh as coke screens, is to deposit the rubber composition from the latex mixture electrophoretically.

This process is very similar to dipping. As the particles of rubber are negatively charged they migrate towards the anode § and form a spongy deposit. By using a controlled drying process, or by using dehydrating agents such as strong solutions of brine at high temperatures, the deposit can be made coherent and firm.‖ It is essential, however, to avoid the formation of gases in the deposit of rubber by the decomposition of the electrolyte under the influence of the current and to avoid solution of the electrode itself. Electro-plating racks can be successfully coated in this way.¶

In order to supply a substance which can be applied in a similar manner to rubber sheet, but in the form of a putty, a preparation ** has been marketed under the trade name of Colvule consisting of latex

* U.S.P., 1627278. † U.S.P., 1582219.
‡ B.P., 327452. § B.P., 21441/08. ‖ B.P., 303544.
¶ *Journ. Ind. and Eng. Chem.* (1931), **23**, 463.
** B.P., 379819.

mixed with rubber cement and a vulcanising agent which cures spontaneously or at relatively low temperatures. Acid tanks, blower fans, ships' bottoms, etc., can be coated with this compound for resistance against corrosion and abrasion. Rubber-covered conveyor belts can also be successfully repaired with this compound.

Hydrochloric Acid.—Rubber is a highly satisfactory material to use for this acid. Thus a chemical manufacturer writes: "Two 10 ton capacity wood storage tanks for commercial hydrochloric acid were lined with $\frac{1}{4}$ in. thick sheet rubber. These tanks were put into operation in 1925 and are still in constant use, only one minor repair having been necessary"; or, "For a number of years we have been experimenting with the use of various types of rubber, and so far have found it extremely satisfactory in most cases where we have utilised it. We have had pipe lines, cocks, etc., of ebonite (or hard rubber) in use continuously over a period of some twelve years carrying hydrochloric acid over appreciable distances, and thus far no failure has taken place in these pipe lines. We have used it similarly for acid pastes, transmitting these through the pipe lines by air pressure, and have found it satisfactory. We have used hard rubber for the lining of pipes and various specially designed plant parts for some seven or eight years and find it very satisfactory in use and, where heat transmission is not required, greatly in advance of many other protecting media"; or another similarly states soft rubber has been used "For lining of wooden tanks for the storage and filtering of acid liquors. We have had it in use for some considerable time in this way and it has given us far better service than lead lining, as there is no trouble from creeping, expansion and contraction as with lead linings, and for this and other reasons it lasts longer." Also yet another says, "Previous to 1907 we pumped hydrochloric acid with steam-driven antimony pumps, and conveyed the acid in heavy section lead pipes. The latter had frequently to be renewed and the former gave a lot of trouble. During 1907 we installed two vulcanite pumps and substituted vulcanite pipes for the lead ones. These pumps and pipes have been a great success and are still working, as are the other two, more recently installed. Two years ago we installed four steel storage tanks for hydrochloric acid. These are lined with soft rubber, and only one so far has given trouble, requiring the repair of a small hole in the rubber lining. At the same time we acquired a road tank wagon for the conveyance of hydrochloric acid. This also is steel, lined with soft rubber, and it has given us no trouble." Or another fine chemical manufacturer says, "We use soft rubber on storage tanks for hydrochloric acid and ammonium chloride liquors. The rubber is applied in sheet form in our case, to wooden vessels about 10 ft. diameter. We have had tanks in use for over five years with no apparent action on the rubber beyond a slight hardening of the surface."

Sulphuric Acid.—A rough rule is that rubber will stand up to concentrations of from 60 to 80 per cent. in the cold and 20 per cent. when warm, but this will vary according to local conditions. Dry grinding of phosphate rock is costly and wet grinding is objectionable owing to the fact that it has to be subsequently dewatered. The ideal method is to grind in acid, and this has been accomplished at Providence, Rhode Island, as well as at other places, by lining the shell of the crusher with $\frac{1}{4}$ in. rubber, on top of which were laid strips of hardwood in shiplap form parallel to the axis of the mill, and then a silex block lining was placed on the inside. This gave the regular grinding surface on the inside and the wood protected the rubber from the silex blocks and the rubber protected the outer shell from corrosion by the acid. The mill gave satisfaction for over eighteen months.

Nitric Acid. The limiting concentrations for this acid, are given by different authorities as 2 per cent. in one case and 20 per cent. in the other. The limit is low owing to its strong oxidising properties. Graphite has been mentioned as a suitable filler.

Acetic Acid.—Hard rubber is generally specified for this acid, and as the crude material may contain varying proportions of aldehydes or esters, it is advisable to make a confirmatory test. Thus a chemical manufacturer writes, "Soft rubber linings inside wooden vats show poor adhesion when used with cold acetic acid above 60 per cent. strength. Their use has been discontinued. Below this strength wood alone is satisfactory and needs no protection. Hard rubber linings have been used inside iron vessels and appear to stand cold acetic acid up to glacial strength without stripping. The results after twelve months were satisfactory."

Phosphoric Acid.—A compounded rubber was developed from specially prepared latex. This rubber, which was vulcanised after the tank was lined, imparted no colour to concentrated phosphoric acid. Rubber-lined tanks have been in service for six or seven years without any apparent deterioration (*Chem. Met. Eng.*, 1926, p. 617).

Alkalies.—For ammonia, hard rubber is recommended, and for the other alkalies both hard and soft give protection. "In some cases we have had rubber-lined vessels in use for periods of over two years for moderately strong solutions of alkaline liquors, both hot and cold. Our experience of rubber-lining generally has been satisfactory, and we believe that it will be of increasing use to us." *

Gases.—In so far as gases are concerned, although rubber is to some extent permeable, it has been used successfully, for example, on ducting-carrying sulphur dioxide. This is particularly noteworthy as this gas readily dissolves in rubber. Edwards and Pickering (*Chem. Met. Eng.*, 1920, **23**, 17 and 71) have shown that for a given thickness of

* Private Communication.

soft rubber tubing the permeability of various gases compared to the permeability of hydrogen as unity is as follows :—

Nitrogen	0·16	Carbon dioxide	2·9
Air	0·22	Ammonia	8·0
Oxygen	0·45	Ethyl chloride	200·0
		Water vapour	50–100.

The effect of these gases is slight, but it may have to be considered in some cases, when the use of hard rubber instead of soft rubber would be indicated.

General.—Rubber is, in general, unsuitable for protection against powerful oxidising agents such as nitric and chromic acids, ozone, etc., although it is said that rubber can be used with cold solutions of hydrogen peroxide up to 40 per cent. It has been suggested to apply rubber coatings in successive layers of increasing graphite content to withstand the action of nitric acid (German Patent 407543 or B.P. 229247). Halogens are naturally difficult substances to deal with, but a patented method * of making rubber resistant to chlorine and alkalis consists in adding about 10 per cent. of graphite to hard rubber and over-vulcanising the mixture. A suggested composition is graphite 10 per cent., sulphur 33 per cent., and rubber 57 per cent.

Some writers state that halogens can also be dealt with, while others state the reverse. No doubt the surface of the rubber will be attacked by the halogen, but the action may not proceed far owing to the hard resistant nature of the product produced. Rubber hydrocarbon halides are extremely resistant to chemical attack and are used for this purpose—as examples, " Duroprene " and " Tornesite " may be quoted.

For ventilation in mines, rubber tubes can be used. It is claimed that pine tar incorporated in the rubber improves its resistance to fungus ; and paraffin wax resists the slight acidity of the mine waters (B.P. 199516).

Rubber is an excellent protective layer for pickling or etching baths ; for pickling baths it is said (*Journ. Ind. & Eng. Chem.*, 1931, **23**, 466) to be advisable to have a lining of acid-proof brick to avoid damage to the rubber coating when material is thrown in. An alternative is a sufficiently thick layer of rubber. Rubber is also suitable for vessels containing plating solutions for electrodeposition, photographic solutions, dyes, ammonia salts, etc.

Pure water containing dissolved oxygen is stated to have a swelling effect on soft rubber, with eventual deterioration. The addition of an electrolyte is said to prevent this action.

Oil resisting rubber is extensively used in the form of inking rolls on printing presses instead of gelatine. These rubber rollers have

* B.P. 18269/08.

given continuous service for eight years. Also as rubber surface engraving plates, newspaper blankets, and blankets for offset printing for taking the ink from zinc plates (*Journ. Ind. and Eng. Chem.*, 1923, **15**, p. 675).

A large use for hard rubber linings for tanks and pumps is in the silk dyeing industry for handling stannic chloride solutions used in weighting silk. It is stated to give satisfaction for this purpose providing that reasonable care is taken at the time of installation and that the quality of the rubber sheeting is the best that can be made to withstand the conditions to which it will be subsequently subjected.

While in the foregoing a list has been given of general recommendations, it must be remembered that if it has been stated that rubber is not wholly suitable for any particular chemical, it may be that better methods of compounding have been or may be developed by which the resistance of the rubber is improved.

Rubber-Like Materials.

Koroseal.—This material is a synthetic rubber-like material, and is obtained by treating highly polymerised vinyl halides with plasticisers at elevated temperatures. It can be processed on lines similar to those used for rubber, and among the claims made for this material are a marked stability over a wide range of temperatures, resistance to vegetable and mineral oils, no impairment of physical properties after immersion in concentrated nitric acid, hot strong caustic soda, chlorine, ozone, or sulphur chloride. Koroseal is available in the form of sheets, tubing, or practically any of the range of shapes of rubber compounds. The cost of Koroseal is several times that of other compounds due to the higher cost of raw material and also to the higher cost of manipulation. It is claimed that the higher cost is in many cases justified because of the improved chemical and physical properties.

Koroseal is not suitable for use with

(1) Organic compounds containing chlorine.
(2) Organic compounds containing nitro-groups.
(3) Aliphatic or aromatic ketones.
(4) Aromatic amino-compounds.
(5) Gasoline or other solvents.

Another so-called synthetic rubber is known as " Duprene " and is made by the polymerisation of vinyl acetylene under controlled conditions. Duprene has some interesting properties. The addition of sulphur for vulcanisation is not required, as certain catalysts such as magnesium oxide have the desired effect. It also possesses good resistance to heat and is remarkably stable towards oxidising agents. Duprene has also good resistance to oil. A class of rubber-like materials

with even greater resistance to oils has been produced from ethylene dichloride and alkali polysulphides. A material of this type, known as "Thiokol," is resistant to most commercial solvents.

Asphalt as a Chemical Engineering Material.

Asphalt is defined by the British Standards Institute as a material or mechanical mixture in which the asphaltic bitumen is associated with inert mineral matter. *Asphaltic bitumen* is defined by the same body as natural or naturally occurring bitumen, or bitumen prepared from natural hydrocarbon or from derivatives of natural hydrocarbon by distillation or oxidation or cracking ; solid or viscous, containing a low proportion of volatile products possessing characteristic agglomerating properties and substantially soluble in carbon disulphide.

Natural or rock asphalt is a natural product, and as such is unsuitable for direct use as a flooring or lining material for chemical works. *Mastic asphalt* is the material with which chemical engineers are chiefly concerned, and it is in effect a manufactured article containing a higher bitumen content than the natural rock asphalt, and it can be hand-laid in any position. (See Attwooll, "Principles of Manufacture of Mastic Asphalt" [*Proc. Chem. Eng. Group Soc. Chem. Ind.*, 1929–30, **11** and **12**, 113].)

Such mastic asphalt may be divided into three main classes, i.e. materials designed exclusively for building work, those for paving and flooring, and acid-resisting asphalts.

Acid-resisting tanking asphalt for lining of tanks, ducts and the like, where temperatures do not exceed 80° F., will successfully withstand hydrochloric acid 1·10 sp. g., sulphuric acid 1·40 sp. g., and nitric acid 1·31 sp. g., and it is unaffected by all concentrations of acetic acid. Such asphalt is unaffected by alkaline solutions of any strength, but cannot be used for petroleum or coal tar, distillates, organic solvents or vegetable oils.

For such purposes the asphalt is in the form of a bituminous base which provides the corrosion-resisting qualities together with an inert filler or loading substance of a mineral and insoluble nature which increases the viscosity of the mixture to resist deformation. There appears to be no standardisation in this connection, and there are innumerable mixtures for different specific purposes. The loading material is usually of a siliceous nature such as granite. A silica base is used for high-grade work for high temperatures and highly concentrated conditions.

Macdonald (*Proc. Chem. Eng. Group Soc. Chem. Ind.*, 1929–30, **11** and **12**, 121) discusses actual experience in the use of mastic asphalt in chemical works, a brief summary of which is as follows :—

Floors.—Asphalt provides a jointless homogeneous covering which if properly laid and treated will remain liquor proof for years even with

highly corrosive substances. Since such floors must carry weight, the material is heavily loaded with filler, and usually granite chippings are used. It is highly important that such floors should be washed down frequently to avoid standing parts of corrosive liquor, which if allowed to stand would in turn disintegrate the floors under heavy traffic. Trucks for use on such floors should have wide wheels, tables should have wide feet and so on to avoid local stress concentrations which might cause indentations.

The thickness of asphalt floor coverings is between $\frac{3}{4}$ in. and 2 ins. and it is laid on in two separate layers. On brick or concrete the asphalt is laid direct, but in the case of wood flooring felt and expanded iron are used to prevent actual contact. The jointing of the asphalt to walls, stanchions, etc., should be carried up about a foot or so to avoid "creeping" of liquor behind the joint when washing or hosing down.

Channels, Open Drains, etc.—Here again mastic asphalt has a very useful field, and one of the greatest advantages is freedom from joints. Also asphalt is useful as jointing for earthenware pipe-work and so on.

Asphalt-lined Tanks.—Success in the lining of tanks with mastic asphalt depends upon correct choice of material, care in laying, and an efficient "key" between the lining and the supporting walls. Normally the asphalt is laid in two layers, each about $\frac{3}{8}$ in. thick. In addition, all corners receive a bevelled fillet and the lip edge of the tank will receive careful treatment to avoid creeping behind the lining. Expanded metal fixed to the tank wall is often used to act as an efficient key. In the case of wooden tanks, felt is placed behind the expanded metal and the whole nailed down together to prevent contact of wood and asphalt. With brick or concrete tanks, "chasing" provides sufficient key. The mixtures used for tank linings are usually rich in bituminous base and weak in filler, which is present only in sufficient quantity to prevent "flowing" at the working temperatures.

Absorption and Reaction Towers.

Mastic asphalt can be used to line towers and chambers for gas absorption provided that the working temperature is not excessive. Macdonald quotes an example of two brick towers lined with asphalt for absorbing in water nitrous fumes and the products of decomposition of aqua regia.

Plastics in Chemical Plant Construction.

The application of plastics in chemical engineering is a recent development. The materials likely to have the largest field are the thermo-setting group, i.e. the resinoids made from phenols and aldehydes, urea and formaldehyde, acetylene derivatives, polyolefin

resins and polyhydric alcohols such as glycerol condensed with polybasic acids such as phthalic acid. The thermo-plastic group, e.g. bitumen shellac, cellulose acetate and vinyl resins, has not been extensively used in plant construction, apart from celluloid for battery boxes.

The plastics covered by what is now known as the " plastics industry " may be defined as materials which take shape and form by the application of heat below 205° C., with or without pressure, and retain that form on cooling. Hence this classification excludes materials such as plaster of Paris, putty, clay, and like materials.

These plastics are made in many forms, i.e. as (1) clear resinoids without any fillers, either in lumps ground into powder or cast into rods, sheets, tubes or special shapes, (2) as resinoids with the incorporation of various fillers yielding cements, moulded articles or laminated products, or (3) as resins dissolved in various solvents giving varnishes or lacquers. Each of these three classes includes a large number of different products depending upon the raw materials and proportions used, method of manipulation and the type and amount of filler.

From the point of view of the chemical engineer perhaps the most important property possessed by these plastics is chemical inertness. The choice of the type of plastic for a particular problem is governed mainly by the concentration of the chemicals in contact with it and the maximum temperature of the reaction concerned, and if the reaction will permit of the construction of plant and equipment entirely from plastics without a supporting medium such as metal or wood.

Two classes of product come under this latter heading :—

(*a*) *Resinoid Plastics,* in which asbestos and other mineral fillers may be incorporated to yield a material which is sufficiently stiff to be self-supporting, and yet which can be cast or shaped and then hardened.

(*b*) *Resinoid Plastics* impregnated with paper fabric or asbestos in sheet form, then rolled or built into sheets pressed and heated to produce a hard, tough product either in tube or sheet form by means of which vats, cylinders, tubes and piping can be constructed.

Equipment made from either of the above classes does not soften and will withstand temperatures up to 150° C. (H. V. Potter, *Proc. Chem. Eng. Congress, London,* 1936, **1**, 312).

The Säureschutz Gesellschaft of Berlin, and also Kestner of London, were two of the pioneers in connection with the uses of resinoid plastic plant, and the following description of " Haveg," the proprietary name for the products of the former company, is of interset in this connection.

Haveg is produced by using a specially selected asbestos base and combining it with a phenol formaldehyde type of resin. The acid-resisting properties of the resin combined with the acid-resisting properties of the asbestos provide a material which is highly resistant throughout the mass.

After thorough mixing the asbestos resin compound is placed in the desired moulds and subjected to heat and pressure to form it into a single solid piece of the shape and size required. The specific gravity of Haveg is 1·6 and it has a compression strength of 10,400 lbs. per sq. in. Haveg can be machined and therefore permits of the introduction of new outlets or fittings to existing tanks or stills. Minor repairs can be made on the user's premises.

The chemical resistance of Haveg is given in Table 30.

TABLE 30.

CHEMICAL RESISTANCE OF HAVEG.

"Haveg 41" is resistant to :—		"Haveg 43" is resistant to :—
ACIDS :—	SALTS AND OTHER CHEMICALS :—	Hydrofluoric acid
Acetic, any conc.	Aluminium acetate	Fluosilicic acid
Fatty acids	Aluminium chloride	Hydrofluoric acid mixtures
Formic, up to 40 per cent.	Aluminium oxalate	Fluorides
Hydrochloric, any conc., any temp.	Aluminium sulphate	Fluosilicates
Hydrobromic, any conc.	Ammonia	Fluorine compounds
Lactic, any conc.	Ammonium sulphate	
Oxalic, any conc.	Aniline salts	
Phosphoric, any conc.	Benzene soaps	
Sulphuric, up to 50 per cent.	Calcium chloride	
Sulphurous	Calcium hypochlorite	
Tannic	Carbonated waters	
Tartaric	Chlorine	
	Chlorine water, saturated	
BASES :—	Chloride of lime, solutions	"Haveg" is not resistant to :—
Ammonia	Copper sulphate	
Caustic lime	Ferric chloride	
Neutral soap solutions	Ferrous chloride	
Phosphates	Ferrous amm. citrate	
Potassium carbonate	Hydrogen peroxide	Acetone
Sodium carbonate	Hydrogen peroxide	Chromic acid in higher concentrations
Sodium sulphide (alk. free)	Hydrogen sulphide	Nitric acid
	Magnesium chloride	Organic bases, as pyridine
SOLVENTS :—	Manganese sulphate	Potassium hydroxide
Alcohol	Milk of lime	Sodium hydroxide
Carbon tetrachloride	Oxalates	Sodium hypochlorite
Ethylene chlorhydrin	Paraffin	Sulphuric acid, hot concentrated
Hydrocarbons	Potassium iodide	
Oils	Sulphur, molten	
Petroleum	Sulphur monochloride	
Trichlorethylene	Sodium peroxide solutions	
	Water glass	
	Zinc chloride	

NOTE—Other types of Haveg are now made which are resistant to alkalis.

Fig. 60 shows a Haveg reaction tower 18 ft. diameter × 10 ft. high, fitted with steel reinforcing bands to permit of high internal pressure. Fig. 61 shows a reaction tank with heating coil and stirrers wherein all contact parts are of Haveg.

In addition to the above products, Haveg can be used for filter press frames, centrifugal pumps, blowers, drying trays, cocks and general pipe-work.

Apart from equipment made wholly from resinoid plastics and fillers, such plastics find wide application as protective coatings for metal and other equipment. Also, laminated resinoid material has been successfully used in the fabrication of acid-resisting piping.

Haveg cements are now available for the construction of tanks, etc., in ceramic material, and similar purposes.

General Notes on the Properties of Plastics.

Effect of Heat.– The effect of heat on thermo-setting plastics varies to a certain extent with the type of resin concerned and with the amount and nature of the filler. The resinoids forming the binders of such plastic products are organic materials and can be burnt away at temperatures well below red heat. By the use of mineral inert fillers with phenol-resinoids, temperatures up to 200° C. can be reached without serious carbonisation. The behaviour under conditions of elevated temperature depends upon the length of time over which the heating occurs. Nearly all plastic materials show some slight deformation under load at high temperatures and some types are liable to blister and warp.

Phenol-formaldehyde mouldings and laminated forms should be satisfactory for continuous use at temperatures up to 130° C., with the possibility of reaching 150° C. occasionally. Above these temperatures the material is likely to become brittle. All phenol-formaldehyde materials are practically non-inflammable, but all grades are combustible at high temperature.

Certain phenol-formaldehyde materials are practically unaffected by gases at temperatures up to 100° C., and this property is of great value in the manufacture of fan blades, valves and parts of chemical plant coming into contact with corrosive gases.

Plastic materials have been shown to exhibit considerable resistance to extreme cold. For some time laminated materials have been used at the low temperatures found in refrigerator work, and for their application special odourless grades are made so that the foodstuffs stored in the refrigerators shall not be tainted. These grades of plastics can be used even in direct contact with fruit juices, milk products and alcoholic liquors.

Wooden articles can often with advantage be impregnated with

resinoid varnishes. Wood impregnated with such material and afterwards hardened by heat can be used in service under wet conditions.

The plastics industry has recently provided a number of oil-soluble resins which can be used in the manufacture of paints and varnishes to give resistance to chemical attack and atmospheric corrosion. Resins are now available with as high a resistance to alkalis as to acids, and give valuable protection when used as fans and equipment subject to attack by chemical fumes and gases.

Wood.

Perhaps the most popular timber in Great Britain for chemical plant construction is pitch pine, but in U.S.A. and Canada by far the most commonly used woods are Californian Redwood and Tidewater red cypress. Redwood is becoming increasingly popular in Great Britain owing to the scarcity of pitch pine of late years.

I am indebted to the Californian Redwood Association for the following notes about their product:

The comparative properties of Redwood are given in the table on opposite page (*Tech. Bull.* 305, 1932, Forest Prod. Res. Lab., U.S. Dept. Agric.).

The chemical industry uses a large quantity of redwood for tank purposes, and this wood has proved its value in storing or processing, for example, many organic acids, including in particular acetic and tannic acids. Redwood tanks have long been used in the leather industry, and recent inspection of such tanks in a tannery showed them to be quite sound after forty years' service, even though they were subjected to a five hours' daily boiling of tannic acid solution.

The use of Redwood tanks for boiling water shows that the wood will last almost indefinitely.

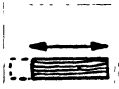
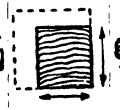
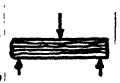
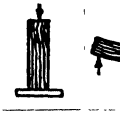
Inorganic Acids.—Apart from those which are strong oxidising agents, such as nitric and chromic acids, the majority of the commercial inorganic acids may be safely stored in Redwood. It is to be noted, however, that at high temperature strong sulphuric and hydrochloric acids will affect all woods, including Redwood, though even at high temperature Redwood will withstand weak solutions (up to 10%) without much attack even over long periods.

Alkalis.—All woods respond to alkali solutions, in particular those of sodium and potassium hydroxide. Such solutions may often, however, be stored in Redwood without appreciable attack.

Mining and Metallurgy.—Potassium and sodium cyanide as employed in metallurgical operations are without action on Redwood. Leaching, agitator and storage tanks for use with acid solutions of copper sulphate are all satisfactorily fabricated in Redwood.

Brewing and Distilling Equipment.—In U.S.A. there is a large

TABLE 51.

Commercial and Botanical Name of Species.	Trees Tested.	Specific Gravity, Oven-dry, based on Volume when Green.	Weight per cubic foot.		Shrinkage from Green to Oven-dry Condition based on Dimensions when Green.			Composite Strength Values.				
			Green	At 12% Moisture Content.	Radial.	Tangential.	Volumetric (Composite Value).	Bending Strength.	Compressive Strength (Endwise).	Stiffness.	Hardness.	Shock Resistance.
												
1	2	3	4	5	6	7	8	9	10	11	12	13
	Number.		lbs.	lbs.	%	%	%	%	%	%	%	%
Redwood * (*Sequoia sempervirens*)	16	0·39	52	28	100	100	100	100	100	100	100	100
Cedar, Port Orford (*Chamæcyparis lawsoniana*)	14	0·40	36	29	192	172	158	99	87	123	89	122
Cedar, eastern red (*Juniperus virginiana*)	5	0·44	37	33	129	118	116	81	84	58	150	175
Cedar, western red (*Thuja plicata*)	15	0·31	27	23	100	125	113	72	72	79	70	80
Cedar, northern white (*Thuja occidentalis*)	5	0·29	28	22	88	118	103	60	50	57	56	72
Cypress, southern (*Taxodium distichum*)	26	0·42	50	32	158	155	155	95	89	99	96	117
Douglas fir (*Pseudotsuga taxifolia*) (Coast type)	34	0·45	38	34	208	195	181	108	104	132	109	125
Douglas fir (*Pseudotsuga taxifolia*) (Rocky Mountain type	10	0·40	35	30	150	155	154	90	81	104	96	103
Fir, lowland white (*Abies grandis*)	10	0·37	44	28	133	180	157	87	80	114	80	111
Fir, noble (*Abies nobilis*)	9	0·35	30	26	188	208	188	89	74	109	72	105
Fir, silver (*Abies amabilis*)	6	0·35	36	27	188	250	212	84	74	107	69	108
Fir, white (*Abies concolor*)	20	0·35	47	26	133	175	142	87	71	93	78	92
Firs, white (Average of four species)	45	0·35	41	26	158	198	164	87	74	103	76	102
Hemlock, western (*Tsuga heterophylla*)	18	0·38	41	29	179	198	179	89	82	105	93	112
Pine, loblolly (*Pinus tæda*)	10	0·50	54	38	229	188	190	112	101	121	115	143
Pine, longleaf (*Pinus palustris*)	34	0·55	50	41	221	188	186	128	119	138	141	158
Pine, northern white (*Pinus strobus*)	18	0·34	36	25	96	150	124	76	65	87	65	85
Pine, shortleaf (*Pinus echinata*)	12	0·49	51	38	212	205	191	117	101	124	126	171
Pine, sugar (*Pinus lambertiana*)	9	0·35	51	25	121	140	118	77	66	82	70	85
Pine, western white (*Pinus monticola*)	14	0·36	35	27	171	185	176	83	73	100	65	100
Pine, ponderosa (*Pinus ponderosa*)	31	0·38	45	28	162	158	145	78	67	82	76	89
Spruce, Sitka (*Picea sitchensis*)	25	0·37	33	28	179	188	173	87	73	105	81	117

* Columns 6 to 13 are based on figures for comparative properties for redwood of 2·4, 4, 67, 53, 103, 137, 54, and 65 respectively, which, owing to the greater number of tests, supersede the comparative figures given in U.S. Department of Agriculture Technical Bulletin 158 (5).

amount of Redwood used for tanks for fermenting purposes, and also for pressure storage tanks in the beer industry.

Redwood tanks have been made in sizes up to 1,700,000 gallons capacity. Fig. 62 shows a Redwood tank in a chemical plant. The long agitator arm causes ploughs to keep the contents in constant motion. Fig. 63 shows a group of Redwood pressure storage tanks in a brewery cellar. Frequently this type of braced tank is designed for quite high internal pressures—up to 200 lbs. per sq. in.

Wood Pipe for Chemical Plant.—Wood pipework is used extensively in chemical works, as it provides a cheap light conduit for the con-

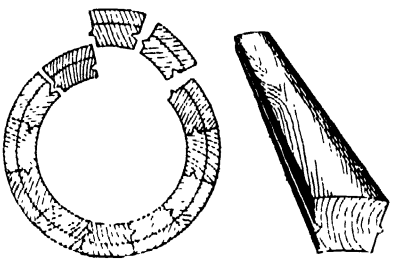


FIG. 64.—Form of stave for wood pipe.

veyance of a wide variety of corrosive liquors. It is cheap in first cost and easily repaired.

Two designs of pipe are used—one wherein the wood staves are held by circular and continuous bands, and the other of the wire-wound type. Referring to Fig. 64, it will be seen that the staves are machined to the correct circle on the sides and the correct radius on the edges where there is a small locking tongue or groove. For

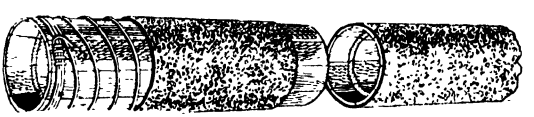


FIG. 65.—Wood stave pipe, slip joint.

pressures up to 200 lbs. per sq. in. the finished stave thickness is about $1\frac{1}{8}$ in. for pipes 6–12 ins. dia., $1\frac{3}{16}$ in. for those from 13–18 ins. dia., and $1\frac{1}{4}$ ins. for pipes up to 24 ins. dia. (J. D. Watson, *Chemical Age*, 1936, **35**, 52). For low pressures a cheap form of wood pipe is seen in Fig. 65. For joining purposes one end of the pipe is bored out to form a socket and the other turned down to form a spigot, one being a push fit within the other. Swelling of the pipe by wetting will render such pipes and joints quite tight for low pressure work.

The material for pipes is either Douglas fir or Redwood, and pipes can be made in lengths up to 20 ft., for maximum pressures of 250

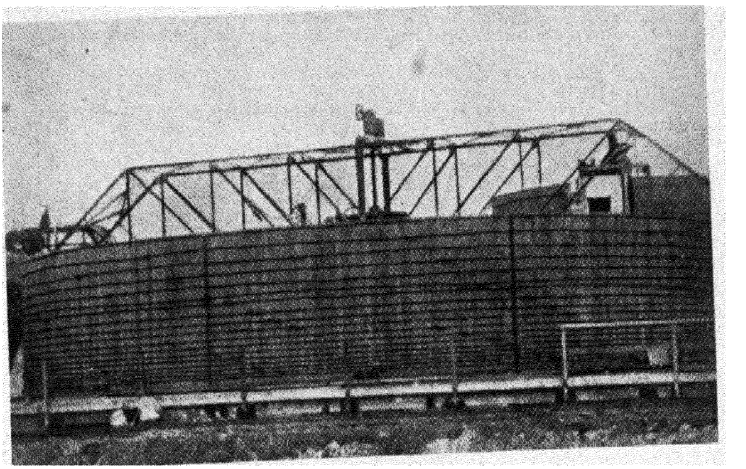


FIG. 62.—Redwood tank in chemical plant. The agitator mechanism keeps the contents in constant motion.

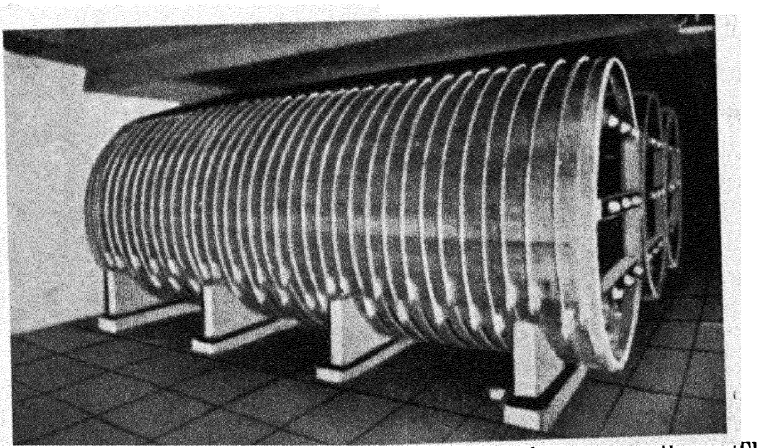


FIG. 63.—Redwood pressure storage tanks in brewery cellar. The heads are braced by steel tie rods—frequently this type of tank is designed to carry a load of 75 tons on the braced head.

[*To face page* 176.

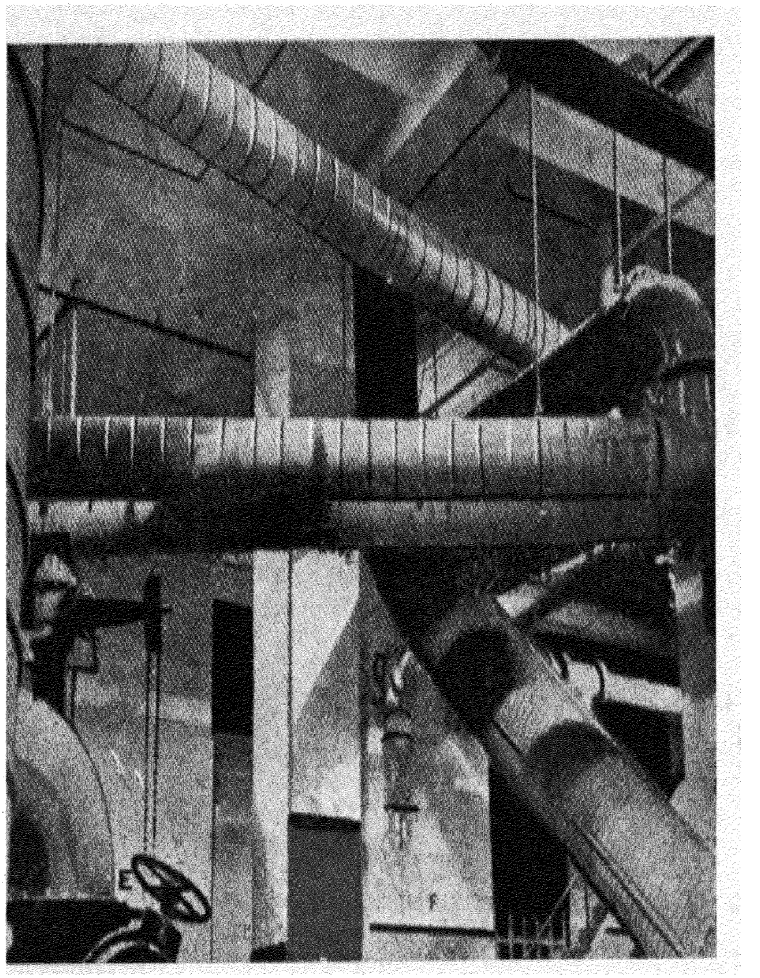


FIG. 66.—Continuous and wirewound wood stave pipe installed in a paper mill at Powell River, British Columbia. All fittings, such as bends, tees, etc., are copper-lined. Valves are bronze fitted, all to avoid paper stain in the manufacture of paper.

[*To face page* 177.

lbs. per sq. in. The wire winding may be of galvanised steel or, where conditions require it, of non-corrosive material such as stainless steel, phosphor bronze, etc. It should be wound with sufficient tension to bed into the timber, but not to weaken it unduly thereby.

It is often necessary to give external protection to wood pipe, and a cheap method (and quite effective) is formed by dipping the pipe in a bath of hot asphalt, followed by rolling in fine sand. A burlap wrapping gives additional protection.

Fig. 66 shows continuous and wirewound wood stave pipes installed in a paper mill at Powell River, British Columbia. All fittings, such as bends, tees, etc. are copper lined, and valves are bronze fitted to avoid stain in the manufacture of paper.

Acid-resisting Cements.

In chemical plant construction, acid-resisting cements for jointing or repair purposes are widely used. Most of these materials are of a proprietary nature. For example, Messrs. Prodorite manufacture in Great Britain the range of Acid-proof Cements developed by the I.G. in Germany, and market it under the name "Cement Prodor." It is useful in any situation where acid liquors or fumes are present, and its special self-setting property permits of its use in enclosed spaces where air drying cannot be obtained. This cement is widely used for building acid tanks, towers, chimney linings and the like with acid-resisting brick or tile. The cement is supplied in powder form, and must be mixed with the solution provided. When set it is hard, and is resistant to strong or weak acids, hot or cold, and will stand up to a great deal of hard work.

CHAPTER VI.

THE DESIGN AND CONSTRUCTION OF PRESSURE VESSELS FOR THE CHEMICAL INDUSTRY

Introductory.

THERE are five principal methods whereby pressure vessels may be constructed, viz. by casting, soldering and brazing, riveting, welding and hollow forging. Cast vessels are usually of comparatively small dimensions, and for moderate pressures. Soldering and brazing methods are confined to small non-ferrous vessels. Riveted construction follows the same general principles which have been developed for steam-boiler practice, but due to recent marked advances in the art of fusion welding, riveting is fast being replaced by welded construction carried out under careful control. Hollow forging is employed for vessels for the very highest pressures and severe operating conditions, as for example in the hydrogenation of coal, and the synthesis of ammonia and methyl alcohol.

In Great Britain the only official regulation for the actual design of steam boilers and pressure vessels is contained in the appropriate sections of the Board of Trade Instructions as to the survey of Passenger Steamships. These instructions are in respect of the general principles of design, and rules for computing the dimensions of the various stressed parts of pressure vessels, such as boilers, steam-pipes, air receivers and Diesel engine starting-bottles. There are no corresponding rules for vessels for land service, but in so far as steam boilers are concerned, the Board of Trade rules are usually applied because all boiler explosions in this country are investigated by the Board of Trade under the Boiler Explosions Acts of 1882 and 1890. These Acts contain clauses to the effect that (*a*) notice of all boiler explosions with full particulars must be sent to the Board of Trade within 24 hours, and (*b*) the word " Boiler " is defined as any closed vessel used for generating steam, for heating water or any other liquid, or into which steam is admitted for heating, steaming, boiling or other similar purposes.

The Factories Act of 1937 requires that every steam boiler for the generation of steam must be equipped with certain fittings, that boiler and accessories must be properly maintained, and that such boilers must be examined by a competent person every fourteen months. In

practice, such examinations are carried out through one or other of the Boiler Insurance Companies.

The Factories Act of 1937 extends the principle of steam-boiler inspection (as required by the 1901 Factory and Workshops Act) to include practically every other type of steam-pressure vessel and air receiver, in that such vessels must be examined by a competent person once every twenty-six months.

There are certain other statutory requirements in regard to pressure vessels in works designated as Chemical Works under the Chemical Works Regulations, 1922 (S.R.O., No. 731, of 1922). Para. 5 requires that every still and every closed vessel in which gas is evolved or into which gas is passed and in which the pressure is liable to rise to a dangerous degree, shall have attached to it and maintained in proper condition a proper safety valve or other equally efficient means to relieve the pressure. Para. 6 of these Regulations deals with the provision of breathing apparatus and lifebelts, and this leads naturally to paras. 7, 8, 9, 19, 20, which govern the entry of workpeople into vessels, chambers, structures of any sort, and any room or place in which there is reason to apprehend the presence of a dangerous gas or the existence of an irrespirable atmosphere. These regulations are of the utmost importance in regard to the design of plant and methods used in construction in regard to access, cleaning and repairs.

From the aspect of working pressure it is convenient to divide pressure vessels for the chemical industry into two groups.

(1) *Vessels for service at pressures not higher than about* 1000 *lbs. per sq. in.* and wherein the " thin-cylinder " formula may be applied. This pressure limit may be raised if high-tensile alloy steels are used, since in such cases this working stress may be considerably higher than plain carbon steels and consequently the wall thickness is sufficiently thin for the " thin-cylinder " theory to be applied.

(2) *Vessels for service at pressures higher than* 1000 *lbs. per sq. in.* and wherein the " thick-cylinder " or Lamé's theory may be applied.

Each of these two groups may be again subdivided on the basis of the *working temperature* of the pressure vessel concerned, since if the working temperature of the stressed parts is within the region wherein " creep " occurs, the above principles of design based upon the *thin-cylinder* and *thick-cylinder* theories must be modified accordingly. The modification consists in substituting the safe working stress at the working temperature for the safe working stress (based upon ordinary tensile, etc., tests) usually adopted for design below the temperature at which creep occurs.

A pressure vessel consists essentially of " a middle and two ends." The middle portion is practically always cylindrical in shape, and the ends may be either flat, dished, or hemispherical. The principles underlying the design of the shell or cylindrical portion will first be discussed.

Shells of Vessels Designed on "Thin Cylinder" Theory.

If a thin circular cylinder is subjected to internal fluid pressure, a tensile stress arises in the walls of the material, and this is usually described as the "hoop stress." When the thickness of the cylinder walls is small compared with the internal diameter of the cylinder, it is assumed that the hoop stress is uniformly distributed throughout the cross-section of the material.

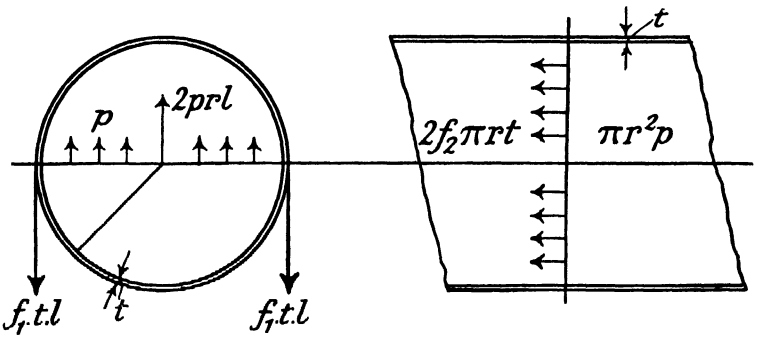


FIG. 67.

Referring to Fig. 67, let r be the internal radius, and t the thickness of a thin cylinder subjected to an internal pressure of p, causing a hoop tension f_1 in the walls of the cylinder. Considering the equilibrium of the half-cylinder of length l,

$$2f_1 l.t = 2p.r.l,$$

whence

$$f_1 = \frac{pr}{t} \text{ or } \frac{pd}{2t},$$

where d = internal diameter of the cylinder.

If the cylinder be closed at the ends the shell will be subjected to a longitudinal tension as well as a hoop tension. So that if f_2 = longitudinal tension,

$$f_2.\ 2\pi rt = p\pi r^2,$$

whence

$$f_2 = \frac{pr}{2t} \text{ or } \frac{pd}{4t},$$

whence it will be seen that the intensity of longitudinal stress is just half the circumferential or hoop stress.

In addition to the two principal stresses, f_1 and f_2, there is a third principal stress which is a radial pressure and varies from a maximum of p at the inner surface of the shell to zero at the outer surface; this stress is quite small in the cases where the thin-cylinder theory is applicable, and hence is neglected.

The following is an example of a cylinder designed on the basis of the "thin-cylinder" principle.

At the Chemical Research Laboratory, Teddington, there are two large high-pressure gas bottles, each of 3 cu. ft. water capacity, and made from heat-treated nickel-chrome-molybdenum steel. The bottles are used for pressures not exceeding 250 atms. at ordinary temperature, and are 6 ft. 6 ins. long, 9½ ins. internal diameter, and with ½-in. walls.

It is required to find the hoop stress in the walls of the shell. *Note.*—250 atms. = 1·67 ton per sq. in.

$$f_1 = \frac{pd}{2t}$$

$$= \frac{1{\cdot}67 \times 9{\cdot}5}{2 \times 0{\cdot}5}$$

$$= 16 \text{ tons/sq. in.}$$

If these bottles had been supplied in low-carbon mild steel, to withstand the pressure the walls would of necessity have to be at least twice as thick, in which case the "thin-cylinder" formula would not be applicable. In such circumstances it is necessary to apply the thick-cylinder formulæ, and these will now be discussed.

Shells of Vessels for Service over 1000 lbs. per sq. in.

Thick Cylinders subjected to Fluid Pressure.

The following theory is due to Lamé :—

Let R_2 and R_1 respectively (Fig. 68) be the internal and external radii, and let p_2 and p_1 be the internal and external pressure intensities.

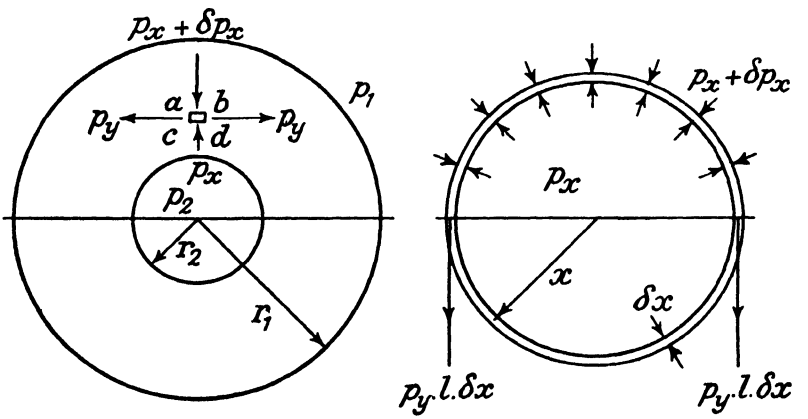


FIG. 68.

Let p_x and p_y be the intensities of radial compression stress and circumferential tension respectively at any variable radius x, the third principal stress being parallel to the axis of the cylinder. Then considering the equilibrium of half of any very thin cylindrical element

of radius x, thickness δx, and length l, the outward pressure on the curved surface, that is the outward resultant of the pressure on inside and outside, must be equal to the total hoop tension across a diametral plane or

$$(p_x \times 2\,x\,l) - (p_x + \delta p_x)2(x + \delta x)l = 2p_y l \delta x,$$

whence

$$-p_x.\delta x - x\delta p_x - \delta x \delta p_x = p_y.\delta x,$$

and when δx is reduced indefinitely,

$$p_y = -p_x - x\frac{dp_x}{dx} = -\frac{d(p_x x)}{dx}.$$

Another relation between p_x and p_y depends upon an assumption as to longitudinal strain. It is assumed that plane transverse sections remain plane under the pressure, an assumption which must be nearly true at considerable distances from the ends. This means that the longitudinal strain at any point in a cross-section is independent of x, and therefore constant.

Hence

$$e = \frac{1}{\mathrm{E}}\left(f_1 - \frac{p_y - p_x}{m}\right).$$

Since e, E and f_1 and m are constant, $p_y - p_x$ must be constant.

Taking

$$p_y - p_x = 2a,$$

substituting for p_y its value from the first equation, we get

$$-2p_x - x\frac{dp_x}{dx} = 2a.$$

Whence

$$p_x = \frac{b}{x^2} - a$$

where a and b are constants to be determined from known internal and external radial pressures and radius.

Also we can get

$$p_y = \frac{b}{x^2} + a.$$

When the external pressure is zero, from these equations we get

$$p_x = p_2\frac{\mathrm{R}_2^2}{\mathrm{R}_1^2 - \mathrm{R}_2^2}\left(\frac{\mathrm{R}_1^2}{x^2} - 1\right)$$

$$p_y = p_2\frac{\mathrm{R}_2^2}{\mathrm{R}_1^2 - \mathrm{R}_2^2}\left(\frac{\mathrm{R}_1^2}{x^2} + 1\right)$$

whence we find that the greatest intensity of hoop stress in a cylinder is at the inner skin of the metal next to the bore (and where $x = \mathrm{R}_2$), and is

$$p_{y2} = p_2\frac{\mathrm{R}_1^2 + \mathrm{R}_2^2}{\mathrm{R}_1^2 - \mathrm{R}_2^2}$$

The greatest intensity of radial stress (p_x) is also at the inner skin

next to the bore of a vessel, and is there numerically equal to the internal pressure p_2.

Some very interesting experiments in connection with the failure of thick cylinders when subjected to high internal pressure were carried out by Cook and Robertson (*Engineering*, 1911, **92**, 786). They were able to reach pressures as high as 15 tons per sq. in., and the following table gives particulars of the results obtained by bursting a mild steel cylinder of about 2 ins. outside diameter and with the stated ratio of external to internal diameter :—

TABLE 32.

Ratio External to Internal Diameter (K).	Ultimate Strength of Material (lbs. per sq. in.).	Maximum Pressure (p) (lbs. per sq. in.).	Maximum Pressure calculated from Formula $\left(p = f\frac{K^2 - 1}{K^2 + 1}\right)$.
1·35	54,400	16,900	15,800
1·53	54,400	23,200	21,900
1·58	54,400	24,850	23,400
1·67	58,800	27,200	27,700
1·67	58,800	27,350	27,700
1·71	58,800	30,200	28,700
1·77	54,400	30,850	28,000
1·79	54,400	30,500	28,600
1·79	54,400	32,300	28,600

From which, although Lamé's theory for the distribution of stress does not hold when the material is stressed beyond the elastic limit, it so happens that the values of the maximum pressure agree fairly closely, as will be seen from Table 32 with the values which would be obtained by calculation from Lamé's formula

$$p = f_{\text{ult.}}\frac{K^2 - 1}{K^2 + 1},$$

where $f_{\text{ult.}}$ = ultimate strength of material,

K = initial ratio $\frac{\text{external}}{\text{internal}}$ diameter,

p = maximum pressure.

Up to the yield point the authors found that the following equation held true :—

$$p = 0{\cdot}6f\frac{K^2 - 1}{K^2},$$

where f is a hoop tensile stress not higher than the yield point.

The above results are, of course, only applicable to mild and other ductile steels, but there is no doubt that if suitable alloy steels are used

for high-pressure work, and these are heat-treated to give good ductility, the data obtained by Cook and Robertson are quite applicable.

It is not permissible, of course, to apply these data to cylinders whose ratio external to internal diameter is considerably larger than those used by Cook and Robertson. The formula

$$p = f_{\text{ult.}} \frac{K^2 - 1}{K^2 + 1}$$

means that if K is very great the expression becomes $p = f_{\text{ult.}}$. This implies that an infinitely thick wall will not prevent a cylinder from failing if the applied internal fluid pressure is numerically greater than the ultimate strength of the material.

The Design of End Plates or "Heads" of Pressure Vessels.

(1) *Dished or Cambered Ends.*—The design of dished ends has recently received much attention, and the two outstanding publications on this subject are those by Hoehn, Chief Engineer to the Swiss Association of Steam Boiler Proprietors (see *Engineering*, 1929, CXXVIII, 1) and W. M. Coates (*Trans. A.S.M.E.*, 1930, **52**, 117), the latter entitled "The State of Stress in Full Heads of Pressure Vessels." This paper gives a good bibliography of the subject. The following notes are taken from Hoehn's work :—

Dished ends in service fail rather where the fatigue is greatest rather than where the stress is, and it is of interest to note that failures are far more frequent when such ends are used for unfired boilers, which are subject to wide variations of pressure, than in power station practice.

It has been usual to fix the thickness of a dished end by assuming that the major portion of the plating formed part of a spherical shell the stress f on which would be given by $f = \frac{pR}{2t}$, where p denotes the internal pressure, R the radius of the dish, and t the thickness. A large factor of safety has been adopted to cover the errors involved in this extremely rough assumption. In actual service, failures never occur along a line which would have formed part of a great circle of the above sphere, but along a ring coaxial with the axis of the end, and the really dangerous stresses are the bending stresses developed owing to the encastrement at the joint with the drum. Hoehn shows that a much better agreement between calculation and experience is obtained by regarding such ends as approximating to a section of an ellipsoid.

In general, dished ends are three-centred curves (see Fig. 69), and occasionally the profile is a true ellipse along a meridional section. This latter form Hoehn states to be the best; but if three-centred curves, known usually as "basket handle" profiles, are to be adopted,

then he regards it as important that the ratio of the two radii of curvature shall be as large as practicable. With a given flange diameter and given depth, the proportions of an elliptic profile are fixed, but there are an infinite number of basket handle curves having the same depth and the same external diameter. The form recommended by Hoehn is obtained as indicated in Fig. 69, where b denotes depth of dishing, a the flange radius. The two would thus in the case of an elliptic profile be respectively the minor and the major axes. Completing rectangle ABCO, diagonal AC is drawn, and angles BAC and BCA bisected, giving point F. From F drop perpendicular to AC to cut CO produced, at the centre M from which the crown of the dish is struck. The line AO is cut at E, and a circle struck from E

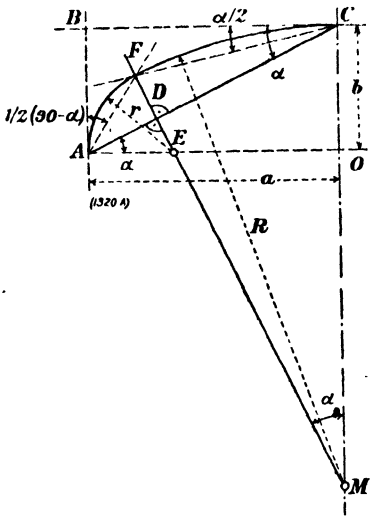


Fig. 69.

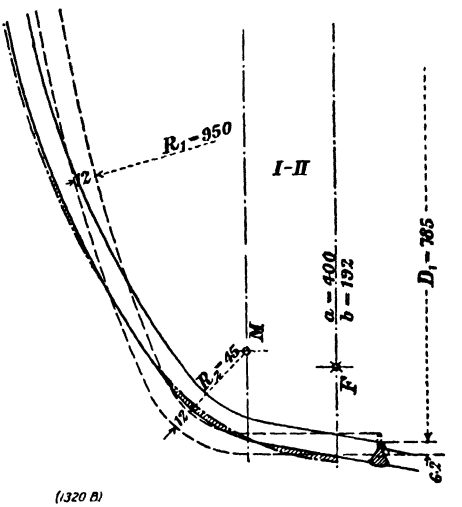


Fig. 70.

will pass through both A and F, thus completing the profile. If ratio $\frac{a}{b} = k$, then $\frac{r}{R} = \frac{\sqrt{k^2+1} - k}{\sqrt{k^2+1} - 1}$, and the ratio is the maximum possible for given values of a and b.

When a dished end is exposed to pressure the dishing deepens and the corner of the dish flattens, as indicated in Figs. 70 and 71. Hence the profile becomes more elliptical. Fig. 70 shows conditions within the elastic limit, and Fig. 71 shows permanent set produced by much higher pressure. Taking at the flattened section a circular fibre on the external face of the dish, this is shortened, as also is the corresponding fibre on the interior face.

Take next the section made by a diametral plane through the dishing, then in the region of the " corner " the fibres on the external face are shortened, whereas on the internal face they are stretched.

From experimental measurements of these strains, the corresponding stresses are deduced from the well-known equations

$$Ee_1 = P - \frac{1}{m}Q$$

$$Ee_2 = Q - \frac{1}{m}P$$

where e_1 = measured strain on a diametral section,
e_2 = ,, ,, at right angles thereto,
P and Q are the corresponding stresses,
$\frac{1}{m}$ = Poisson's ratio.

Hoehn points out that as the radial and ring stresses are of opposite signs at the inner surface of the corner, there must be heavy shearing

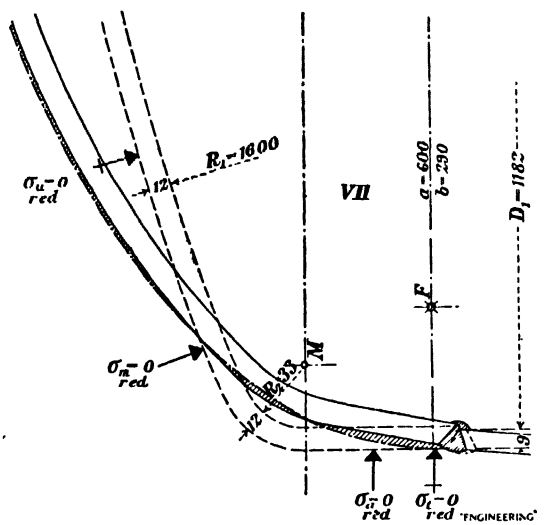


FIG. 71.

strains along directions making an angle of 45° with the meridians, but has never known failure attributable to these. The cracks occurring in practice do so along a ring, so that the danger lies with the stresses in the diametral planes. The bending stresses on these corners are the heavier because, as is well known when a curved bar is submitted to bending, the stress does not follow the straight line law as one passes from the compression to the tension side of the beam, and the stress is very much greater at the inner surface than in the corresponding case of a straight beam.

Hoehn carried out experiments with ten dished ends, of which two were of elliptic profile and remainder of the basket-handled type. The data so obtained were supplemented by particulars of 500 failures

of dished ends in service, and as a result of this comprehensive analysis, Hoehn recommends the following for proportioning dished ends having basket-handed profiles.

$$S = 1{\cdot}65\frac{pak}{Kz_1}\cdot\frac{20\frac{r}{R} + 3}{20\frac{r}{R} + 1}$$

where k = ratio of depth of end to half its diameter, and must be greater than 2 and less than 3·5;

S = plate thickness in cms.;

p = working pressure atm.;

z_1 = unity, unless there is a manhole, when its value should be diminished (see note later).

a = radius of flange (see Fig. 69).

$\frac{r}{R}$ = see Fig. 69. Not to be less than 0·04;

K = 3,600 kgs./cms.² (22·8 tons/sq. in.) for milder steels.

= 4,100 kgs./cms.² (26 tons/sq. in.) for harder boiler making steels. *Note.*—Hoehn recommends that only soft steels be used for dished ends.

= 2,200 kgs./cms.² (13·7 tons/sq. in.) for copper ends for temp. below 100° C. Above this temp. K should be reduced by 100 kg./cms.² for every 20° rise in temp.

= 4,000 kgs./cms.² (25·4 tons/sq. in.) for steel castings.

= 1,800 kgs./cms.² (11·4 tons/sq. in.) for cast iron.

Hoehn suggests that best ratio of $\frac{a}{b} = k$ is 2·5.

For cases where the profile of the end is a true ellipse, the formula for the thickness of the end should be

$$S = 1{\cdot}55\frac{pak}{Kz}\cdot\left(\frac{\frac{20}{k^3} + 2{\cdot}5}{\frac{20}{k^3} + 1}\right)$$

This formula is valid for values of k up to 4·0, but Mr. Hoehn considers it would be well not to exceed the value 3·5.

(2) *Flat End Plates.*—Except in small sizes all flat heads must of necessity be stayed to prevent excessive bending and deformation. Hence, wherever possible, dished end plates, which rarely require staying, are to be preferred. The theoretical equations most often quoted in connection with the strength of flat plates are those by Grashof, "Theorie der Elastizitat und Fertigkeit," 1878.

In the case of a circular flat plate fixed at the edges and under

uniform load, the largest stresses (f_s) are those in a radial direction at the circumference.

$$f_s = \tfrac{3}{4}\left(\frac{m^2 - 1}{m^2}\right)\frac{pr^2}{t^2}$$

where f_s = intensity of stress in a radial direction, lbs./sq. in.,

$\frac{1}{m}$ = Poisson's ratio, t = thickness of plate, ins.,

r = radius of plate ins.

p = intensity of pressure lbs./sq. in.

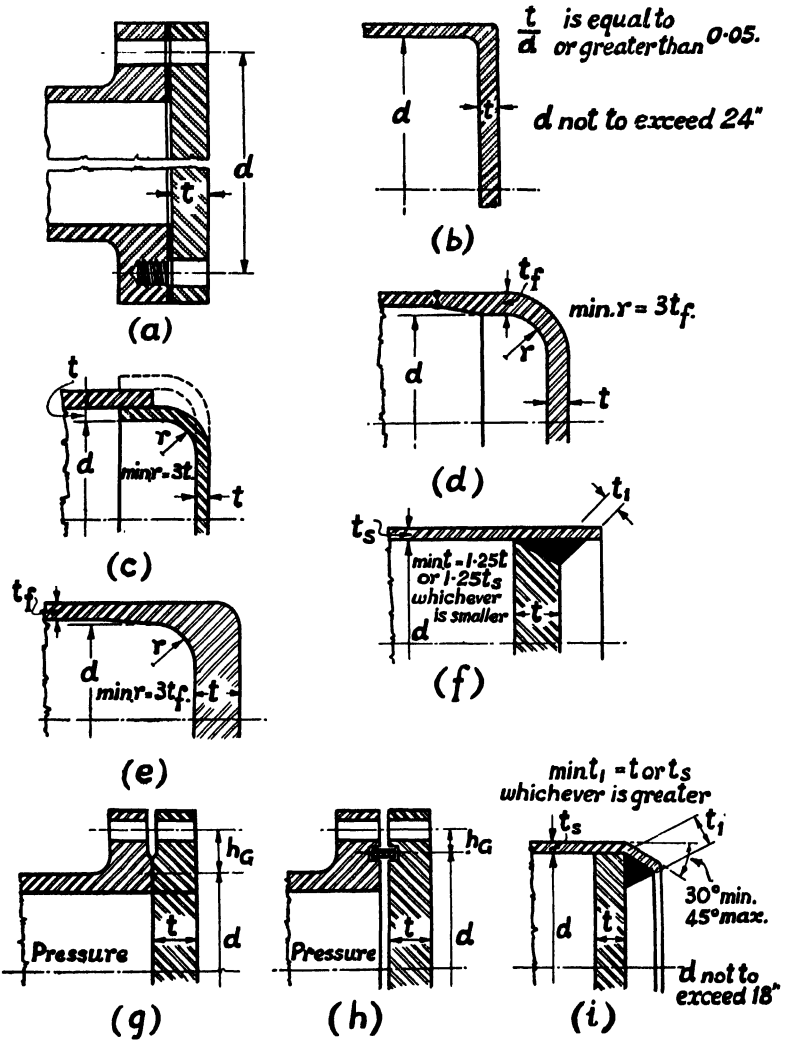


FIG. 72.

If $m = 3$, this equation becomes,

$$f_s = \frac{2pr^2}{3t^2}$$

whence $t = \sqrt{\frac{2pr^2}{3f_s}}$.

The following notes on the design of *flat heads* are taken from the A.S.M.E. Boiler Code (1935 edition) (Unfired Pressure Vessels), Section U. 39.

The minimum thickness of unstayed flat heads, cover plates, blank flanges, etc., shall be calculated as follows :—

$$t = d\sqrt{\frac{C \times P}{S}},$$

where t = thickness of plate in ins.,
d = dia. of head in ins., (see Fig. 72),
P = max. permissible working pressure in lbs./sq. in.
S = max. permissible stress (see Table below).
C = 0·162 for heads as Fig. 72*a* and *b*.
= 0·30 as Fig. 72*c*, if made in approved manner.
= 0·25 for heads as Fig. 72*d*, if welding carried out in an approved manner. Also for 72*e* (head integral).
$= 0{\cdot}30 + \frac{1{\cdot}40 \times W \times h_G}{H \times d}$ for plates bolted to shells in such a way that the tightening of the bolts tends to dish the plate. Fig. 72*g* and *h*. (W = total bolt load—lbs., and H = total end force on O.D. of gasket.)
= 0·50 for heads as Fig. 72*f* and 72*i*.

TABLE OF VALUES OF S.

Maximum Allowable Stress (S) in the Material of Flat Heads in Carbon Steel at Various Temperatures (lbs./sq. in.).

Max. Temp. (° F.).	Flange Material. Minimum Tensile Strength at Ordinary Temperatures (lbs./sq. in.).			
	45,000	55,000	60,000	75,000
700	9,000	11,000	12,000	15,000
750	8,220	10,000	11,200	13,000
800	6,550	8,000	9,000	10,200
850	5,440	6,750	7,400	8,300

For ends other than of bolted flange type the max. permissible working stress should be about $\frac{8}{10}$ of above.

Dished Heads.—The A.S.M.E. Boiler Construction Code (1935 edition) gives the following rules for unfired pressure vessel *dished heads* with pressure on the concave side:

$$t = \frac{8{\cdot}33 \times P \times L}{2 \times T.S.}$$

where t = thickness of plate in ins.,
P = working pressure in lbs./sq. in.,
TS = Tensile strength of plate lbs./sq. in.,
L = radius to which head is dished.

The radius of the head shall not be greater than the diameter of the shell to which it is attached, and due allowance must be made for any openings cut in the end plate. If the pressure is on the *convex* side of a dished head the working pressure shall be not more than 60% of that from above formula (which only applies when the pressure is on the concave side).

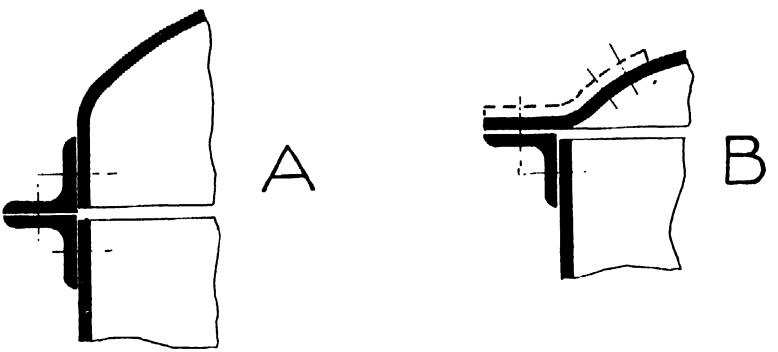


FIG. 73.

Bolts for Bolted Flat Heads.—The A.S.M.E. Boiler Code (loc. cit.) recommends that carbon steel bolts and nuts should *not* be used when the working pressure exceeds 160 lbs./sq. in. and/or the working temperature exceeds 450° F.; design stress not to exceed 11,000 lbs./sq. in.

The National Boiler & General Insurance Co., Ltd., gives the following rules in regard to bolted covers of low pressure vessels.

Dished Bolted Covers.—Dished covers are frequently connected to vessels by means of bolts. A desirable design for such covers is that indicated at A on Fig. 73.

In design A the bolted joint is under the same general conditions of stress as would exist if the cylindrical vessel itself were divided in the middle and a bolted joint connected the halves together. The dished cover may be designed in so far as the strength of the plate is concerned according to the following rules:—

Tensile stress K_t for mild steel should not exceed 6000 lbs. per sq. in.

(other materials proportionately). Then if P = pressure lbs./sq. in. in vessel, T = thickness of dished cover in ins., and R = radius of camber of cover in ins., then

$$K_f = \frac{P \times R}{2T}$$

A weaker form of dished end cover is shown at B on Fig. 73. This consists of a dished plate, the bolted joint being formed on the flat continuation of the dished portion. Ends of this kind are very much weaker than the dished end shown at A, and the same considerations regarding stress distribution for calculation purposes do not apply.

With end covers of this form the bolt-holes are sometimes slotted to the edge of the cover, the bolts being arranged on a hinged pin.

The tendency for the nuts to slip off the edge of the flange of covers with slotted holes and hinged pins should receive special attention. Generally the nut or the washer below the nut should fit into a suitable recess on the flange to prevent slipping.

The strength of this type of cover can be improved by reinforcing the rim as indicated at B, Fig. 73. The reinforcing ring should be securely riveted to the cover plate. Whenever possible, however, an end as shown at A should be adopted.

TENSILE STRESS PERMISSIBLE ON JOINT BOLTS (MILD STEEL).

The net section of the bolt for calculation purposes is to be taken at the bottom of the thread (Whitworth Standard Threads).

Diameter of Bolt (ins.).	Pitch should not exceed (ins.).	Stress in lbs. per sq. in.		
		A.	B.	C.
$\frac{5}{8}$	$3\frac{1}{8}$	3,600	4,500	6,300
$\frac{3}{4}$	$3\frac{1}{2}$	4,950	5,850	7,650
$\frac{7}{8}$	$3\frac{3}{4}$	5,850	6,750	8,550
1	4	6,300	7,200	9,000
$1\frac{1}{8}$	$4\frac{1}{4}$	6,750	7,650	9,450
$1\frac{1}{4}$	$4\frac{1}{2}$	7,200	8,100	9,900
$1\frac{3}{8}$	$4\frac{3}{4}$	7,650	8,550	10,350
$1\frac{1}{2}$	$4\frac{7}{8}$	8,100	9,000	10,800

Note.—Pitch is given to the nearest $\frac{1}{8}$ in.

Bolts.—In the design of many types of unfired pressure vessels bolted joints are included. The above table gives the maximum calculated stress which should be allowed on such joint bolts, depending on the periods at which they require to be removed. The figures given refer to ordinary mild steel bolts. The area on which the pressure is to be calculated is that inside the inner edge of the joint. Where joints

require to be unfastened frequently, resulting in greater wear and tear of the bolts and nuts, special deep nuts should be provided.

The jointing material should be as thin as practicable.

In the above table—

A applies to joint bolts screwed and unscrewed daily or more frequently.

B applies to joint bolts screwed or unscrewed at intervals of a few weeks.

C applies to the joint bolts of jacketed pans and similar vessels where the joints are seldom taken apart.

As a general rule bolts below $\frac{3}{4}$ in. diameter should not be used, especially for conditions A and B. For small vessels where the joints are not frequently broken $\frac{5}{8}$-in. bolts may be used if they comply with the table.

Openings in Shell and End Plates.

The compensation for shell openings of the manhole type is arranged in the following way (see Fig. 74) :—

The rule is that the sectional area (excluding parts cut out by rivets in riveted construction), formed by way of compensation within 4 ins. of the shell, should exceed the area cut away by the manhole opening and rivet by at least 10 per cent. of the area cut away.

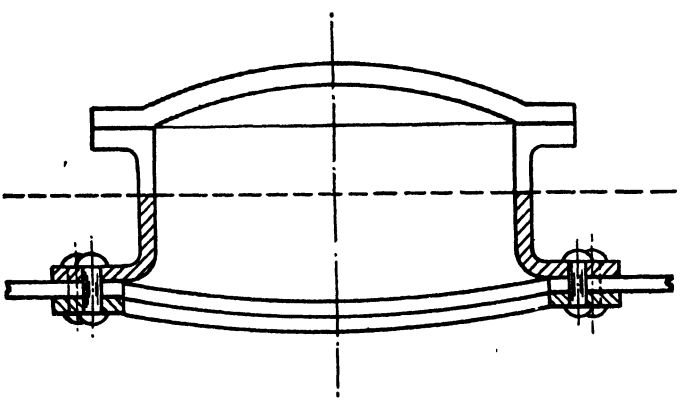


FIG. 74.

The shaded portion shows the portion to be included in the calculation.

Such openings should not cut across or be too near welded seams, nor should they be " in line " if it is possible to arrange otherwise.

Note.—The Board of Trade Rules provide that manholes in cylindrical shells shall have their shorter axes arranged longitudinally, and where the cylindrical shell is cut for a manhole, compensation must be provided and must

be such that the strength in the way of the hole is not less than that required for the longitudinal joint. No compensation, however, need be provided if the holes are less than $2\frac{1}{2}$ times the shell thickness plus $2\frac{1}{4}$ ins.

The two following rules are from the Board of Trade Rules for compensation for holes.

Manholes and Mudholes in Flat Plates.—When a flat plate is flanged to stiffen it at a manhole or sight hole, to permit the same working pressure as would be allowed upon an unpierced plate, the depth of the flange measured from the outer surface is to be at least equal to :—

$$\sqrt{T \times w}$$

where T = the thickness of the plate in ins.,
w = the minor axis of the hole in ins.

When a *dished end* has a manhole in it the thickness of the plate must be increased by $\frac{1}{8}$ in., and the total depth of flange of the manhole from the outer surface in ins. is to be at least

$$\sqrt{T \times w}$$

where T = the thickness of the plate in ins.,
w = the minor axis in ins.

Manhole Openings in Dished Heads.—From experiments made by Siebel and Koerber at Dusseldorf in 1926, it appears that the following reasoning should apply to the compensation for openings in dished ends.

Take unity as the thickness for ends with no openings, the thickness of the end should be increased by the ratio $\frac{425}{350}$ plus 1 mm. for ordinary manholes in the middle of the end, and for small handholes by the ratio $\frac{375}{350}$ plus 1 mm. Hoehn suggests that when manholes are provided in the end, the end should be cone-shaped in their neighbourhood.

Design of Stressed Parts of Pressure Vessels in Compression

(see also page 235 for details of thin shells under External Pressure).

The following rules, taken from the A.S.M.E. Boiler Code, 1935 edition, apply to flanging quality mild steel, or similar ductile materials, for working pressures not exceeding 500 lbs. per sq. in., and for maximum working temperatures of 700° F.

Shell Thickness.—The minimum thickness of shell plates in compression shall be found from the chart (Fig. 75), wherein

L = length between end plates or supports such as stiffening rings,
D = outside diameter of vessel in ins.,
t = min. thickness of plates in ins.

To use the chart the value of $\frac{L}{D}$ is found, and with the given working pressure the corresponding value of $\frac{t}{D}$ is read off. With this value of $\frac{t}{D}$ the required thickness is found. If a vessel has a greater $\frac{L}{D}$ ratio

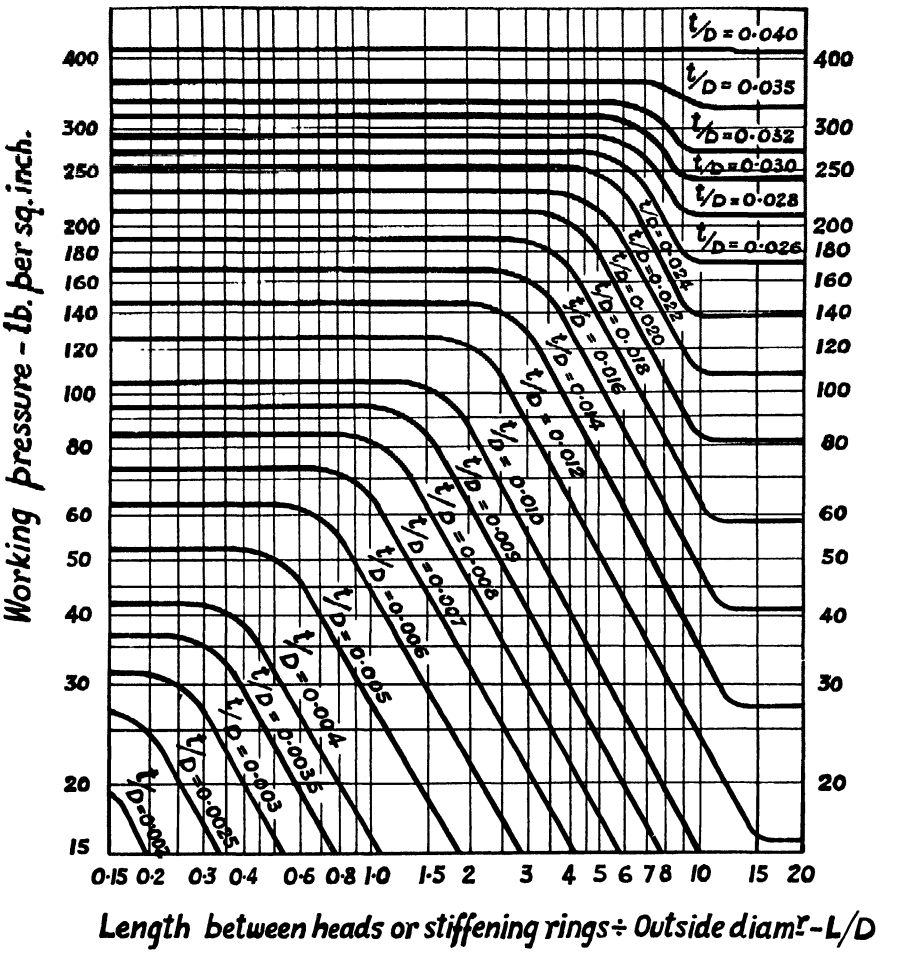


FIG. 75.

than 20, the same $\frac{t}{D}$ ratio shall be used as for an $\frac{L}{D}$ ratio of 20. In no case shall the working pressure be taken as less than 15 lbs. sq. in.

Example.—Pressure vessel 12 ft. long, between end-plates 96 ins. O.D. External working pressure, 15 lbs. per sq. in. Required shell thickness t.

$$\textit{Solution} \begin{cases} L = 12 \times 12 = 144 \\ D = 96 \end{cases} \qquad \frac{L}{D} = \frac{144}{96} = 1{\cdot}5.$$

From Fig. 75, for a working pressure of 15 lbs. per sq. in. and ratio $\frac{L}{D} = 1{\cdot}5$, ratio $\frac{t}{D} = 0{\cdot}0046$. Hence

$$t = 0{\cdot}0046 \times D = 0{\cdot}0046 \times 96 = 0{\cdot}44.$$

Naturally the strength of the longitudinal joint must be taken into account before finally fixing t. It is important in the design of vessels for external pressure to fix stiffening rings if the vessels are of long length, and also to note that "out of roundness" of the cylindrical portion must be the minimum possible under manufacturing conditions.

Cast Pressure Vessels.

The British Standards Institution have issued Specification No. 186 of 1923 for the shapes, dimensions, etc. of standard steam jacketed plain cast-iron and enamelled pans, and particulars given therein will serve as a guide for sizes and conditions outside the scope of the specification.

In the case of cast vessels of good-quality material where B.S.I. No. 186 does not apply the following formulæ may be used :—

(1) For cylindrical shells $P = \frac{F(T - \frac{1}{8})}{d}$

(2) For circular flat surfaces $P = \frac{F_1 \times T^2}{d^2}$

(3) For square flat surfaces $P = \frac{F_2 \times T^2}{l^2}$

Where P = internal working pressure lbs. per sq. in.
T = thickness of material in ins.
d = inside diameter of vessel in ins.
l = length of side of flat surface in ins.

The constants in the formulæ are given in the table below :—

Constant.	Cast Iron.	Gunmetal.	Cast Steel.
F	4,000	6,000	10,400
F_1	24,000	30,000	52,000
F_2	16,000	20,000	34,700

The above formulæ are taken from "Instructions as to the Survey of Passenger Steamships," Vol. I, H.M. Stationery Office. By permission of the Controller.

In the case of other metals and alloys, particulars of their mechanical properties will be found in Chapters I, II, and III, and the value for the constant F can be found by comparing the mechanical properties

of the material in question with the three materials given in the above table.

Except in very small castings it is not advisable to select thicknesses less than $\frac{1}{2}$ in. for cast iron, cast steel and similar materials and $\frac{3}{8}$ in. for gunmetal and the bronzes. Where there are large branches, doors, or other openings in the shell of such castings, the dimensions of the parts thus affected must be accordingly increased.

Cast-Iron Stayed Plates and Similar Vessels.—The following notes relate to cast-iron steam-heated plates, chests and platens such as are used in various kinds of appliances for garment pressing, hot-plates, ironing machines, and in connection with some types of process plant. (Reproduced by permission from the Rules of the National Boiler and General Insurance Co., Ltd.).

Note.—Cast iron should not be used in connection with superheated steam.

In order as far as possible to avoid internal stresses in the metal owing to unequal contraction of the structure when cooling down after casting, abrupt changes in thickness should be avoided, all corners being well rounded to form as large a radius as practicable.

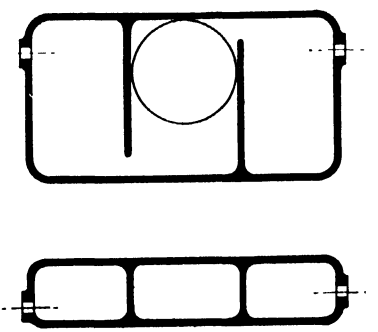


FIG. 76.

It is to be noted that the strength of cast iron varies considerably, and it is recommended that for new forms of vessels a specimen vessel constructed of the standard material which will be regularly employed should be tested to destruction.

Wherever possible, complex structures should be avoided, as in a complex casting it is difficult to ensure sound material throughout, and in addition concentrations of stress are liable to occur in certain portions of the structure.

Provision should always be made for free access of steam throughout the whole of the pressure parts ; drainage facilities should be adequate and suitably arranged so that condensate may be readily and effectively drained away.

Figs. 76, 77, 78 show diagrammatically examples of cast-iron stayed surfaces.

Fig. 76 indicates a relatively strong arrangement, as each compartment almost forms a rectangular box, the length of which does not materially exceed the width.

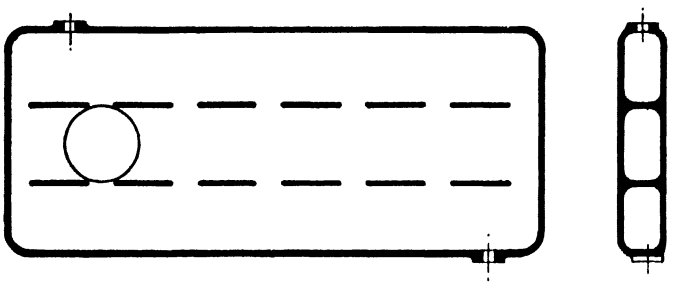


FIG. 77.

Fig. 77 shows stays intermittently arranged dividing the interior into a series of rectangular compartments, the length of which does materially exceed the width.

Fig. 78 shows a similar but less desirable form of staying, as the stays are continuous and cracks tend to extend along the whole length of the stay.

All stays or ribs should be well proportioned and of reasonable length; preferably they should not be continuous. Cylindrical or

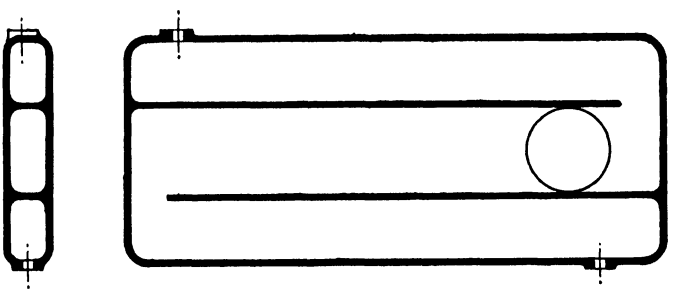


FIG. 78.

square-shaped studs are occasionally used to stay flat cast-iron surfaces, but forms of stays of this kind are liable to break off, leaving the flat surfaces unsupported. All cast stays should be connected by easy fillets to the surfaces they are designed to support.

The general proportions to be adopted in the design of such stayed surfaces are indicated approximately by the rules which follow.

Before employing these rules it should be ascertained that the material to be used is of average strength and of normal chemical com-

position, that the casting will receive ordinary care in the foundry and will be reasonably free from blow-holes.

P = working pressure in lbs. sq. in.
C = constant for each description of staying.
t = thickness of flat plate in 16ths in.
A = area of largest circle which can be inscribed within an unstayed area (see Figs. 76–78).

The diameter of the inscribed circle should not exceed 12 ins.

$$P = \frac{C \times t^2}{A}$$

C = 60 when the largest inscribed circle cuts three points of support and a fourth point of support is not further distant from the circumference of the inscribed circle than one-half of the diameter of that circle (see Fig. 76).

C = 45 when the largest inscribed circle cuts four points of support, the stays being intermittently arranged (Fig. 77).

C = 30 when the largest inscribed circle cuts two points of support, the stays being continuous (see Fig. 78).

An important consideration in the design of cast iron platens used in a hydraulic or screw-pressing machine is that a considerable load is applied to the external surfaces. In such cases it must be seen that, irrespective of the strength of the structure to withstand internal steam pressure, the metal should be of adequate thickness to withstand the external loading to which it will be subjected.

Riveted Construction of Pressure Vessels.

The general practice of riveting in chemical pressure-vessel work follows closely the technique long developed for steam-boiler construction. It is of importance to note that apart from failure by leakage a riveted joint can fail only in certain well-defined ways :—

(1) Failure of rivets in shear.
(2) Tearing of plate through a line of rivet-holes.
(3) Combined tearing of plate and shearing of rivets.
(4) Lap rupture.

These four possibilities form the basis for the design of riveted joints : (1) is accounted for by providing an adequate section of rivet-material in shear ; (2) by providing an adequate section of plate to resist the tearing process ; (3) by taking account of the weakest section of the plate and adding to its strength the resistance of the rivets which would have to shear in order to allow the tearing to take place ; and (4) by providing adequate material between rows of rivet holes and between the holes and the plate edges.

In general, the efficiency of a riveted joint may be defined as the

ratio between the minimum calculated resistance to failure, and the ultimate tensile strength of the solid plate, and this ratio is normally used in the calculation of the working pressure. It should be noted that it is the ultimate tensile strength of the plate material which provides the criterion of efficiency for riveted joints, and, so far as pressure vessels are concerned, this criterion has been found by experience to be entirely satisfactory.

Riveted construction, however, does not permit of good design in the case of many chemical pressure vessels: first, because of the interference of riveted joints with a smooth interior; second, the stresses set up in the shell and rivets in the riveting process often lead to rapid local corrosion; third, because many metals do not lend themselves to riveted work.

The following rules on riveting of boilers are taken from the Board of Trade Rules (loc. cit.) by permission of the Controller of H.M. Stationery Office, and are given as a guide to good practice in the riveting of pressure vessels. Note that these rules apply to "fired" pressure vessels, and for vessels of the unfired type the working pressure may be increased by 10% above that found by these formulæ for fired vessels.

Maximum Pitch of Rivets in Longitudinal Joints.—The maximum pitch of the rivets in the longitudinal joints of boiler shells is to be

$$\text{Maximum pitch in ins.} = C \times T + 1\tfrac{5}{8} \text{ ins.},$$

where T is the thickness of the plate in ins., and C is a coefficient as given in the following table:—

Number of Rivets per pitch.	Coefficients for Lap Joints.	Coefficients for Double Butt-strapped Joints.
1	1·31	1·75
2	2·62	3·50
3	3·47	4·63
4	4·14	5·52
5	—	6·00

Distances between Rows of Rivets and between Rivets and Plate Edges.—(*a*) The clear space between a rivet hole and the edge of a plate should not be less than the diameter of the rivet hole, i.e. the centre of the rivet hole should be at least $1\frac{1}{2}$ diameters distant from the edge of the plate.

(*b*) In zigzag riveted joints, whether lapped or fitted with butt straps, in which there is an equal number of rivets in each row, the distance between the rows should not be less than $0{\cdot}33p + 0{\cdot}67d$.

(*c*) In chain-riveted joints, whether lapped or fitted with butt straps, in which there is an equal number of rivets in each row, the distance between the rows should not be less than $2d$.

(*d*) In zigzag riveted joints in which the number of rivets in a row is one-half of the number in an adjacent row, the distance between the rows should not be less than $0{\cdot}2p + 1{\cdot}15d$. The distance between rows in which there are the full number of rivets should be not less than $0{\cdot}165p + 0{\cdot}67d$.

(*e*) In chain-riveted joints in which the number of rivets in a row is one-half of the number in an adjacent row, the distance between the rows should be not less than $0{\cdot}33p + 0{\cdot}67d$ or $2d$, whichever is the greater. The distance between rows in which there are the full number of rivets should be not less than $2d$.

In the above p = pitch of the rivets in the outer rows,
d = diameter of the rivet holes.

Thickness of Butt Straps. The outer butt strap of a longitudinal seam should be of sufficient thickness to permit of efficient caulking, and it should have an effective strength not less than $\frac{5}{8}$ that required for the shell plate.

Where the number of rivets at the edges of the shell plate is double the number at the edges of the butt straps, then :—

$$T_B = \tfrac{5}{8}\frac{(p - d)}{(p - 2d)}T$$

where T = thickness of shell plate in ins.,
T_B = thickness of outer butt strap in ins.,
p = pitch of rivets in outer rows at edges of butt strap in ins.,
d = diameter of rivet hole in ins.

The inner butt strap should be $\frac{1}{8}$ in. thicker than the thickness required for the outer butt strap.

Methods of Calculating the Strength of Riveted Joints.—The percentage of strength of a riveted joint is found from the following formulæ (I), (II), (III) : (I) and (II) are applicable to any type of joint ; (III) is applicable only to joints in which the number of rivets in inner rows is double that in the outer row. The lowest value given by the application of these formulæ is to be taken as the percentage of strength of the joint.

(I) Percentage of strength of plate at joint as compared with solid plate

$$= \frac{100\,(p - d)}{p}$$

(II) Percentage of strength of rivets as compared with the solid plate

$$= \frac{100(S_2 \times a \times n \times C)}{S_1 \times p \times T}$$

(III) Percentage of combined strength of the plate at the inner row of rivet holes and of the rivets in the outer row

$$= \frac{100(p - 2d)}{p} + \frac{100(S_2 \times a \times C)}{S_1 \times p \times T}$$

where p = pitch of rivets at outer rows in ins.,
d = diameter of rivet holes in ins.,
a = sectional area of one rivet in sq. ins.,
n = number of rivets which are fitted in the pitch p,
T = thickness of plate in ins.,
C = 1·0 for rivets in single shear as in lap joints,
C = 1·875 for rivets in double shear as in double butt-strapped joints,
S_1 = minimum tensile strength of plates in tons/sq. in.,
S_2 = shearing strength of rivets, which is taken generally to be 23 tons/sq. in., and may be 85 per cent. of the minimum tensile strength of the rivet bars.

Circumferential Seams.—(*a*) The riveting of the seams joining the end plates to the cylindrical shell shall be not less than 42 per cent. of that of the solid plate. Where the shell plates exceed $\frac{5}{8}$ in. in thickness the seams connecting the shell plates to the end plates are to be double riveted.

(*b*) The circumferential seam at or near the middle of the length of single-ended boilers should have a strength of joint not less than 60 per cent. of the solid plate. The inner circumferential seams of double-ended boilers should have a strength of joint not less than 62 per cent. of the solid plate. In any case, there shall be three rows of rivets when single-ended boilers have shell plates over $1\frac{3}{8}$ ins. in thickness and when double-ended boilers have shell plates over $1\frac{3}{16}$ ins. in thickness. Where the shell plates exceed $\frac{1}{2}$ in. in thickness the intermediate circumferential seams of double-ended boilers are to be at least double riveted.

(*c*) The circumferential seams in the shell of a vertical boiler shall be not less in strength than 42 per cent. that of the solid plate. When the seams are not complete circles, and when the plates exceed $\frac{5}{8}$ in. in thickness, they shall be double riveted.

Working Pressure of Boiler Shells.—(*a*) For steel cylindrical shells the maximum working pressure to be allowed shall be calculated from the following formulæ :—

If the thickness of the shell plates does not exceed $1\frac{3}{4}$ ins.

$$\text{W.P.} = \frac{(t - 2) \times S \times J}{C \times D}.$$

If the thickness of the shell plates exceeds $1\frac{3}{4}$ ins. and double butt straps are fitted

$$\text{W.P.} = \frac{t \times S \times J}{2{\cdot}85 \times D}$$

where W.P. = the working pressure in lbs./sq. in.,
t = the thickness of the shell plates in 32nds of an in.,
S = the minimum tensile strength of the steel shell plates in tons sq. in.,
J = the percentage of strength of the longitudinal seams,
C = a coefficient, which is 2·75 when the longitudinal seams are made with double butt straps; 2·83 when the longitudinal seams are made with lap joints and are treble riveted; 2·9 when they are made with lap joints and are double riveted, and 3·3 when they are made with lap joints and are single riveted,
D = the inside diameter of the outer strake of plating of the cylindrical shell measured in ins.

N.B.—The Factor of Safety must be in no case less than 4.

Much of the following applies both to riveted and welded pressure vessels, except where expressly stated to the contrary.

Hemispherical Ends.—When the end is a hemisphere without stays,

$$\text{W.P.} \quad \frac{(t - 2) \times S \times J}{C \times R}$$

where W.P. = the working pressure in lbs. sq. in.,
t = the thickness of plates in 32nds of an in.,
S = the minimum tensile strength of the plates in tons/sq. in.,
J = the minimum strength of riveted joints per cent. of solid plate,
R = inner radius of curvature in ins.,

$$C = \begin{cases} 3{\cdot}3 \text{ for single riveting.} \\ 2{\cdot}9 \text{ for double riveting.} \\ 2{\cdot}83 \text{ for treble riveting.} \end{cases}$$

Dished Ends (Convex Outside).—The working pressure on the ends of steam chests, etc., except air receivers, dished to partial spherical form is to be obtained from the following formula:—

$$\text{W.P.} = \frac{15 \times S \times (t - 1)}{R}$$

where W.P. = the working pressure in lbs./sq. in.
t = the thickness in 32nds of an in.,
R = the inner radius of curvature of the end in ins., which shall not exceed the diameter of shell,
S = the minimum tensile strength of plate in tons/sq. in.

The inside radius of curvature at the flange must not be less than four times the thickness of the end plate and in no case be less than 2·5 ins. (See also Schuster's rules, page 225, for welded construction, Hoehn's rules on page 184, and A.S.M.E. Rules, page 190.)

Special Note.

It is to be noted in the foregoing practical formulæ that no allowance has been made for loss of strength by corrosion, and hence the dimensions found by such methods are *minimum* dimensions. It is, therefore, necessary to consider each case individually, and make such provision as may appear desirable from the corrosion aspect. The formulæ given are based upon the working pressure being carried at ordinary temperature so that " creep " of the stressed parts does not occur. If it is desired to use the formulæ for high-temperature work in the " creep region," then the creep properties of the material as discussed on page 117, Chapter IV, must be taken into consideration.

Rules for Welded Construction of Pressure Vessels.

Before discussing the various rules for welded construction of pressure vessels it is considered desirable to describe in detail the various methods of welding followed by notes on design.

The Fabrication of Pressure Vessels and Accessories by Welding.

The welding processes used in the manufacture of pressure vessels, fabricated plate work and accessories may be broadly classified as follows :—

(1) Forge and hammer welding.
(2) Electric resistance butt welding.
(3) Atomic hydrogen process.
(4) Metallic arc fusion welding.
(5) Acetylene welding.

(1) *Forge and Hammer Welding.*

The forge and hammer welding method of pressure-vessel construction is closely allied to the oldest known method of welding, and has been used for generations in the manufacture of furnace and flue tubes for Lancashire and Cornish boilers. This method has recently been developed, chiefly in Germany, for the fabrication of large pressure vessels, and the following description of the technique adopted by Messrs. Thyssen of Mulheim Ruhr is of interest in this connection.

The pressure vessels are made from standard qualities of steel plate,

and for the cylindrical portion, the plate is first put through rolls to obtain circular shape. The welding of the longitudinal seam is carried out with a water gas flame of a reducing nature, and the edges of the plate being welded are worked by means of rolling at welding temperature. After completion of the longitudinal seam, this is then closely examined, and if satisfactory the vessel is annealed and an internal hydraulic pressure of 50 per cent. above the desired working pressure is applied. The ends of the vessel are then closed in, and manhole and other openings fitted.

Upon completion, the vessel is then highly stressed by application of an hydraulic pressure of three or four times the working pressure, and finally the vessel is heat-treated to relieve internal stresses.

During the past twelve years, Messrs. Thyssen have supplied more than 1250 such vessels, chiefly in the form of steam drums for water-tube boilers, and in the majority of cases the working pressures were in excess of 500 lbs. per sq. in.

(2) *Electric Resistance Butt Welding.*

For joining of parts of tubular structures this method offers many advantages, and it can be used with great facility in the construction of elements of tubular heaters and heat exchangers. It has the advantage that when the weld is complete there has been no addition of metal from any outside source. The method of operation is to place the tubes to be welded one into each of two clamps which form the electrodes of the machine. One of the clamps is stationary and forms part of the rigid structure of the machine, and the other forms a sliding head attached to a mechanically operated ram capable of either slow or rapid movement. The tubes are held so that the ends, which have been machined square, just butt, and the current is then switched on and the whole process is automatically completed.

Current flows between the two clamps through the tubes, and when the ends of the tubes meet a resistance is set up due to discontinuity of the structure. This resistance raises the temperature of the metal at the ends of the tube, a certain amount of metal is flashed off, and when at the right plasticity an upset or forge blow is imparted to form the weld.

The current used is supplied through a transformer, the secondary windings being tapped to give voltages ranging between 5–8 volts. The cost of equipment and of power consumption in this process limits the size of work to tubular structures in which the cross-sectional area to be welded does not exceed about 30 sq. ins.

(3) *Atomic Hydrogen Process.*

The use of atomic hydrogen is one of the later developments in the field of welding and appears to have certain advantages. Although an

electric arc is used, its application is indirect, and up to the present covered electrodes have not been utilised to any extent. It may be looked upon as supplementary to metallic arc welding rather than as a competitive process.

An arc is maintained by an alternating current between two tungsten wire electrodes and a stream of hydrogen gas is introduced around the arc. The temperature of the electric arc is sufficiently high to cause dissociation of the hydrogen molecules, and the atomic hydrogen on leaving the zone of the arc at once recombines to form again hydrogen in the molecular state. The latter process is a reversal of the heat input from the electric arc, energy is given up, and provides the heat required for welding.

Such a process may appear to be a complicated method of providing the heat required for welding, but by this means it is possible to produce a flame of high temperature composed of a single gas without the usual combination with oxygen, whilst, in addition, the welding can be carried out in an envelope of burning hydrogen so that the metal constituting the weld can be maintained free from atmospheric contamination without a slag coating.

(4) *Metallic Arc Fusion Welding.*

In view of the importance of this method in the fabrication of pressure vessels, the subject will be dealt with at length. I am indebted to Messrs. Babcock & Wilcox, and Messrs. John Thompson for assistance in the following notes. (See also Davy, *Proc. Inst. Chem. Eng.*, 1935, **13**, 133, from which much information is extracted.)

When the early development of welded pressure vessels began, electric arc welding offered great possibilities. An automatic machine had been devised for welding cylindrical containers made from thin steel plates. This machine worked well with bare wire electrodes, but the class of weld which could be made was unsuitable for pressure vessels since metal deposited in the weld from bare electrodes contains a number of major defects, such as incomplete fusion with parent metal, slag inclusions and porosity.

Apart from the presence of such defects, the use of the bare electrode results in considerable atmospheric contamination of the weld metal, this contamination being exaggerated by the instability of the arc when using electrodes of this type. The atmospheric contamination causes oxide and nitride inclusions in the weld metal which tend to make the metal brittle, even if present only in minute quantities.

The weld metal must have physical and chemical properties similar to those of the parent metal, and means must be provided to replace in the weld metal the carbon, silicon and manganese lost due to volatilisation of these elements in the arc. Coated electrodes therefore have to be used, and machines have to be developed capable of feeding such

electrodes without stopping and starting at short intervals for electrode replacement. The manufacturer has to consider vessels up to 80 ft. in length, in which long longitudinal seams are a necessity. Means have been found for automatically feeding long-coated electrodes to provide a continuous weld. The advantage of such a method of working, combined with constant, mechanically regulated short arc conditions, will be easily appreciated. Weld metal can be laid down within definite temperature limits so that the class of structure can be controlled throughout the welding operation.

The electrode consists of two portions, the steel wire and the coating attached thereto.

The wire is delivered in coils and the first operation involves the cleaning of its surface and straightening and cutting it into the 8-ft. lengths suitable for the automatic welding machines. In the second operation projections are stamped by the machine on to the wire at a regular pitch. These projections just protrude through the electrode coating, so that electrical contact can be made with the contactors of the feeding device on the automatic machines. In order that the automatic welding process is not interrupted, the electrodes are made so that the one can fit into the other, thus providing what is essentially a continuous electrode. After the stamping operation, the wire is fed to the machine which extrudes the coating, and applies a carefully controlled thickness of the coating to the wire.

The Welding Technique.—The deposition of weld metal by means of the metallic arc involves a close study of three main variables: –

(*a*) the electrical input to the arc;

(*b*) the speed at which the electrode travels along the seam being welded; and

(*c*) the shape of the groove formed by the abutting plates.

The quality of weld metal deposited from an electrode depends largely on the amperage and voltage of the arc.

The second variable may be considered as follows: –with given electrical conditions and an excessive speed of travel of the electrode along the seam, the heat generated in the vicinity of the arc will not be sufficient to fuse the sides of the groove being welded, and at the junction between the weld metal and the plate there will remain a thin film of non-metallic material, for instance slag, which will constitute a definite weakness at the joint. Time is naturally an important factor in raising the temperature of the parent metal to the degree necessary.

If the speed of the electrode is too low, three conditions can follow. First, the run of weld metal deposited is of too great a thickness so that subsequent recrystallisation by the succeeding run is confined to a relatively small depth of the metal. Secondly, the heat generated in the vicinity of the arc causes excessive fusion of the plate, and pockets enclosing slag are formed. Thirdly, the slag arising from the electrode

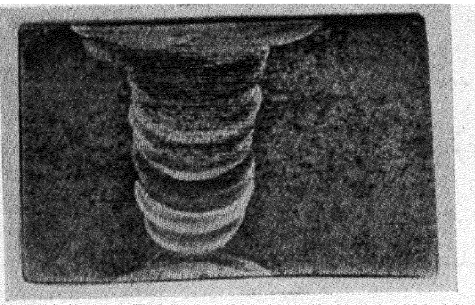


FIG. 79.

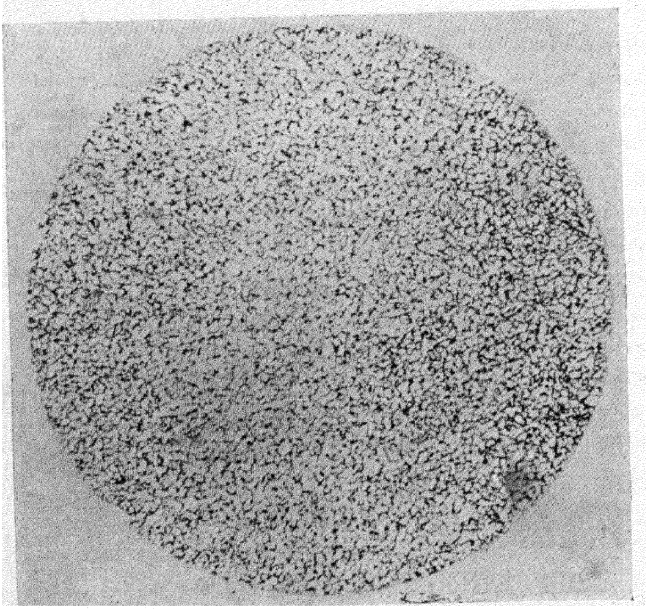


FIG. 80.

[*See page* 207.

coating, instead of being controlled to freeze behind the arc, will flow in front of the electrode and become overlapped by the weld metal.

Having once, therefore, determined the electrical input to the arc for good-quality weld metal, the speed of travel of the electrode must be considered in relation to the shape of the groove in the plate. A groove, having the U-shaped section shown in Fig. 79, is almost universal for heavy plate because the change in the width of the groove after each layer of weld metal has been deposited is almost negligible, and because the almost vertical line of fusion is admirably suited to X-ray inspection. The minimum dimensions of the groove are controlled by the electrode used. The narrower the groove, the less the amount of weld metal necessary and the cheaper the fabrication. The factor of primary importance which determines the minimum width of groove is the first layer of weld metal deposited. If the groove is too pointed at the root of the weld, inadequate penetration at the base of the groove will follow.

Regarding size of electrodes, it might appear that the most economical procedure would be to use electrodes of large cross-section, thereby filling a deep groove in two or three runs. It sometimes happens in such cases that cheapness and speed do not go hand in hand with the soundness of weld in the manufacture of pressure vessels. The four major considerations are :—

(*a*) distortion of the vessel due to unbalanced contraction where large amounts of weld-metal are laid down ;

(*b*) the retention of a coarse columnar structure, because of the restricted depth to which the refining effect of the superposed run of weld-metal can penetrate ;

(*c*) the trapping of slag in the weld-metal due to freezing before the slag has floated to the surface of the weld run ;

(*d*) high current density necessary with large electrodes produces excessive porosity.

The multi-layer weld is most attractive (Fig. 79). The comparatively thin layers of weld-metal permit the full flotation of slag before freezing, and with suitable electrode coatings a protective slag with a low specific gravity can be ensured. Whilst the current density can be maintained sufficiently high to ensure good fluidity of weld-metal and complete fusion, the smaller section electrodes do not necessitate current densities of the class which bring about porosity. The refinement of the grain structure due to successive layers of weld-metal and marked freedom from slag or porosity is best seen by examination of the photomicrograph shown in Fig. 80.

Attention must also be paid to the disturbed area in the parent metal immediately on each side of the weld. There are many practical difficulties which prevent the normalising of the finished drum. It is not possible to heat the finished drum to a temperature of the order of

900° C. to recrystallise the material. In addition, considering the weld-metal, this recrystallisation would be undesirable because the rate at which the whole mass of the drum could be cooled through the upper 400° C. of the temperature curve would be such that a grain structure of very much coarser type would result in the heat-treated weld itself, and the laminar structure of the plate would lose the fibrous nature which makes it particularly suited to carry circumferential stresses, such as the hoop stress, etc., to which the drum is subjected in service. The only theoretical reason upon which recrystallisation in such a vessel can be advocated is to remove the disturbed area in the parent metal immediately adjacent to the point at which fusion between the weld-metal and parent metal takes place.

Fig. 81 shows a panoramic photomicrograph of the transition structure from the line of fusion to the original laminar plate structure. This photomicrograph is taken at a magnification of 100 diameter. The photomicrograph is accompanied by the Brinell hardness taken at various points across the transition area, and these readings serve to indicate the extent to which disturbance has taken place.

In discussing the structure of the parent metal adjacent to the weld, reference has been made to the important question of heat treatment. In considering this question, it is desirable to bear in mind the class of vessel which may have to be handled. Any attempt to normalise the large shells, now fabricated at a temperature above the critical range of about 900° C., would result in serious deformation because of the plasticity of the metal at that temperature. For metallurgical reasons, rapid cooling through the temperature range between 900° and 600° C. would be necessary, but it would be impossible with hollow cylindrical vessels because of the danger of unequal stresses due to contraction and the considerable heat contained in the large mass of metal presented by the vessel.

The heat treatment to which vessels are subjected consists of bringing the metal to a temperature of 600° C., and maintaining it at that temperature for a period of 1½ hours for each inch of thickness of the weld, the vessel being allowed to cool slowly afterwards in suitable screens. There can be no doubt that low-temperature stress relief treatment is beneficial (see structure indicated in Fig. 80). Suggestions have been made from time to time that a higher stress relief temperature ranging between 650° and 700° C. should be employed. Whilst there is no doubt that the plasticity of the metal will increase with temperature, it has to be remembered that within this temperature range the carbide forms spheroidal aggregates at a relatively rapid rate, and any small benefit would only be gained at the expense of the structure of the metal.

Non-Destructive Tests.—In welded pressure vessels, test plates can easily be provided at each end of the longitudinal seam, these plates

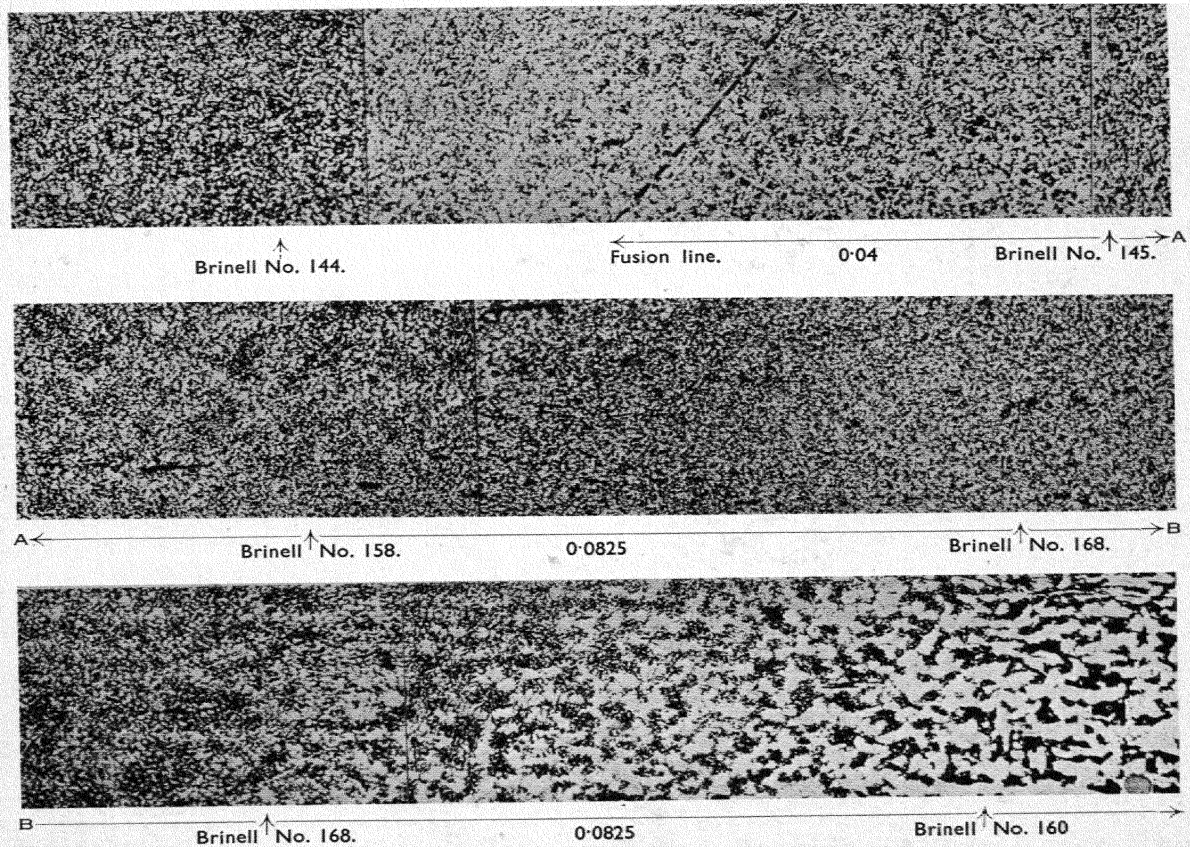


FIG. 81.—Panoramic photomicrograph of transition structure × 100 dia.

[*Facing page* 208.

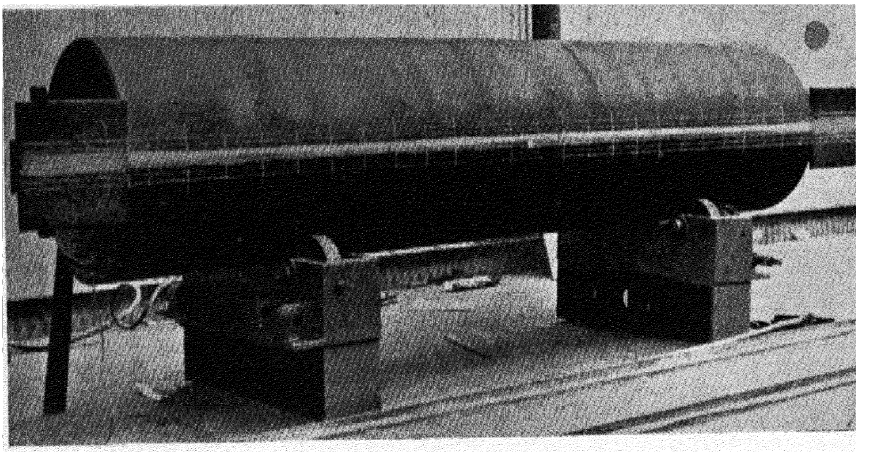


FIG. 82.—Welded cylinder with test plates in position.

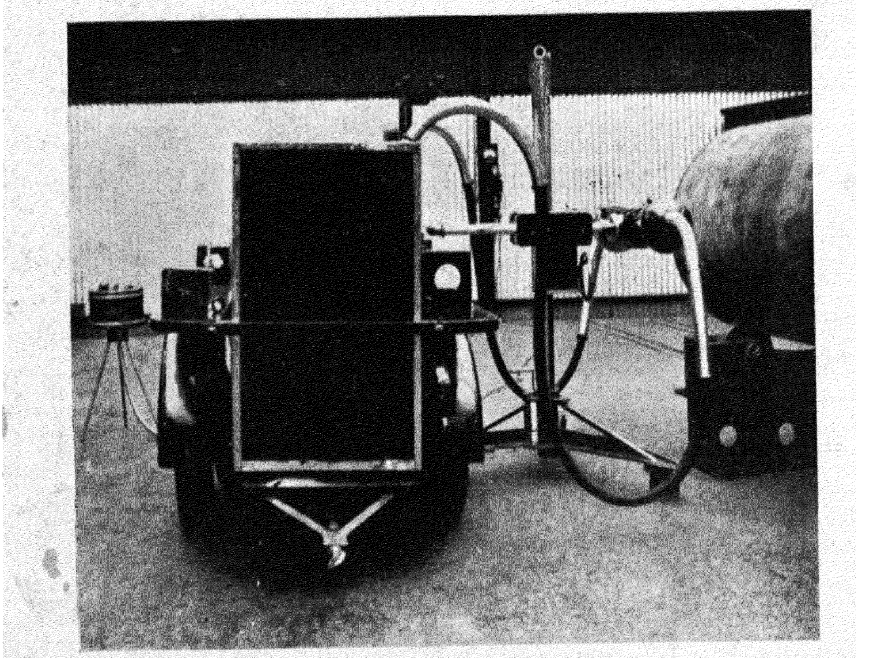


FIG. 83.—X-Ray apparatus for radiographic inspection.

[*Facing page* 209.

being tacked on prior to welding and butt-welded as part of the longitudinal seam of the vessel.

Fig. 82 shows a welded cylinder with the test plates in position. After the welding is completed and the plates removed, they are given a controlled and recorded heat treatment exactly similar to that to which the drum is subjected, and are afterwards cut up into suitable specimens for transverse tensile, bend, all-weld-metal tensile, weld-metal density, and impact tests, whilst the material is also examined microscopically.

Such plates, however, cannot be produced when welding circumferential seams, as machine-welded circumferential seams are continuous. Some means, therefore, have to be found whereby it is possible to establish that the quality of the weld-metal shown by the mechanical tests of the test plates is identical with that in the whole length of the longitudinal and circumferential seams. Examination by X-rays has proved to be the most satisfactory means for attaining this end. By radiographic inspection of every inch of the weld and of the test plates, it is possible to establish a direct comparison between the weld-metal in the test plates and the weld-metal in the vessel itself.

Fig. 82, apart from showing the test plates in position, also indicates a longitudinal seam marked up ready for the addition of the lead tabs which are used for identification and density measurement in the taking of X-ray photographs.

Fig. 83 shows the X-ray apparatus arranged for operation, and it should be noted that the tripod carrying the controls of the X-ray plant is well behind the X-ray tube, so that the operator is safe from indirect rays and their harmful effect.

The radiographic inspection is considerably simpler than might be supposed. The X-rays emitted by the tube penetrate the weld from the outside of the vessel, so that the radiograph is produced on a highly sensitised film carried in a cassette secured to the inner surface of the drum along the weld. The radiograph produced in a shadow picture, and the reading of these radiographs, whilst initially difficult, soon becomes with practice comparatively easy.

The most satisfactory way of obtaining a first-class knowledge of the meaning of radiographs is that of making welds under conditions which are deliberately varied, examining them by X-rays, making sections, and afterwards comparing these with the pictures produced and studying the history of the weld.

The code of the American Society of Mechanical Engineers provides a set of radiographs which are chosen to indicate acceptable or unacceptable welds, and this comparative basis for examination has proved satisfactory since its inclusion in the Code in 1931.

Fig. 84 is a radiograph of a welded seam which would be unacceptable for pressure service. It illustrates a weld which has been made

with a lightly coated electrode giving insufficient protection against atmospheric contamination. Considering the type of electrode used for this particular weld, the weld might be thought good, but it is apparent that the structure is exceedingly porous, this being due to the high ferrous oxide content of the weld-metal.

An illustration of defect in an otherwise perfect length of welding is shown in radiograph Fig. 85—an isolated slag inclusion is disclosed. The conditions of welding may have been good and the operator himself may have observed nothing to explain the occurrence of this isolated inclusion of slag. Its existence would possibly be due to a very small fault in a portion of the electrode coating. End test plates would not indicate its existence but X-ray examination discloses it. The Code of the American Society of Mechanical Engineers specifies that the length of a slag inclusion shall be less than one-third of the thickness of the weld, so that in the case of the defect in Fig. 85 a repair would be necessary.

Fig. 86 shows a type of porous weld caused by too great an electrical input to the arc, and such marked porosity is not likely to occur in practice where an automatic welding machine is utilised, but Fig. 87 shows a small porous portion which has occurred through momentary variation of the controlled arc. Here again, only an X-ray examination would show its existence. Fig. 88 shows a radiograph of a high quality weld.

Examples of fusion welded vessels by Babcock & Wilcox are seen in Figs. 89–90. The autoclave in Fig. 89 is of the jacketed type and the shell is 5 ft. 6 ins. I.D. × 12 ft. 2 ins. long. The plate thickness of the shell is $3\frac{7}{16}$ ins. and of the jacket $1\frac{5}{16}$ in. The working pressure of the inner pan is 600 lbs. per sq. in. and of the jacket 400 lbs. per sq. in. The weight of the vessel is 27 tons.

The bubble tower (Fig. 90) is 90 ft. long × 12 ft. diameter, and the plate thickness is $1\frac{1}{4}$ in. The working pressure is 150 lbs. per sq. in. at 700° F., and the weight 170 tons.

Messrs. John Thompson have recently constructed one autoclave 6 ft. diameter × 8 ft. long, shell $3\frac{1}{8}$ ft. thick for a working pressure of 900 lbs. per sq. in., one vessel 6 ft. diameter with plates $3\frac{1}{8}$ ins. thick tested to 1500 lbs. per sq. in., and it is of interest to record that for some large boiler-drums welded by this firm over $\frac{1}{4}$ ton of weld-metal was deposited during the course of the welding operations.

Messrs. Krupp of Essen have also carried out several notable examples of welded work, by the metallic arc process, as will be seen from the example given in Fig. 91, which is a reaction vessel for oil-cracking plant and is 14,000 mm. (45 ft. 10 in.) long, diameter 2,020 mm. (6 ft. $7\frac{1}{2}$ in.), with a wall thickness of 98 mm. ($3\frac{7}{8}$ ins.). The working pressure is 35 atmospheres at a temperature of 500° C.

The Blaw Knox Company of Pittsburgh, U.S.A., have fabricated a

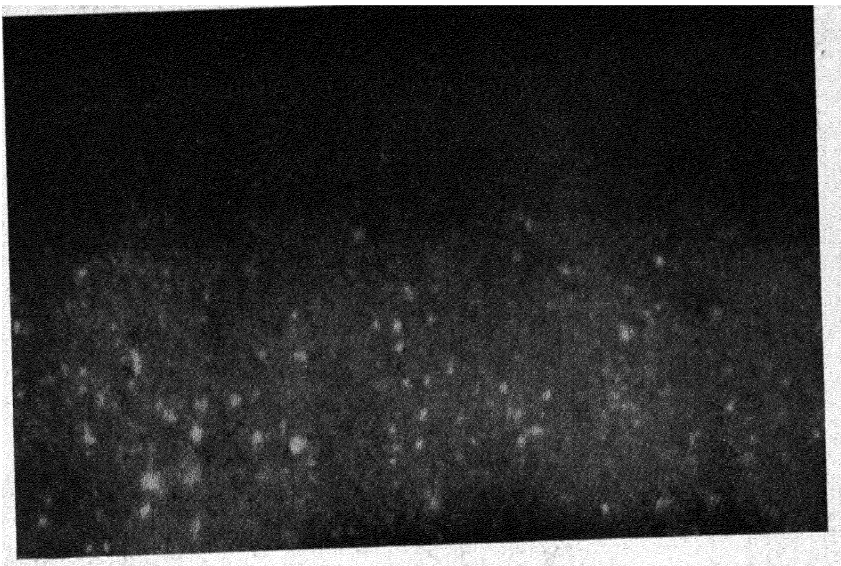


FIG. 84.—Radiograph of weld made with too lightly coated electrode.

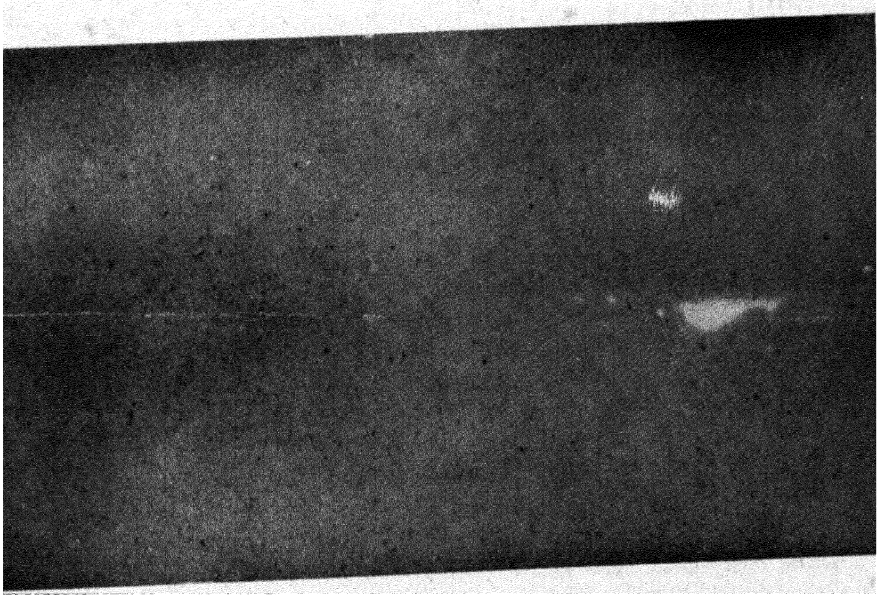


FIG. 85.—Radiograph showing isolated slag inclusion.

[*Facing page* 210.

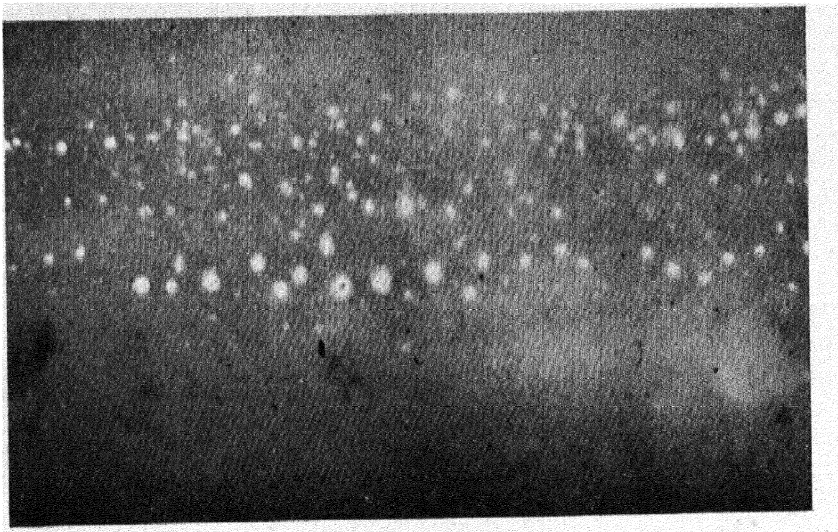


FIG. 86.—Radiograph of porous weld.

[*See page* 210.

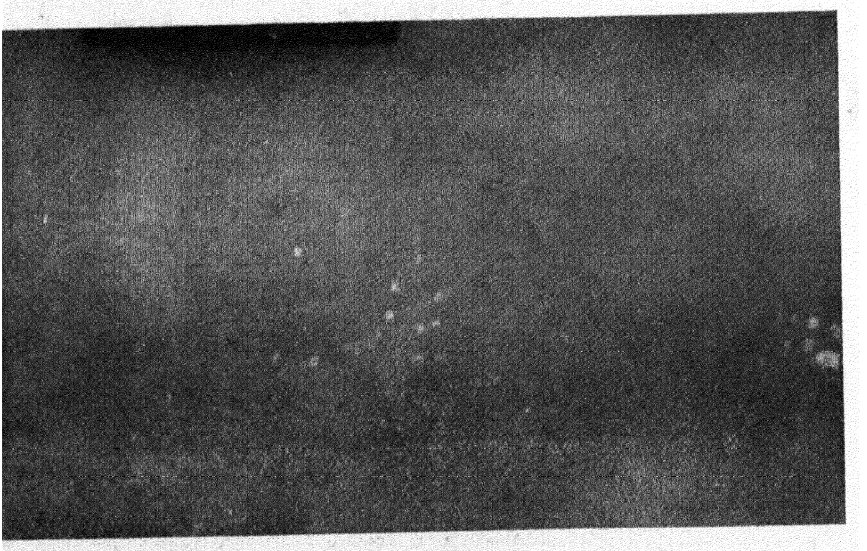


FIG. 87.—Radiograph showing isolated porosity.

[*See page* 210.

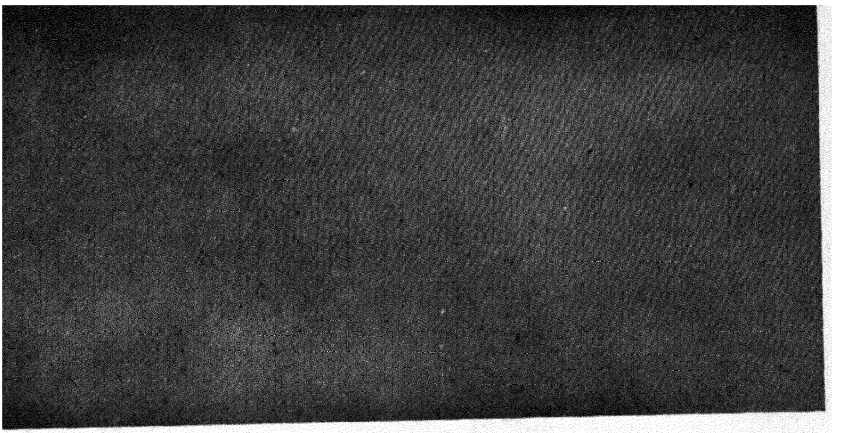


FIG. 88.—Radiograph of high quality weld.

[*See page* 210.

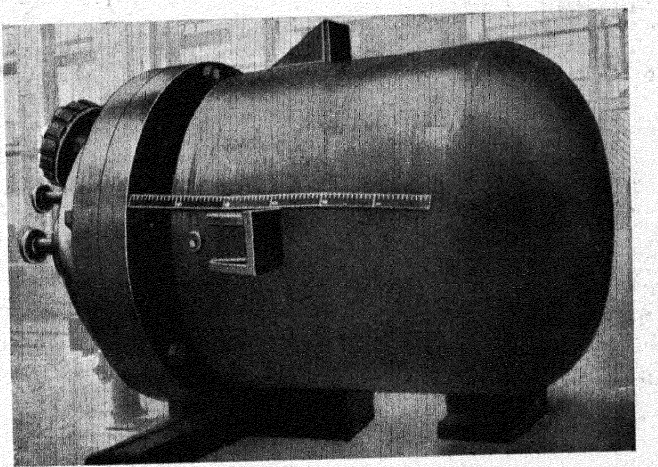


FIG. 89.—Welded jacketed autoclave by Babcock & Wilcox, Ltd.

[*See page* 210.

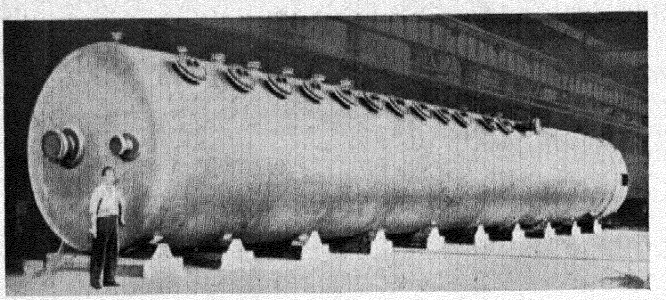


FIG. 90.—Welded Bubble Tower.

[*See page* 210.

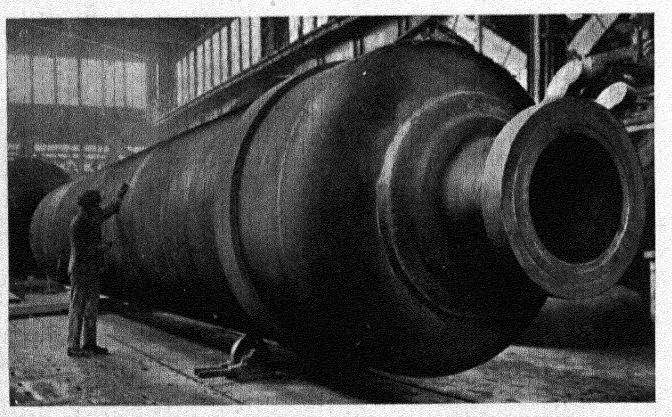


FIG. 91.—Welded vessel by Fr. Krupp.

[*See page* 210.

large number of electrically welded pressure vessels to the requirements of the A.S.M.E. Code, Class 1. A large reaction vessel for the oil industry fabricated by Blaw Knox is seen in Fig. 92. It is 50 ft. long, 10 ft. inside diameter and 2½ ins. wall thickness, and was made from high-tensile steel for a working temperature of 900° F. The test pressure was 1020 lbs. per sq. in.

In accordance with good modern practice, all Blaw Knox welded vessels made from low-carbon steel are annealed at 1400° F., and Fig. 93 shows the furnace used for this purpose.

(5) Acetylene Welding.

Compared with even a few years ago, the standard of oxy-acetylene welding, both in cost and quality, shows remarkable progress. The methods of making oxy-acetylene welds can be classified under the following headings :—

(1) Leftward welding.
(2) Rightward welding.
(3) Upward vertical welding (double reinforcement)—
Method *A* : welding from one side only.
Method *B* : welding simultaneously from both sides.

For a description of leftward and rightward welding, the reader is referred to Chapter I, page 6.

Upward Vertical Welding, Method "A." (Oxy-Acetylene Process.)

Direction of Welding.—The welding rod, the flame and the seam are in the same vertical plane. The sheets to be joined are arranged in a vertical position, the weld being made in a vertical position.

Direction and Position of the Flame.—The tip of the blowpipe, and consequently the flame, is inclined at an angle of 30° to the horizontal. The distance of the tip of the luminous part of the flame from the metal should be about $\frac{1}{16}$ in.

Direction and Position of the Welding Rod.—The welding rod makes an angle of 20° with the horizontal, in a direction opposite to that of the tip of the blowpipe. The end of the rod is held in the molten metal and just within the edges to be joined.

Size of the Welding Rod.—The diameter should be based upon the thickness of the sheet or plate and should be equal to one-half the thickness of the material to be welded.

Movement of the Flame.—After forming a small hole by melting the two edges—the hole being maintained during the welding of the seam—only a steady upward movement in the direction of the seam is necessary.

Movement of the Welding Rod.—The welding rod is drawn backward and forward in the molten metal.

As compared with the methods of rightward and leftward welding, it ensures complete control of the double reinforcement, as in rightward

welding, but does not give the same reducing flame protection on the reverse side of the seam. It is therefore not so well adapted for metals which oxidise readily at a red heat. The power of the blowpipe being less, the speed of welding is consequently less, and the cost of welding slightly higher. The advantages include the decreased importance of the gap between the edges and the small demands made upon the concentration of the welder. Penetration is much more certain than with leftward welding.

Upward Vertical Welding, Method "B."

Note.—This method requires the services of two welders, welding simultaneously on either side of the seam.

Direction of Welding.—The welding rod, the flame and the seam are in the same vertical plane. The plates to be joined are arranged in a vertical position, the welds being made in an upward direction.

Direction and Position of the Flames.—The tip of each blowpipe, and consequently the flame, is inclined at an angle of 30° to the horizontal. The distance of the tip of the white cone of the flame from the metal should not exceed $\frac{1}{16}$ in.

Direction and Position of the Welding Rods.—Each welding rod makes an angle of 20° with the horizontal, and in a direction opposite to that of the tip of the blowpipe. The end of the welding rod is held in the molten metal, within the edges to be joined.

Size of the Welding Rods.—The diameter of the welding rods should be 10 gauge.

Movement of the Flames.—As soon as the first common pool of metal has been obtained, by each welder penetrating one-half of the plate at the same level, only a steady upward movement is necessary.

Movement of the Welding Rods.—A transverse or zigzag movement is given to the end of the rod in the molten metal.

The advantages of this method are:—

(1) Variations in the width of the gap between the edges do not seriously affect the results.
(2) The technique is rapidly acquired, and small demand is made on the concentration of the welders.
(3) First-class results are continuously obtained.
(4) Distortion is reduced to a minimum owing to the constant cross-section of the welded zone.
(5) Improved economy due to the low consumption of gases as a result of the better utilisation of the available heat.
(6) Within the recommended range of thicknesses no chamfering of the edges is necessary.

The soundness and quality of the welds obtained by this method make it particularly valuable where the parts have to support considerable stress, as in the case of welded pressure vessels, containers, tanks,

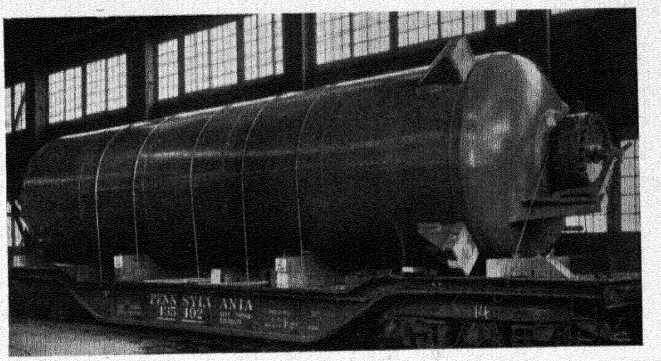


FIG. 92.—Large welded vessel for oil industry by Blaw Knox & Co., Ltd.

[*See page* 211.

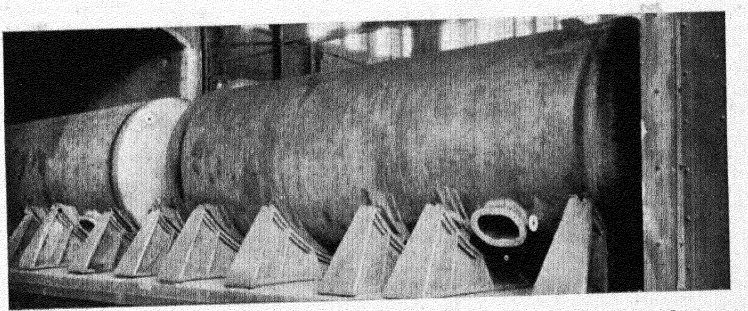


FIG. 93.—Welded vessels by Blaw Knox being put into annealing furnace.

[*See page* 211.

[*To face page* 212.

etc., where the two sides are accessible. The protecting effect of the reducing-zone of the flame is obtained, an advantage not secured by leftward or upward vertical welding, method " A."

Design of Welded Pressure Vessels.

The design of welded pressure vessels was recently fully discussed by Dorey (*Proc. Inst. C.E.*, 1937, **5**, 621), and the following notes on this subject are abstracted from this paper.

Design.

There are four types of fusion butt-welded joints suitable for pressure vessels :—

(*a*) Single-V butt-weld.
(*b*) Double-V butt-weld.
(*c*) Single-U butt-weld.
(*d*) Double-U butt-weld.

These types are shown in Fig. 94 and, whilst there are a number of variations depending upon angle of V and on whether the plate edges are fully or only partially chamfered, the main point to note is that in all cases the weld is made from both sides of the plate in order to ensure full penetration of the weld-metal.

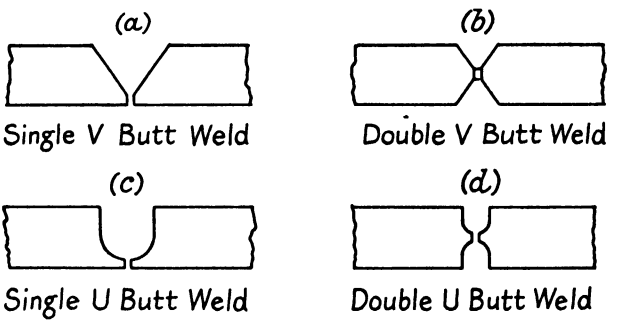


FIG. 94.

Before the precise dimensions of a joint can be determined, it is necessary to take into account the shrinkage characteristics of the weld-metal which is to be deposited. This is largely a question of experience and it is usual in V butt-welds to allow a gap at the root of the weld which varies between $\frac{1}{16}$ and $\frac{5}{32}$ in., depending upon the plate-thickness. In the case of boiler-drums manufactured in Great Britain, however, the U-type of joint has been found to be the most suitable. The welding procedure adopted necessitates cutting out from the underside of the joint the whole of the first run of weld-metal deposited in the U. On account of this, and of the fact that only high-quality ductile weld-metal may be deposited, it is unusual to allow any definite shrinkage-

gap whatever, and the plates forming the joint are butted as closely as practicable. This form of joint is shown in Fig. 95. It has a number of practical advantages which include :—

(1) A uniform deposition of weld-metal in each layer.
(2) Straight runs are possible with a minimum amount of weaving.
(3) It is specially suitable for automatic welding.
(4) It facilitates X-ray examination, because the sides of the joint are practically in line with the direction of the rays.

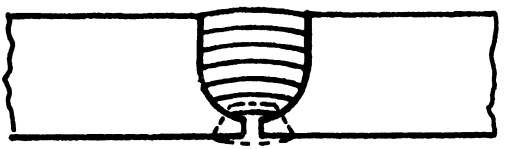


FIG. 95.

A further important point in regard to the design of welded joints is that of position. In any welded structure the aim should be to place the welded joints at positions free from stress-concentrations, and to ensure, so far as is possible, uniformity of the service stresses likely to be imposed on the weld. For example, where joints have to be made between plates of unequal thickness, such as between shell and tube plates, or between shell plate and dished end plates, it is necessary to reduce the thickness of the thick plate to that of the thin plate in the vicinity of the weld. Again, where a vessel is of such length that it has

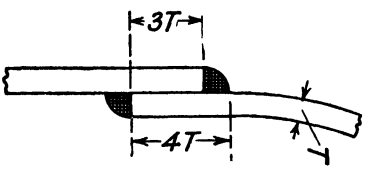


FIG. 96.

to be made up in several sections joined together by girth-seams, the longitudinal welded joints should be staggered so that no two are in a direct line.

With a view to avoiding undesirable stress-concentrations in the welded joints, holes for boiler mountings should be cut in the solid plate remote from the joints. It will be appreciated that this is a reasonable precaution, having regard for the necessity of allowing the welded joints to develop their maximum efficiency. The question of allowable working stresses in the welded joints of pressure vessels will be discussed later after consideration of other important factors involved in the assessment of joint-efficiency.

The lap-joint with inside and outside fillet-welds represents a form of joint which is sometimes used for the attachment of dished ends to cylindrical drums. Due to the force " couple " which exists when such

a joint is strained in tension, it cannot be recommended for high-class pressure vessels, and certainly should never be used for the longitudinal seams. In the design of a lap-joint for dished ends there are two important factors :—

(1) There must be sufficient overlap in order to obtain a reasonable flow of stress-lines.

(2) The outside fillet-weld must be clear of the knuckle of the dished-end flange.

Appropriate proportions for such a joint are indicated in Fig. 96.

Workmanship in Welding of Pressure Vessels.

With welded joints the allowable efficiency or ratio of joint-strength to the strength of the solid plate must depend upon a reasonably good standard of workmanship, since there can be no doubt that the quality of a welded joint is more easily affected by human inconsistencies than, say, a riveted joint.

Defects which might be due to faulty workmanship are as follows :—

(1) Imperfect fusion with parent-plate.

(2) Slag inclusions.

(3) Gas pockets.

(4) Contamination of weld-metal.

(5) Overheating of weld-metal or parent-plate.

Items (1), (2) and (3) and to some extent (4) will be detected by X-ray examination which must, in consequence, play an important part in the assessment of joint-efficiency (see page 223). Item (4) indicates defects due to large fluctuations in arc-length, improper manipulation of electrodes, or, in the case of oxy-acetylene welding, an improper admixture of the gases in the flame. Under a careful system of supervision it is unlikely that these defects will be extensive throughout a welded seam, and the total effect of such local contamination (local not only in relation to the length of the seam but also in relation to the depth) need not be regarded with undue alarm. With regard to (5), serious overheating (that is to say, overheating which cannot be rectified by subsequent heat treatment) is unusual in the case of electric arc welding as carried out in high-class welding shops, because the factors of current values and electrode fluidity should always be subject to special control. A possible cause of overheating, however, would be the maintenance of the arc in one position for too long a period. Fortunately, the defect would be readily revealed by visual inspection, due to the fact that it would be accompanied by serious undercutting at that particular position.

The purport of the foregoing remarks on workmanship is to show that this factor can without difficulty be accounted for in assessing the joint-efficiency, by providing—

(1) adequate supervision of the welding work,

(2) careful inspection of each run of weld-metal,

(3) X-ray examination of the finished joint.

It is the practice with reputable firms in Great Britain for an experienced supervisor to be responsible for the detailed inspection of each run of weld-metal as deposited in the welded joints of important pressure vessels. His duties also include the supervision of the arrangement of the vessel for welding, and the control of the current values. Such close supervision must be regarded as an essential factor in fusion-welding, as it is only by means of this supervision that the reliability of workmanship can be accepted as equivalent to that involved in high-class riveting for boiler construction.

Material for Welded Pressure Vessels.

In Great Britain, for steel pressure vessels the material usually specified is mild steel made by the acid or basic open-hearth process. The ultimate tensile strength of the plates lies between the limits of 26 and 30 tons per sq. in., or between 28 and 32 tons per sq. in., depending upon the tensile range specified. The minimum elongation required on a gauge-length of 8 ins. is 23 per cent. for the 26–30 ton steel and 20 per cent. in the case of 28 32 ton steel. In certain cases the plates are normalised after rolling, and it is good practice to anneal (stress-relieve) the plates after bending them to the required shape.

The analysis of such plates will vary slightly, but in the main will comprise the following :—

Carbon	from 0·15 to 0·25 per cent.
Silicon	„ 0·05 „ 0·20 „
Manganese	„ 0·40 „ 0·60 „
Sulphur	0·03 per cent.
Phosphorus	0·05 „

Material conforming to this analysis, using the upper limits for carbon and manganese and the lower limit for silicon, should yield the following test-results in the as-rolled condition :—

Limit of proportionality	11·5 tons/sq. in.
Yield point	15·5 „ „
Ultimate tensile strength	29 „ „
Elongation	35 per cent. on 4 diameters
Brinell hardness number	128
Endurance limit (direct stress)	± 12·4 tons/sq. in.

Lower-tensile steel plates would be accompanied by lower carbon and manganese contents, but the range of silicon indicated in the above analysis permits the use of steel in either the fully " killed " or semi-" killed " condition.

It has long been the practice in riveted-boiler construction to use steel which may be said to be fully " killed," and which in consequence possesses a silicon content of about 0·2 per cent. For the purposes of welding, however, opinion is turning in favour of low-silicon steel.

The requirements of other authorities in regard to plate-material for welding are as follows :—

United States.—The regulations here are based on the requirements of the Power Boiler Construction Code of the American Society of Mechanical Engineers. These requirements permit a range of steel for welding purposes ; the maximum allowable carbon content for steel considered to be of weldable quality is 0·35 per cent. (see Table 33).

Germany.—In Germany regulations are in force in respect of forge welding of boiler-drums, but in general, fusion welding is only permitted in cases where the welded seam is covered by butt-straps. It is the practice, however, to give special permission, by means of Ministerial Decrees, to certain firms to enable them to manufacture fusion-welded boiler-drums without straps. The existing regulations are now being revised and a draft of new regulations has recently been submitted by the Committee appointed for that purpose.

The analysis of plate material most commonly used in Germany for welding purposes is :—

Carbon	from 0·1 to 0·3 per cent.
Manganese	0·5 per cent. (max.)
Phosphorus	0·05 „ „ „
Sulphur	0·05 „ „ „
Silicon	up to 0·25 per cent.

Steel associated with this analysis is usually supplied in two ranges :—

(i) From 34 to 41 kgs. per sq. mm., with an elongation of from 28 to 25 per cent. on 200 mm., and a reduction of area of from 80 to 70 per cent.

(ii) From 41 to 48 kgs. per sq. mm., with an elongation of from 25 to 20 per cent. on 200 mm., and a reduction of area of from 70 to 60 per cent.

Until recently steel of 48 kgs. per sq. mm. was considered to be the limit for good weldability.

Whilst the existing German regulations do not include any stipulations in regard to impact-testing of boiler-plate, the German Steam Boiler Committee have given considerable thought to the subject, and it is of interest to note that a Charpy test value of 10 metre-kgs. per sq. cm. is regarded as appropriate for plate thicknesses up to 15 mm. and 8 metre-kgs. per sq. cm. for plate thicknesses above 15 mm. These values are quoted in connection with plate material of the 34–41 kgs. per sq. mm. quality, but in view of the well-known lack of consistency in impact-test results on rolled-steel plates the figures should not be regarded as a final criterion.

Recent progress in Germany has, however, made it possible to adopt welding also for steels of higher tensile strength, and for slightly alloyed steels. These steels include the above-mentioned qualities of mild steel

with the addition of 0·5 per cent. of molybdenum, the steel having a tensile strength of from 35 to 50 kgs. per sq. mm. ; ordinary mild steel containing 0·25 per cent. of molybdenum and 0·25 per cent. of copper, with a tensile strength of from 41 to 53 kgs. per sq. mm. ; a special non-ageing carbon steel with a tensile strength of from 47 to 56 kgs. per sq. mm. ; and this steel with the addition of 0·25 per cent. of molybdenum and 0·25 per cent. of copper. The above-mentioned steels are approved for electric-arc fusion welding, while in the case of water-gas welding, approval has been given for the use of a mild steel containing 0·25 per cent. of molybdenum and 0·25 per cent. of copper, with a tensile strength of from 44 to 56 kgs. per sq. mm., and for a steel having reduced ageing properties and a tensile strength of from 44 to 53 kgs. per sq. mm.

Switzerland.—In Switzerland the regulations governing the construction of welded boiler-drums are issued by the Swiss Association of Owners of Steam Boilers (Schweizerischer Verein von Dampfkessel-Besitzern). These regulations, promulgated in January 1932, specify two qualities of mild-steel plate, and whilst both qualities may be used for welding, Quality I is recommended by the Association for that purpose.

Quality I.

Ultimate tensile strength . . . 35–44 kgs./sq. mm.
Strength to be used in design . . 38 ,,

Quality II.

Ultimate tensile strength . . . 41–50 kgs./sq. mm.
Strength to be used in design . . 42 ,,
Yield-point for both qualities, not less than 0·55 of the ultimate tensile strength.

The table gives the figures for elongation corresponding to the ranges of tensile strength covered by the two qualities of plate material.

	Quality I.	Quality II.
Ultimate tensile strength (kgs./sq. mm.) . . .	35–38	41–44
	38–41	44–47
	41–44	47–50
Elongation on $10d$ or $11{\cdot}3\sqrt{A}$ (per cent.) . . .	30–28	26–24
	28–26	24–23
	26–24	23–22

Note.—A deviation not exceeding 10 per cent. is permissible in respect of these elongation figures. d denotes diameter of round specimen. A denotes cross-sectional area of rectangular specimen.

No specified chemical analysis.

Sweden.—In Sweden, whilst considerable development has taken place in regard to the welding of structures and unfired pressure vessels, the welding of boiler-drums is not yet an accepted practice. No detailed regulations have been issued in respect of welded pressure vessels, but in general it can be said that the plate-material used for water-gas welding has a minimum tensile strength of 38 kgs. per sq. mm. and a carbon content of from 0·12 to 0·15 per cent. The material is of the low-silicon (semi-" killed ") type. For fusion welding, higher tensile strength is generally used, the material having a range of from 44 to 55 kgs. per sq. mm. and a carbon content of from 0·16 to 0·20 per cent.

Italy.—In Italy there are no detailed regulations except for a Ministerial Decree which deals broadly with the application of welding to pressure vessels, and which merely states that the plates are to be of a quality suitable for welding.

It is, perhaps, remarkable that although evidence indicates that Continental engineers are fully abreast of welding developments, no authoritative attempt has been made to establish a construction code governing the details of welding as applied to pressure vessels.

Even to-day the only authority to issue such a code in Europe is Lloyd's Register of Shipping, which, in July 1934, published " Tentative Requirements for Fusion Welded Pressure Vessels intended for Land Purposes." It is anticipated, however, that the new German Regulations already in draft form will be published in the near future.

Certain European authorities contemplate the acceptance of welded pressure vessels in their official regulations in that they do not prohibit them. Others, such as the Swiss Association of Owners of Steam Boilers, go so far as to legislate for the design of welded pressure vessels, leaving the details of construction and testing to the discretion of the expert inspectors. In other cases, for example in Czechoslovakia, construction is generally carried out in accordance with the requirements of the Boiler Construction Code of the American Society of Mechanical Engineers.

In France also, specifications are at present in preparation, and the material considered suitable * conforms to the following analysis :—

Carbon	from 0·05 to 0·15 per cent.
Manganese	„ 0·3 „ 0·6 „ „
Silicon	trace
Sulphur	less than 0·03 per cent.
Phosphorus	„ „ 0·03 „ „
Ultimate tensile strength	38 kgs./sq. mm. (± 3)
Minimum elongation	22 per cent. on 200 mm.

* M. R. Meslier, *Construction and Survey of Welded Vessels intended for Compressed, Liquefied or Dissolved Gas*, XI, Congrès de l'Acétylène et de la Soudure Autogène, Rome, June 1934.

TABLE

AMERICAN SOCIETY OF MECHANICAL ENGINEERS :

Specification.	Quality.	Grade.	Chemical Analysis. Carbon (per cent.). For Plate Thickness of ¾ in. or under.	Carbon (per cent.). For Plate Thickness over ¾ in.	Manganese (per cent.).	Phosphorus (per cent.). Acid.	Phosphorus (per cent.). Basic.
S.1	Flange	—	—	—	0·3 to 0·6	0·05 max.	0·04 max.
	Firebox	—	0·25 max.	0·30 max.	0·3 to 0·6*	0·04 max.	0·035 max.
S.2	Flange	Grade A	0·15 max.	0·17 max.	0·35 to 0·60	0·06 max.	0·04 max.
	Firebox	Grade A	0·15 max.	0·17 max.	0·35 to 0·60	0·04 max.	0·035 max.
	Flange	Grade B	0·20 max.	0·22 max.	0·35 to 0·60	0·06 max.	0·04 max.
	Firebox	Grade B	0·20 max.	0·22 max.	0·35 to 0·60	0·04 max.	0·035 max.
S.4	—	Class 1	0·35 max.	0·35 max.	0·40 to 0·70	0·05 max.	0·035 max.
	—	Class 2	—	—	—	—	—
S.26	Flange	—	0·32 max.	0·35 max.	0·90 max.	0·04 max.	0·04 max.
	Firebox	—	0·32 max.	0·35 max.	0·90 max.	0·035 max.	0·035 max.
S.27	—	Grade A	0·35 max.	0·50 to 0·90	0·04 max.	—	0·035 max.
		Grade B					

* 0·3 to 0·5 for plate thickness of ¾ in. or under.

33.

POWER BOILER CONSTRUCTION CODE.

Tensile Properties.						
Sulphur (per cent.).	Silicon (per cent.).	Yield Point (lbs. per sq. in.).	Ultimate Tensile Strength (lbs. per sq. in.).	Elongation on 8 ins. (per cent.).	Reduction of Area (per cent.)	Remarks.
0·05 max.	—	$\frac{\text{U.T.S.}}{2}$	55,000 to 65,000	$\frac{1{,}500{,}000}{\text{U.T.S.}}$	—	—
0·04 max.	—	,,	55,000 to 65,000	$\frac{1{,}550{,}000}{\text{U.T.S.}}$	—	—
0·05 max.	—	,,	45,000	$\frac{1{,}500{,}000}{\text{U.T.S.}}$	—	—
0·04 max.	—	,,	45,000	$\frac{1{,}650{,}000}{\text{U.T.S.}}$	—	—
0·05 max.	—	,,	50,000	$\frac{1{,}500{,}000}{\text{U.T.S.}}$	—	—
0·04 max.	—	,,	50,000	$\frac{1{,}650{,}000}{\text{U.T.S.}}$	—	—
0·05 max.	—	,,	60,000	26 on 2 ins.	42	—
—	—	—	—	—	—	Not permitted for welding
0·05 max.	0·25 max.	$\frac{\text{U.T.S.}}{2}$	70,000 to 82,000	$\frac{1{,}600{,}000}{\text{U.T.S.}}$	—	—
0·04 max.	0·25 max.	,,	70,000 to 82,000	$\frac{1{,}600{,}000}{\text{U.T.S.}}$	—	—
0·04	0·25	,,	65,000 to 77,000	$\frac{1{,}750{,}000}{\text{U.T.S.}}$ on 2 ins.	—	—
max.	max.	,,	70,000 to 82,000	$\frac{1{,}750{,}000}{\text{U.T.S.}}$ on 2 ins.	—	—

Rules for Design of Welded Joints of Pressure Vessels.

Joint Efficiencies.—In considering the question " What is a reasonable figure to assign for welded joint-efficiency ? " it would be well to take note of the joint-efficiencies and factors of safety allowed by those authorities which have legislated for welded joints in pressure vessels.

Great Britain.— The only published rules governing design of Class I fusion-welded pressure vessels are Lloyd's Register's " Tentative Requirements for Fusion Welded Pressure Vessels intended for Land Purposes." These are at present under revision, but in the meantime may be regarded as the accepted standard for both land and marine work in Great Britain. The formula for the allowable working pressure in the shell is $\frac{25{\cdot}5 \times S \times (t - 2)}{D}$ = working pressure in lbs. per sq. in.

where S = the ultimate tensile strength of the plate in tons/sq. in.
t = the plate thickness in 32nds of an in.
D = the internal diameter of the shell in ins.

The constant (25·5) represents a joint-efficiency of 82 per cent., combined with a factor of safety of $4\frac{1}{2}$, and this is equivalent to 91 per cent. with a factor of safety of 5.

As the result of the experience obtained since the Tentative Requirements were first issued, it is now considered that a joint-efficiency higher than 82 per cent. could be allowed for Class I pressure vessels, and especially for those vessels operating under reasonably static conditions of temperature and pressure. Under the revised Requirements, joint-efficiencies up to 90 per cent. are permissible.

United States of America.—The Power Boiler Construction Code of the American Society of Mechanical Engineers permits a joint-efficiency of 90 per cent., combined with a factor of safety of 5. The formula for working pressure in lbs. per sq. in. is

$$\frac{TS \times t \times E}{FS \times R}$$

where TS = the ultimate tensile strength of the plate in lbs./sq. in.
t = the minimum thickness of the shell-plate in ins.
E = the joint efficiency = 90 per cent.
FS = the factor of safety = 5.
R = the internal radius of the shell in ins. If the shell thickness is greater than 10 per cent. of the radius, the outer radius is to be used for R.

For temperatures above 700° F., the working stresses given in Table 34 are specified in this Code in place of $\frac{TS}{FS}$ in the above formula.

For Class 2 unfired pressure vessels the A.S.M.E. code specifies a joint-efficiency of 80 per cent. to be used in the above formula. The

same joint-efficiencies are permissible by the Rules and Regulations of the Bureau of Navigation and Steamboat Inspection, U.S. Department of Commerce, but in this case the allowable factor of safety is $4\frac{1}{2}$ instead of 5.

The specification governing the welding of pressure vessels issued by the Bureau of Engineering of the U.S. Navy, states that the joint-efficiency of welded joints under the cognizance of this Bureau shall be taken as 80 per cent. of the strength of the parent-metal, except where the quality of the weld can be and is fully explored by radiographic or exographic photography, or other method satisfactory to the Bureau, in which case a joint-efficiency of 90 per cent. will be acceptable.

TABLE 34.

Maximum Temperature (° F.).	Minimum Specified Tensile Strength of Plate Material (lbs. per sq. in.).				
	45,000	50,000	55,000	60,000	75,000
	Working Stresses (lbs. per sq. in.).				
700 . .	9,000	10,000	11,000	12,000	15,000
750 . .	8,220	9,110	10,000	11,200	13,000
800 . .	6,550	7,330	8,000	9,000	10,200
850 . .	5,440	6,050	6,750	7,400	8,300
900 . .	4,330	4,830	5,300	5,600	6,000
950 . .	3,200	3,600	4,000	4,000	4,000

The joint "Code for the Design, Construction, Inspection, and Repair of Unfired Pressure Vessels for Petroleum Liquids and Gases," issued by the American Petroleum Institute in conjunction with the American Society of Mechanical Engineers, gives the following formula for allowable working pressure in the shell :—

$$\text{Working pressure in lbs. per sq. in.} = \frac{2SE(t - c)}{D_m}$$

where S = the maximum allowable working stress in lbs./sq. in. corresponding to the operating temperature.

E = the joint-efficiency.

t = the shell-thickness in ins.

c = the corrosion allowance in ins.

D_m = mean diameter in ins. before the corrosion allowance is added.

The maximum joint-efficiencies allowed by this Code for various types of welded joints are given in Table 35.

TABLE 35.

Type of Joint.	Limitations.	Joint-efficiency (per cent.).
Double-welded butt-joint	None.	80
Single-welded butt-joint with backing-up strip	Joints not over 1¼ in. thick.	80
Single-welded butt-joint without backing-up strip	Joints not over ⅝ in. thick.	70
Double full-fillet lap-joint	Circumferential joints only, not over ⅝ in. thick.	65
Single full-fillet lap-joints with plug welds	Circumferential joints only, not over ⅝ in. thick.	65
Single full-fillet lap-joints without plugs	Attaching dished ends convex to pressure, not over ⅝ in. thick.	55

These figures may be modified, however, by multiplying by certain factors as follows :—

(1) *Construction Factors.*

Where shell plates are made of firebox-grade steel to certain specifications of the American Society for Testing Materials, factor . . . 1·0
Where shell plates are made of flange-grade steel to certain specifications of the A.S.T.M., factor . . . . . 0·97
For certain other qualities of steel, factor . . . . . 0·92

(2) *X-ray Factor.*

When all the main welded joints of a vessel are :—
Radiographed, factor . . . . . 1·12
Not radiographed, factor . . . . . 1·0

(3) *Heat-Treatment Factor.*

When a joint has been stress-relieved, factor . . . . . 1·06
When a joint has not been stress-relieved, factor . . . . 1·0

It will be noted that for a double-welded butt-joint, which would be used for a Class 1 pressure vessel, the highest joint-efficiency allowed under this Code would be : —

$$80 \times 1{\cdot}0 \times 1{\cdot}12 \times 1{\cdot}06 = 95 \text{ per cent.}$$

Switzerland.—The regulations of the Swiss Association of Owners of Steam Boilers (Schweizerischer Verein von DampfkesselBesitzern) specify the following formula for joints in tension :—

$$S = \frac{D.P.X.}{200\ K.Z.} + 1,$$

where P = the working pressure in kgs./sq. cm.
D = the internal diameter in mm.
S = the minimum shell thickness in mm.
K = the design strength of the plate material in kgs./sq. mm.
X = the factor of safety.
Z = the joint-efficiency.

The following factors of safety and joint-efficiencies are specified :-

Coke Fire Welding (only acceptable in special cases).

Factor of safety	4·5
Joint-efficiency, annealed	55 per cent.
Joint-efficiency, not annealed	40 „ „

Water-gas Welding (must be annealed).

Factor of safety	4·5
Joint-efficiency, manual welding	65 per cent.
Joint-efficiency, machine welding	70 „ „
Joint-efficiency, in special circumstances	85 „ „

Oxy-acetylene Welding.

Factor of safety	4·5
Joint-efficiency for joints welded from one side only, not annealed	50 per cent.
Joint-efficiency for joints welded from one side only, and annealed with blowpipe	55 „ „
Joint-efficiency for joints welded from both sides not annealed	70 „ „
Joint-efficiency for joints welded from both sides and annealed in furnace	80 „ „

Electric Metallic Arc Welding.

Factor of safety	4·5
Joint-efficiency for joints welded from one side only	50 per cent.
Joint-efficiency for joints welded from both sides	70 „ „

Germany.—The present practice in Germany in respect of welded boiler-drums is to allow a joint-efficiency of 90 per cent. to certain firms by means of Special Ministerial Decrees, as previously explained. From the draft of the new Regulations it appears that it is proposed to allow joint-efficiencies of 70 per cent. for all kinds of welding, but special approval, which includes a comprehensive series of tests as previously stated, will be required before efficiencies up to 90 per cent. will be allowed.

Schuster (*Proc. Inst. Mech. Eng.*, 1930, 372) suggested Provisional Rules for Fusion-Welded Non-Fired Pressure Vessels, and gave the following recommendations about the method of fabricating pressure vessels :—

(1) *Scope of Rules.*—The rules apply to vessels containing air or

non-corrosive gas at a temperature not exceeding 600° F., and more especially when the diameter does not exceed 36 ins. For vessels with a diameter not exceeding 20 ins., the rules do not apply when the working pressure is 30 lbs. per sq. in. or less.

(2) *Method of Welding.*—The rules are applicable to vessels welded by the metallic arc process with a flux-coated electrode or by the oxy-acetylene process.

Note 1.—The rule excludes carbon-arc-welding, but in special instances, where the design is approved, the carbon-arc process is permissible for the welding of flanges to tubes not less than $\frac{5}{16}$ in. thick, and for the welding of dished ends to shell plates that are secured independently of the weld, and that are not less than $\frac{3}{4}$ in. thick.

Note 2.—It is recommended, especially when the welding has been carried out by the carbon-arc or acetylene process, that fusion-welded parts should be normalised in a muffle furnace. The temperature should be maintained for a quarter of an hour after the article has been heated uniformly.

As an alternative, though less effective, where serious damage from scaling or warping would result if it were normalised, the article should be heated uniformly to a temperature of 650° C., and then allowed to cool.

(3) *Strength of Joints.*—The rated strength of a welded joint shall at no time exceed half the strength determined by tests on reasonably well-made joints, made to similar form and subjected to similar stresses.

(4) *Material.*—The plate shall be of boiler-quality mild steel with a nominal breaking strength of 26 tons per sq. in. The strength shall lie between the limits of 24 to 28 tons per sq. in., but it shall be assumed that the strength of the plate when welded does not exceed 24 tons per sq. in.

(5) *Plate Thickness.*—The plate of a welded vessel exceeding 12 ins. in diameter shall not be less than $\frac{3}{16}$ in. thick.

(6) *Factor of Safety.*—The minimum factor of safety allowable on the rated strength of a welded joint shall be 4.

(7) *Hydrostatic Test.*—(*a*) The vessel shall be subjected to a hydrostatic test at not less than twice the working pressure, during which it shall be subjected to a hammer test ; the pressure shall then be reduced by more than 50 per cent. of its value, after which it shall be again raised to the original value for 3 minutes.

(*b*) The hammer test shall consist of the plate on both sides of all welds being struck sharp vibratory blows with a hammer not less than 2 lbs. in weight, the blows being struck 2 to 3 ins. apart and close up to the seam. The blows shall be applied as rapidly and heavily as possible, consistent with the metal not being indented or distorted.

(*c*) When the factor of safety of the vessel exceeds 4, the test pressure shall be 50 per cent. of the bursting pressure, calculated on the rated strength of the welded joints.

(8) *Stresses Imparted by Flexible Ends.*—Where a joint or a portion of a joint, circular or longitudinal, is subjected to a bending action

owing to the flexibility of an end, it shall be deemed that the strength of the joint is reduced by 10 per cent.

This shall not apply to a longitudinal seam of which the ends are reinforced in an approved manner to resist bending stresses.

(9) *Lap-Welded Joints.*—(*a*) For a longitudinal seam, a lap weld with a single fillet shall at no time be permitted, and a lap weld with a double fillet shall only be permissible when neither of the plates exceeds $\frac{3}{8}$ in. in thickness.

(*b*) For a circular seam or for affixing an end plate when the shell plate is not constricted, i.e. turned in over the flange of the end plate, a lap-welded joint with a single fillet shall only be permitted when the thickness of the shell plate does not exceed $\frac{1}{2}$ in.

(*c*) When a lap-welded joint has a double fillet, the width of the landing shall be $3t$ for a longitudinal joint, and not less than $3t$ for a circumferential joint, where t is the plate thickness, or with dissimilar plates the greater of the two thicknesses (see Fig. 97*k*).

(*d*) When a lap-welded joint has a double fillet the internal fillet shall be accessible for inspection. Where there is no ready means for inspection it shall be assumed that the fillet is non-existent, and accordingly for a circumferential seam the joint shall be rated as if it had a single fillet only and for a longitudinal seam it shall be prohibited.

(10) *Fillet Welds.*—(*a*) With a fillet of a lap-welded joint the surface of contact in tension shall extend over the full thickness t_1 of the plate. The surface of contact in shear shall have a width not less than t_1 and preferably not less than $1\frac{1}{4}t_1$ (see Fig. 97*a*).

(*b*) A fillet of a lap-welded joint shall by preference have a convex profile. At no time shall the thickness at the throat be less than 0·69 times the plate thickness t_1.

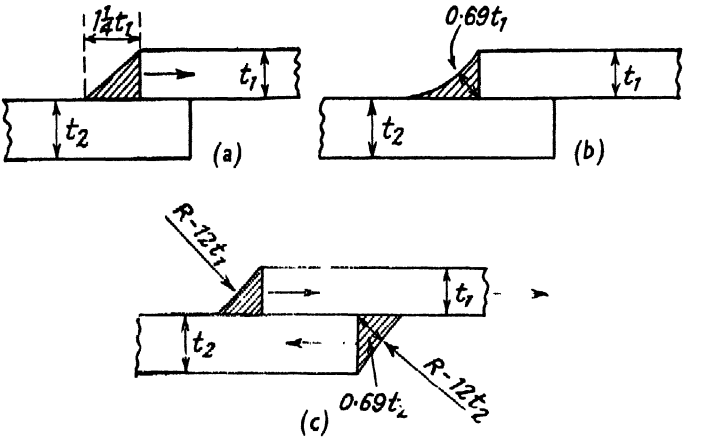
Note.—The throat thickness is defined as the minimum depth of the weld (see Fig. 97*b*). Where the two contact surfaces of a fillet are equal, the rule requires that the contour shall show no appreciable concavity; a minimum throat thickness of $0{\cdot}69t_1$ is equivalent to the radius of the fillet being not less than $12t_1$, which gives an approximately straight contour, the deviation from a straight line being only $0{\cdot}02t_1$ (see Fig. 97*c*).

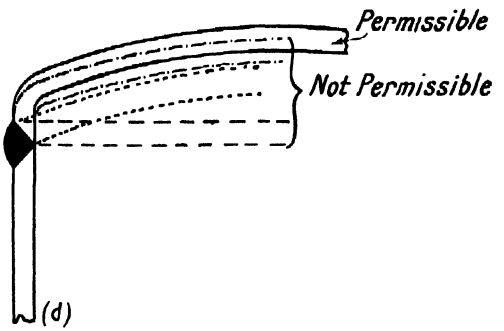
(*c*) With a fillet weld affixing a fitting to the wall of a vessel or a pipe, the throat shall have a minimum thickness of $0{\cdot}58h$, where h is the minimum height allowable for the surface of contact in shear.

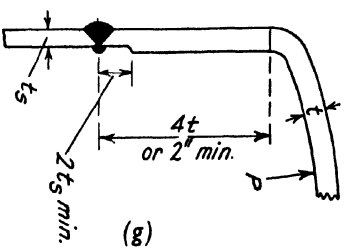
Note 1.—Where the two surfaces of contact of the fillet are equal, this throat thickness is attained by a fillet with a concave profile and a radius equal to $2h$, the deviation from a straight line being $0{\cdot}13t$.

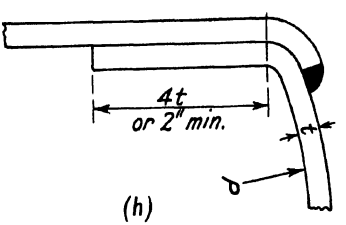
Note 2.—The value required for the dimension h depends on the details of the design and manufacture of the joint. In general the total height for a branch tube should equal $3t$, where t is the thickness of the branch tube.

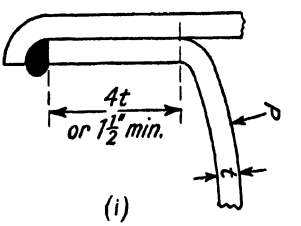
(11) *Butt-Welded Joints.*—(*a*) When the diameter of the vessel does not exceed 24 ins., the strength of a butt-joint with the plate welded at


$1\frac{1}{4}t_1$
t_1
t_2
(a)
$0{\cdot}69t_1$
t_1
t_2
(b)
$R=12t_1$
t_1
t_2
$0{\cdot}69t_2$
$R=12t_2$
(c)


Permissible
Not Permissible
(d)


s_t
$2t_s$ min.
4t
or 2" min.
t
D
(g)


4t
or 2" min.
t
D
(h)


4t
or 1½" min.
D
t
(i)

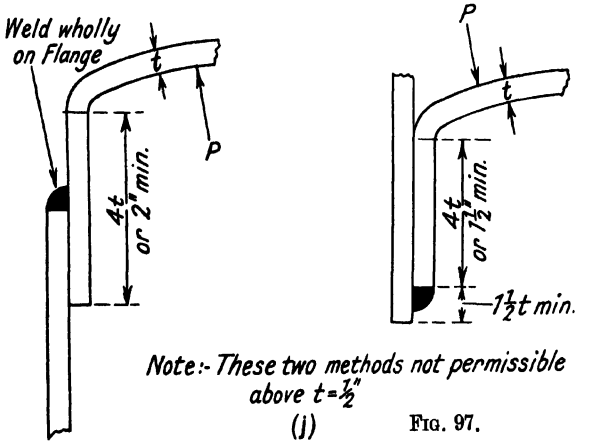

Weld wholly on Flange
t
P
4t
or 2" min.
(j)
P
t
4t
or 1½ min.
1½t min.
Note:- These two methods not permissible above t=½"
Weld wholly on Flange
t
P
4t
2" min.
3t
min.
(k)

FIG. 97.

only one side shall be deemed to be reduced to half the strength of a butt-joint with the plate welded at both sides. For larger diameters this form of construction shall at no time be permitted.

(*b*) When the inside surface of a butt-joint is not accessible for inspection, it shall be assumed that the plate is welded at one side only.

(*c*) The edges of a plate jointed by a butt-weld shall be bevelled, and the included angle of the weld-metal shall be not less than 90° for either a single or a double V weld.

Note.—It is recommended that the total depth of reinforcement at the two surfaces of the plate should be not less than 25 per cent. of the plate thickness.

(12) *Design and Attachment of Dished Ends.* —(*a*) A dished end plate shall have an inside radius not greater than the internal diameter of the shell. The thickness of metal shall be such that the working pressure or the allowable stress to comply with rule 13 is not exceeded, but in no instance shall it be less than the thickness of the shell, and for vessels exceeding 12 ins. in diameter the minimum thickness shall be $\frac{1}{4}$ in.

(*b*) When a dished end is flanged, the length of the flange shall be not less than $1\frac{1}{2}$ ins. for an end convex to the pressure, nor less than 2 ins. with the end concave. The minimum length of the flange shall at no time be less than four times the thickness of the plate. An increase above these specified minimum values is desirable (see Figs. 97*j* and *k*).

Note.—When a dished end is affixed by a lap-joint it is recommended that the end of the shell should be constricted, and that the degree of constriction be not less than that shown by Figs. 97*h* and 97*i*.

(*c*) An end plate shall at no time be fixed by means of a corner weld, and, where a flanged end plate is fixed by a butt-joint, the flange shall form a continuous line with the shell plate.

Note 1.—The term "corner weld" refers to any form of weld, where the flange forms an angle with the shell plate; this is illustrated by Fig. 97*d*. Any similar constructions without flanges, such as those shown by the drawings Fig. 98 are also prohibited.

Note 2.—Several other undesirable forms of end are constructed, e.g. those shown by Fig. 99. These are not permissible, nor is any form of flexible end, the breathing of which imposes a direct bending stress on the weld.

(*d*) An end plate with reversed curvature shall at no time be permitted.

(*e*) The inside radius at a knuckle shall be not less than four times the thickness of the end plate or not less than $1\frac{1}{2}$ ins., whichever is the greater.

(*f*) An end plate convex to the pressure shall be driven into the shell so that the end of the flange lies a distance not less than one and a half times its thickness within the shell.

(*g*) When a dished end of a thickness greater than that of the shell

is affixed by a butt-joint the end of the flange shall be reduced to the thickness of the shell for a length not less than twice its thickness (see Fig. 97*g*).

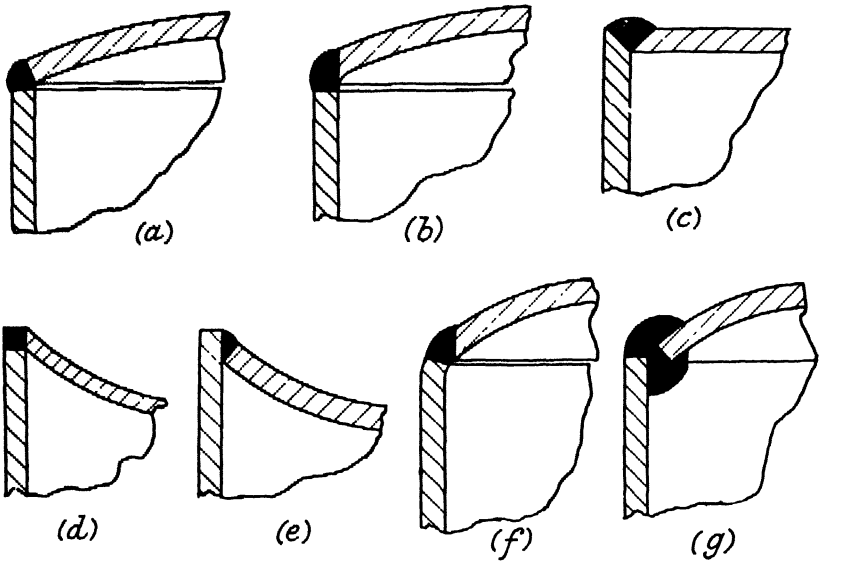


FIG. 98. Ends *not* permissible under heading of corner welds.

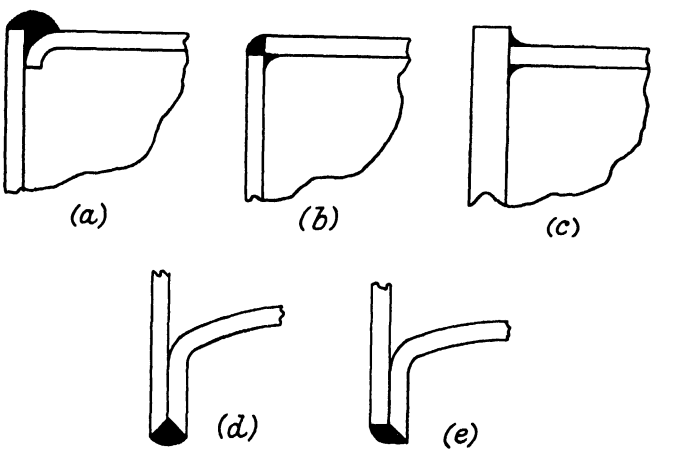


FIG. 99.—Ends not permissible.

(13) *Thickness of Dished Ends.*—(*a*) With an end concave to the pressure the working stress calculated by the formula $\frac{pr}{2t}$ shall be for mild steel of appropriate quality not more than 6000 lbs. per sq. in., irrespective of the general factor of safety adopted for the vessel.

(*b*) With an end convex to the pressure, welded to the shell, the

allowable pressure shall not be more than the bulging pressure p $\left(\text{calculated by Bach's formula } p = \frac{t}{r}\left[73958 - 3272\sqrt{\frac{r}{l}}\right]\right)$ divided by a nominal factor of safety against bulging that is 25 per cent. higher than the desired factor of safety, the value of which is named in the following table.

In the event of r/l having a value lower than that given in the last column of the table, the thickness of the end shall be such that the stress calculated by the formula $\frac{pr}{2l}$ shall be, in the case of mild steel of appropriate quality, not more than 5000 lbs. per sq. in. irrespective of the general factor of safety adopted for the vessel.

Designed Factor of Safety of Vessel.	Nominal Factor of Safety against Bulging to be used for a Welded Vessel with Bach's Formula.	Lowest Value of r/t with which the Working Pressure shall be Determined from Bach's Formula.
4·0	5·0	53·6
4·5	5·625	29·3
5·0	6·25	12·3

Note.—In this connection see also the Board of Trade Rules, A.S.M.E. rules, and also Hoehn's rules at the begining of this chapter.

Copper, Aluminium, etc., Steam-Pressure Vessels.

I am indebted to the National Boiler and General Insurance Co., Ltd., for the following notes on the design of copper and similar pressure vessels (taken from their book, "Steam Boiler Construction").

Copper Steam-Pressure Vessels.—The copper used in the construction of vessels should be in the hard condition, not annealed, and when forming a cylindrical shell subject to internal pressure, or when in tension not exposed to heating by furnace or flue gases, a maximum tensile strength of 5000 lbs. per sq. in. may be allowed. Superheated steam should not be used in vessels made of copper.

When copper is in the annealed condition, as a rule the maximum tensile stress should not exceed 3000 lbs. per sq. in.

The two most common forms of joint used in connection with copper plates are the brazed and the welded joint. Occasionally joints are clamped and brazed, riveted and brazed or riveted and soldered.

For the purpose of calculation the efficiency of an ordinary brazed or clamped and brazed joint should not be considered higher than equal to 50 per cent. of the plate strength.

The design of riveted joints should be carried out on the same lines as for steel plates with steel rivets, but in the design of the copper joint,

account requires to be taken of the effect on the design of the lower strength of copper.

Particularly, it is to be noted that the grip of the copper rivets holding the joint together will not be so great as in the case of steel rivets ; consequently, on these grounds, a closer pitch will be desirable than in the case of steel rivets. Also, the copper rivet being weaker than a steel rivet of the same size, it will be necessary in a given pitch for the copper rivet to be of somewhat larger diameter than a steel rivet would be for the same pitch. The effect of this will be to modify the percentage strength of joint which would otherwise be obtainable.

When used in the construction of vessels of small diameter, such as vacuum stills, and the inner cylindrical container of steam-jacketed pans, the calculated compression at the working pressure should not exceed that given in the table below for the appropriate length between points of substantial support.

Length in ins. between Points of Substantial Support.	*Permissible Compressive Stress in lbs. per sq. in.*
Not exceeding 6 ins.	4000
„ „ 10 „	3000
„ „ 14 „	2300
„ „ 18 „	1800
„ „ 20 „	1600
„ „ 22 „	1450
„ „ 24 „	1350

The thickness of any end plate is not to be less than the thickness of the shell. The radius of camber of end plates should not be greater than the diameter of the cylindrical part.

In calculating the working pressure on the concave side of dished end plates, the following formula is to be used, allowing a maximum calculated stress in tension (f) on the material of 4500 lbs. per sq. in.

$$P = \frac{f \times 2T}{R}, \quad . \quad . \quad . \quad . \quad (1)$$

where P = pressure in lbs./sq. in.
T = thickness of end in ins.
R = radius of camber in ins.

See also Hoehn's rules, page 184.

When the pressure is on the convex side with spherical or truly dished ends and the ratio of the radius R of the end to the thickness T does not exceed 115, a maximum allowable compression K_w of 3000 lbs. per sq. in. may be used, applying the following formula :—

$$P = \frac{K_w \times 2T}{R} \quad . \quad . \quad . \quad . \quad (2)$$

Where the ratio, radius R to thickness T, is greater than 115 the allowable compression is to be determined as follows :—

The calculated compression in lbs. per sq. in. at which bulging will commence was shown by Bach's experiments to be equal to K_b in equation (3).

$$K_b = 36268 - 1706\sqrt{\frac{R}{T}} \quad . \quad . \quad . \quad (3)$$

where R = radius of camber in ins.

T = thickness of copper in ins.

In designing new vessels the allowable compression at the working pressure should not exceed one-sixth of the calculated compression at which bulging will commence. Therefore

$$\text{Allowable compression } K_w = \tfrac{1}{6}\left(36268 - 1706\sqrt{\frac{R}{T}}\right)$$

$$= 6044 - 284\sqrt{\frac{R}{T}} \quad . \quad . \quad . \quad (4)$$

Let

P = designed working pressure.

Then by usual spherical formula :—

$$P = \frac{K_w \times 2T}{R} \quad . \quad . \quad . \quad . \quad (5)$$

Do not use compression higher than 3000 (see note below).

Note.—Maximum $K_w = 3000 = 6044 - 284\sqrt{\frac{R}{T}}$

$$3044 = 284\sqrt{\frac{R}{T}}$$

$$\frac{3044}{284} = \sqrt{\frac{R}{T}} = 10{\cdot}72$$

$$\frac{R}{T} = 115$$

that is, ($K_w = 3000$) may be used in equation $P = \frac{K_w \times 2T}{R}$ for cases where $\frac{R}{T}$ does not exceed 115.

When $\frac{R}{T}$ exceeds 115 use equation (4).

These are suitable allowances where the dished part starts from a good abutment. If, however, the form at the abutment is such as to reduce the power of resistance of the dished end, as at B, Fig. 100, then the allowable compression must be reduced.

Fig. 101 is an example of a pan designed on the foregoing lines.

Copper Steam-Jacketed Pans.—In the construction of these vessels the copper should be in the hard condition, either rolled or well hammered, not annealed.

The plates should be of spherical form. The form should be that of a part of one sphere. It should not be a combination of two curved surfaces of differing radii.

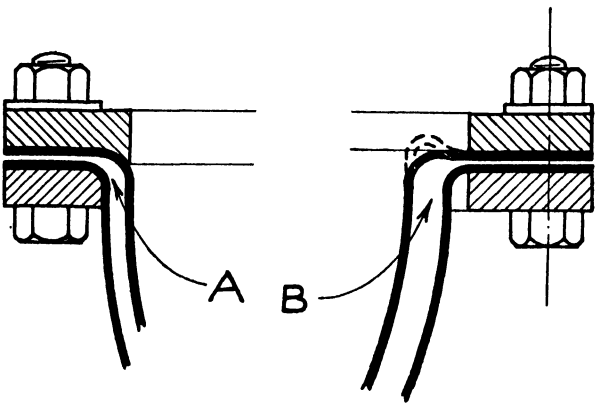


FIG. 100.

The inner and outer shells are connected at the upper part by a flanged and bolted joint. With copper pans the flanged joint is a comparatively flexible structure, and it is therefore important that in the

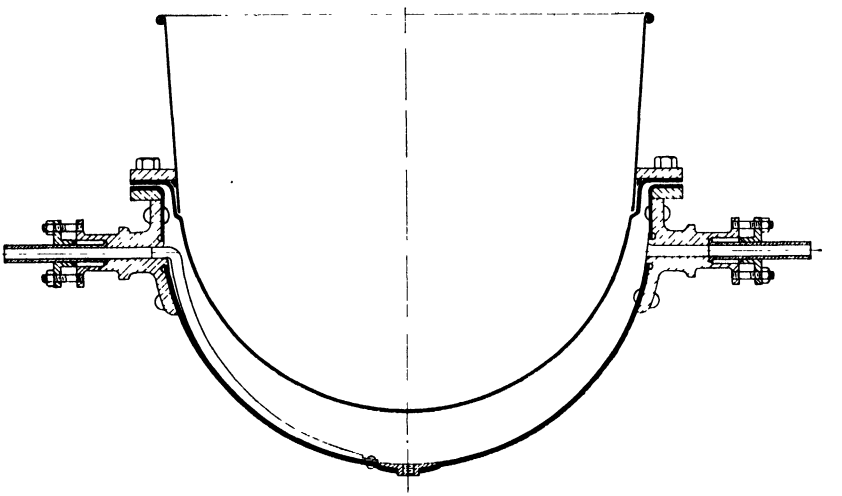


FIG. 101.—Copper-jacketed pan.

design of such connections strengthening rings should be fitted above and below the flange (see Fig. 100). Generally the minimum thickness of such rings should be $\frac{3}{4}$ in. for pans of small diameter.

Care is necessary to ensure that the abutment effectively supports the bend of the flange connecting to the spherical portion, and the spherical curve of the pan should come well up to the abutment as at A, Fig. 100, and not leave a wide section subject to bending as at B.

The lower ring should fit snugly into the radius of the flange of the jacket and the upper ring should be suitably formed to take the vertical thrust of the internal pan by giving effective support at the bend of the flange (see A, Fig. 100). If the support be insufficient, as at B, movement at the root of the flange and cracking may result or the pan may probably move upwards as at B.

Jacketed Cylinders.—The foregoing notes in relation to inner cylindrical shells exposed to external pressure may be applied to many types of vertical- and horizontal-jacketed vessels.

It has to be remembered that in all cases of cylinders and spheres subjected to external pressure, truth of form is of the first importance as regards resistance to collapse.

Aluminium Vessels.—Vessels used in the preparation of foodstuffs and similar articles, also in certain process plant, are sometimes made of aluminium.

Aluminium in sheet form is supplied either in " hard," " half-hard," or " soft " condition, and usually it will be satisfactory to allow a calculated tensile stress at normal atmospheric temperatures of 4000 lbs. per sq. in. for hard condition, 3000 lbs. per sq. in. for half-hard condition and 2000 lbs. per sq. in. for soft condition.

The stress allowable on cast aluminium depends on the purity of the material. According to the analysis of the material under consideration, a stress in tension of from 2000 to 4000 lbs. per sq. in. may be allowed.

Strength of Thin Shells subject to External Pressure.—The strength of thin shells subjected to external fluid pressure has been recently investigated by J. Gilson (*Engineering*, 1934, **138,** 432), and the conclusions drawn may be briefly summarised as follows :—

Let P_c = calculated collapsing pressure in lbs./sq. in.
D = outside diameter in ins.
L = length between flanges or stiffening rings.
t = wall thickness in ins.
E = modulus of elasticity in lb./sq. in.
f_c = compressive yield stress in lbs./sq. in.
K = constant depending upon the design of stiffening ring or end fastening and which varies from about 1·1 for very good rigid fastenings to 0·6 for poor fastenings. An average value of 1.0 should be taken for normal well-designed fastenings, and judgment should be used for intermediate values.

Cylindrical Shells.—For all practical purposes

$$P_c = \frac{KEt^{2.38}}{LD^{1.25}} \left(\text{within the limits } \frac{t}{D} = 0{\cdot}03 \text{ to } 0{\cdot}003 \right).$$

Spherical Shells.

$$P_c = \frac{k_2 fc}{\frac{R}{t} + \frac{fc}{k_3 E}\left(\frac{R}{t}\right)^3}$$

where R = radius of camber in ins.

k_2 k_3 are given in table below :—

Type of Pan.	k_2.	k_3.
One piece pressing truly spherical	1·5	35
Welded up from pressed segments	1·1	20
Welded up from hammered or beaten segments	0·75	12

For thin shallow pans where R is more than 0·5D the value of P_c as obtained from the previous formula should be multiplied by $8\sqrt{2\frac{R}{D}}$ for values of $\frac{R}{D}$ up to about 3. For more shallow pans the treatment should be as for flat plates, and they should be stayed.

For materials of the stainless steel, Monel metal, Inconel and similar classes, for working pressures of 5–100 lbs per sq. in. with a factor of safety of about 4·5, t can be roughly estimated from the formula :—

$$t = \sqrt{\frac{P_w \times R}{C}}$$

where P_w = working pressure lbs./sq. in.

C = 900 for pressed one-piece shells.
680 for welded shells, pressed segments.
500 for welded shells, beaten segments.

The Protection of Steam-Heated Pressure Vessels against Overpressure.

It is essential that steam-heated pressure vessels connected to steam boiler plant should be protected against dangerous overpressure if they are designed to work at a pressure lower than that of the boiler plant. This requirement is stressed in the recent Factories Act 1937, and may be illustrated by the following example :—

Assume that a reducing valve having an inlet bore of 1 in. diameter is supplied with steam at 120 lbs. pressure per sq. in. and is set to reduce the pressure in a low-pressure vessel to 10 lbs. per sq. in., and that no steam is being condensed in the vessel or discharged except through

the safety valves. Also assume that the reducing valve has become deranged and stuck fast in the full open position, thereby allowing high-pressure steam to enter the low-pressure main. The problem to be solved is what should be the safety-valve area under such conditions to ensure that the pressure in the low-pressure vessel is not increased above 10 lbs. per sq. in.

The problem can best be studied from the laws governing the flow of steam through orifices, the supply pipe being considered as an inlet orifice to the low-pressure vessel and the safety valves as outlet orifices therefrom.

The diagrammatic sketch in Fig. 102 shows such a hypothetical arrangement which, although not conforming to what is actually found in practice, will form a basis for considering the question. Here it is assumed that the steam inlet to the low-pressure vessel is an orifice

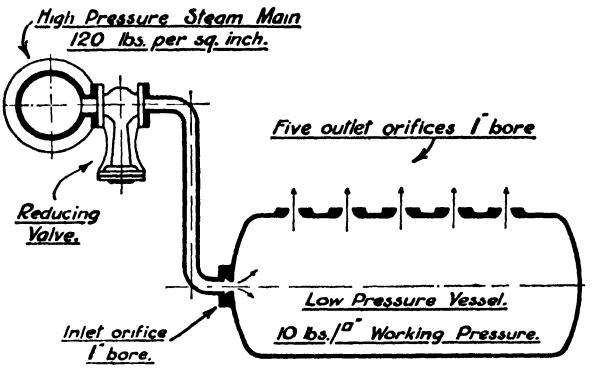


FIG. 102.

1 in. bore, and the outlets to atmosphere are a number of 1-in. bore orifices, and it is required to determine the relative areas of the inlet and discharge orifices.

The following expression for the discharge of dry steam through the respective orifices will apply to this case :—

$$W = 62 \times p\frac{31}{32} \times A \times C,$$

where W = weight of steam discharged in lbs./hr.
p = initial absolute pressure in lbs./sq. in.
A = area of orifice in sq. in.
C = discharge coefficient.

Using this equation for the inlet and outlet orifices, it will be found that the combined area of the outlet orifices will require to be practically five times the area of the inlet orifice.

The weight of steam discharged by the inlet and outlet orifices can

be determined approximately by the more simple form of Napier's expression, namely :—

$$W = 51 \times p \times A \times C.$$

The symbols used in this formula are the same as in the previous formula.

Notwithstanding, the above calculation shows that the combined area of the discharge orifices would require to be five times the area of the inlet orifice ; the number of safety valves of 1-in. bore to secure the same discharge to atmosphere as the orifices would require to be considerably more than five. It is well known that the net lip area past a normal safety valve and its seating is usually only a fraction of the area of the valve itself. Some registration authorities assess an ordinary spring-loaded safety valve as having an active lip area of only one-sixth of the actual area of the valve, and, on this basis, even neglecting the additional frictional losses through the valve passages, it would require 30 safety valves 1 in. in diameter in order to secure the same discharge as five 1-in. bore orifices.

Of course, the assumed conditions do not actually prevail in practice, as pressure drop due to pipe friction, etc., comes into play, but in some cases the actual conditions are not materially removed from the hypothetical example under consideration.

In connection with the problem of providing adequate safety-valve area where low-pressure vessels are supplied with steam through an orifice, it will be of interest to refer to the Board of Trade regulation which governs the supply of steam to evaporators, etc. This regulation makes it a condition where evaporators are supplied with steam through an orifice and are required to work at a comparatively low pressure that definite proportions of supply orifice and safety-valve areas must be observed. The regulation is as follows :—

The steam inlet to the coils should have an orifice the size of which does not exceed that found by the following formula :—

$$d = D\sqrt{\frac{n \times p}{6 \times P}},$$

where d = diameter of orifice in ins.
D = diameter of safety valve in ins.
n = number of safety valves on evaporator.
p = absolute pressure at which the evaporator is worked.
P = absolute pressure of entering steam.

Applying this formula to the conditions assumed in Fig. 102, namely, an inlet orifice 1 in. bore and a reduction of pressure from 120 lbs. to 10 lbs. per sq. in., it will be found that 32 safety valves 1 in. diameter, or their equivalent, would be required under this regulation.

In the case of these large pressure reductions it is a very costly proposition to provide the desired size or number of safety valves to

secure safe working conditions. As a result several devices have been designed to overcome this trouble, and an example is the " Vulcan " Isolator Safety Valve.

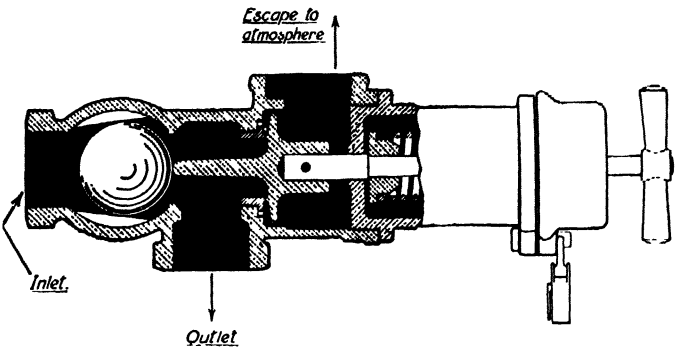


FIG. 103.

This valve is so arranged that when it opens, due to excessive pressure, the supply of steam is automatically cut off.

Fig. 103 shows one arrangement of the valve which is particularly adapted for use with certain classes of low-pressure vessels. It will be observed that the safety valve and the isolating ball valve resting on

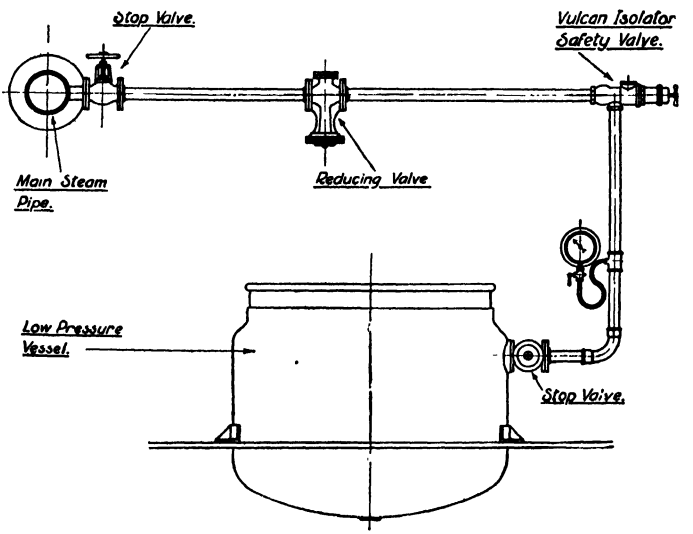


FIG. 104.

an inclined rib are entirely separate from each other, and that the isolating valve is held off its seat by a projection on the safety valve. When the safety valve opens, due to excess pressure, the ball valve " follows " its movement until the steam is shut off from the low-

pressure vessel. It will be seen that the operation of the main safety valve can in no way be retarded by the ball valve, as there is no rigid connection between the two. The main safety valve is provided with a special form of reaction head and spring which are proportioned to ensure the necessary lift with only a slight increment of pressure.

Fig. 104 shows one application of the valve in protecting a low-pressure vessel against overpressure, but it will be readily understood that the valve can be arranged in other methods to suit the prevailing conditions.

In operation the safety valve opens at the pressure at which it is set to lift, and thereby gives warning that there is a slight excess pressure. If the pressure in the low-pressure main accumulates to, say, 2 lbs. or 3 lbs. in excess of the original lifting pressure, the resulting increased lift of the safety valve allows the ball valve to seat itself, and thereby cut off the steam supply to the low-pressure vessel.

The Hollow Forging of Pressure Vessels for Very High Pressures.

The increasing demands of recent years for large high-pressure boiler-drums and chemical reaction vessels has led to the development of hollow forging of such vessels because the wall thicknesses are too great to permit of riveted construction, and in the case of chemical vessels, the materials are frequently of such a composition that welded construction is inadvisable.

Such hollow-forged vessels may frequently have a finished weight of 60–70 tons, which necessitates an ingot from which to forge the vessel of 160–180 tons, and this in turn has led to marked developments in ingot moulding.

In the manufacture of hollow forgings until recently the usual practice was to anneal the ingot after stripping it whilst still hot from the mould, afterwards allowing it to cool very slowly. When cooled, a hole was trepanned through the centre, the object of which was to produce a core of metal which could be closely examined, and also to remove the less pure material from the axis of the ingot.

The next operation was to enlarge the hole by an hydraulic pressing operation after the ingot has been reheated to the necessary forging temperature, and this produces a long tubular forging. Subsequently the drums are normalised, the outside is rough machined and the interior bored. After reheating the ends are closed for manhole openings, in the case of boiler-drums, or are reduced and then flanged in the case of chemical reaction vessels.

It will be realised that the above process is a lengthy and costly one, and attempts have recently been made to reduce both the labour costs and the production time. The first of these consists in hot piercing or punching whereby a hole is made through the ingot without cooling it. In this process the feeder head at the top and the surplus metal at the

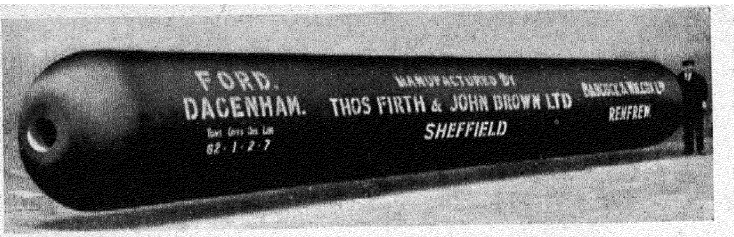


FIG. 105.—Large hollow forging by Thos. Firth & John Brown, Ltd.

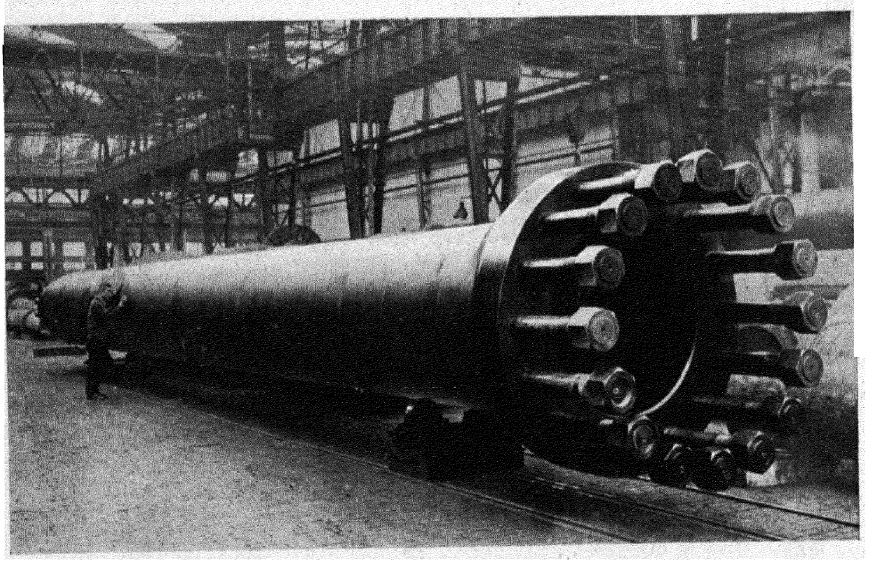


FIG. 105A.—Large chemical reaction vessel by Fried. Krupp, A.G.

[*To face page* 241.

bottom of an ingot is removed by a large cutter, driven through the ingot by means of an hydraulic press. The remaining body of the ingot is then placed vertically beneath a press, and a tubular punch driven axially through, thus removing a core from the centre of the ingot. After this the procedure is as previously described.

Another method recently adopted involves the casting of a hollow ingot, and it has several great advantages. Firstly, economy in raw material is secured, and secondly considerable reduction in time of manufacture is obtained.

Until recently, large pressure vessels were available only in the carbon steels, but now large ingots can be obtained either by open hearth or electric furnace process in alloys such as 3 per cent. and 6 per cent. chrome molybdenum, and the 2½ per cent. nickel-chrome molybdenum types. The subsequent heat treatment of such large masses of alloy steel is a difficult and costly process, but in view of the special features of such alloys, manufacturing costs are not prohibitive.

An example of a large hollow forging by Thos. Firth & John Brown Ltd., is seen in Fig. 105, and one by Friedrich Krupp in Fig. 105A. Particulars of the latter are as follows: Weight, 82 tons; overall length, 59 ft.; diameter inside, 3 ft. 11 ins. It is in special steel for chemical process work.

For more information about the design and construction of high pressure vessels in particular and high pressure chemical plant in general, I would refer the reader to my other book which deals specifically with these subjects.

CHAPTER VII.

PIPES AND PIPEWORK.

Steam-Pipes.

STEAM is used in nearly every branch of chemical engineering, and it is of importance, therefore, that steam supply pipework be well designed, adequate in size for the purpose desired, well covered to prevent unnecessary heat losses, properly drained to prevent possibilities of damage by water hammer and to provide dry steam at the point of use.

With the introduction of mild steel pipework at the beginning of the present century, the manufacture of cast-iron and wrought-iron steam-pipes steadily declined, and within the limits of susceptibility of this material practically all steam-pipe installations are now of mild steel throughout. For extreme temperatures at high pressure alloy steels are imperative, but since these conditions are of recent growth the technique is by no means stabilised.

The A.S.M.E. Boiler Construction Code (1935 edition) gives the following formula for the thickness of steam pipework in steel :- -

(*a*) For pipes not greater than 5 ins. dia. :

$$P = \frac{2S}{D}(t - 0{\cdot}065) \qquad 125$$

(*b*) For pipes over 5 ins. dia. :

$$P = \frac{2S}{D}(t - 0{\cdot}1)$$

where P = working pressure lbs/sq. in.,
t = pipe wall thickness in ins.,
D = outside dia. of pipe in ins.,
S = see table below.

Material.	Working Temperatures not exceeding (° F.)					
	700	750	800	850	900	950
Seamless medium carbon steel	12,400	11,500	9,160	7,520	5,650	4,000
Seamless low-carbon steel .	9,600	9,000	7,020	5,800	4,630	3,440
Fusion welded steel (Spec. S1)	9,900	9,000	7,200	6,070	4,950	3,600
,, ,, ,, (Spec. S2B²)	9,000	8,200	6,600	5,450	4,350	3,240
,, ,, ,,(Spec. S2A²)	8,100	7,400	5,900	4,900	3,900	2,880
Lap welded steel (Spec. S18).	7,600	7,000	5,580	4,630	3,690	2,720

Note.—Steel S1 has carbon 0·25/0·30 per cent., manganese 0·3/0·6 per cent. ; S2B² has carbon 0·20/0·22 per cent., manganese 0·35/0·60 per cent. ; S2A² has carbon not exceeding 0·15/0·17 per cent., manganese 0·35/0·60 per cent.

J. A. Aiton recently gave an interesting paper on modern high pressure–high temperature pipework (*Electrical Power Engineer*, Jan.–Feb. 1933), a summary of which is as follows :—

Pipework for severe operating conditions must be considered from three main aspects—(*a*) the raw material of the pipe, (*b*) the method of manufacture, and (*c*) the working conditions, both as regards pressure and temperature of the gas or fluid being conveyed, and the arrangement of the pipe.

At the higher temperature ranges, the " creep " of steel must be taken into consideration; and if the maximum life of the pipework be taken as twenty years, then it is reasonable to assume that the actual time which the plant will be under service conditions is, say, 100,000 hours. Since the permissible creep in this time may be taken as 1 per cent., it follows that the allowable creep per inch per hour is one-tenth of one-millionth, i.e. 10^{-7} ins. Taking 60 per cent. of this creep as the maximum permitted to allow for contingencies, the following stresses are suitable for 0·17 per cent. carbon steel.

Temperature (° F.).	*Stress* (*lbs./sq. in.*).
900	4880
850	7000
800	7500
750	8000
700	8500

In using the foregoing formula and data in determining pipe dimensions it must be borne in mind that manufacturing difficulties do not permit of 0·15 per cent. carbon steel tubes with wall thicknesses necessary at pressures approaching, say, 1400 lbs. per sq. in. at the maximum working temperature given, viz. 900° F. Recourse must then be had to alloy steels, and since such steel for pipe fabrication has to be capable of being worked at high temperatures in the manufacturing process without subsequent elaborate heat treatment, and of being welded for flanges, etc., without detriment to its mechanical properties in the process, great care is necessary in selection (see Chapter IV, p. 117, for detailed information of suitable steels for such conditions).

For moderate steam or fluid pressures, the following formulæ are taken from the Board of Trade Rules.

(*a*) Solid drawn cold finished steam pipes (28 tons tensile)

$$\text{WP} = \frac{(t - 10)}{\text{D}} \times 120$$

(*b*) Solid drawn hot finished steam pipes (28 tons tensile)

$$\text{WP} = \frac{(t - 12)}{\text{D}} \times 120$$

where WP = working pressure lbs/sq. ins.,
t = thickness in 1/100 in.,
D = internal dia. of pipe in ins.

Welded pipes of iron or steel should comply with the following:

$$WP = \frac{(t - 12)}{D} \times 90$$

For copper pipes the Board of Trade rule is

$$WP = \left(\frac{t - 3}{D}\right) \times F$$

where WP = working pressure lbs./sq. in.
D = internal dia. in ins.,
t = thickness in 1/100 in.,
F for solid drawn steam pipes is 60 and for brazed 45.

Copper pipes should not be used for superheated steam, or for pressures exceeding 180 lbs. per sq. in. and if the diameter is over 5 ins.

For pressures above 75 lbs. per sq. in., steam pipes should be solid drawn. Copper piping made by electro deposition of copper on a mandrel shall not be used for pressure pipework.

Steam-Pipe Connections and Flanges.

To connect saturated steam pipework at pressures not exceeding 150 lbs. per sq. in. and pipe diameter of 2 ins., it is satisfactory to use standard screwed bronze unions, screwed tees, bends or sockets, but above those pressures and diameters it is advisable to use flanges, and flanged tees or bends.

The dimensions of flanges and flanged fittings, and the method of securing flanges to the tube, depends largely upon the working pressure and temperature. To avoid carrying an excessive variety of flanges it is advisable to standardise on as few different sizes as the plant will permit.

Flanges may be fixed to pipes by welding, screwing, expanding or riveting, or by a combination of two or more of these methods. Expanding alone is definitely not recommended for even the lowest pressures.

Welded-on flanges can be supplied for all sizes, temperatures and pressures. The riveted flange is not recommended for high temperature and it is difficult to fit with sizes less than 7 ins. diameter. Screwed flanges are suitable for pressures up to 200 lbs. per sq. in., and screwed and expanded flanges for pressures up to 350 lbs. per sq. in. at temperatures not exceeding 650° F.

Regarding cost, the riveted flange is the most expensive, and the screwed-on flange the cheapest type.

In the case of screwed- and expanded-on flanges it is usual for the expanding to be done with proper appliances at the tube-maker's works. It is important in such cases to note that the pipe is screwed with a

vanishing thread, so that the pipe is not unduly weakened by the expanding process at the end of the thread. If such pipes are likely to be subjected to torsional stress it is well to reinforce the attachment by a light weld fillet at the back of the flange.

For pressures up to 600 lbs. per sq. in. and temperatures up to 750° F., plain-faced flanges (Fig. 106) are in general use, and in con-

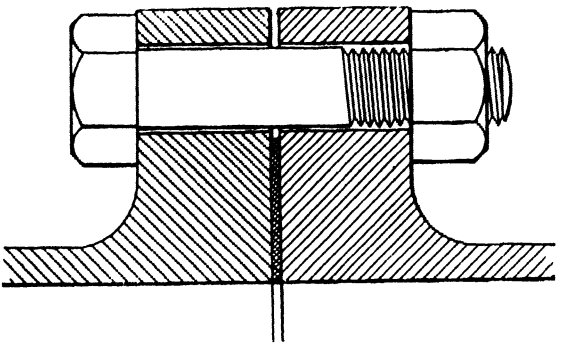


FIG. 106.

junction with thin metallic corrugated joint rings and reliable jointing paste give satisfactory service.

For higher pressures flanges with facing strips are often used (Fig. 107). The spigotted patten (Fig. 108) is also suitable for high pressures.

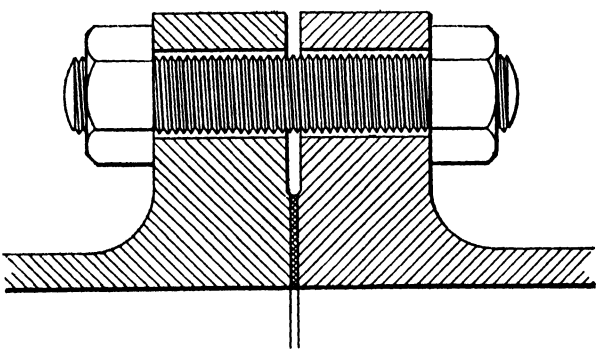


FIG. 107.

Such flanges should be welded to the pipe in a manner as that given in Fig. 109, which is a type which can be well recommended. The chief features of this welded connection are :—

(1) The main weld is a butt-weld and is consequently either in tension or compression but never shear, and consequently a minimum of weld material is required.

(2) The bending stresses on the butt-weld are reduced to a minimum.

(3) In subsequent facing of the flange none of the weld-metal is removed.

The butt-weld should be by the metallic arc process, and the fillet either by metallic arc or carbon arc process.

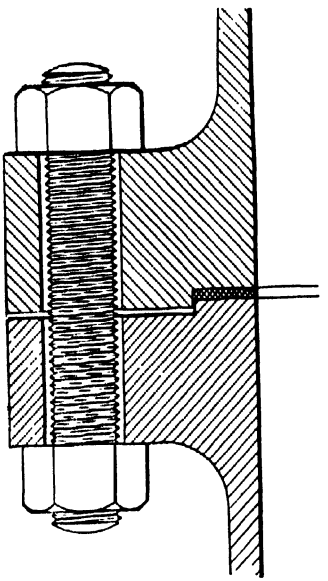


FIG. 108.

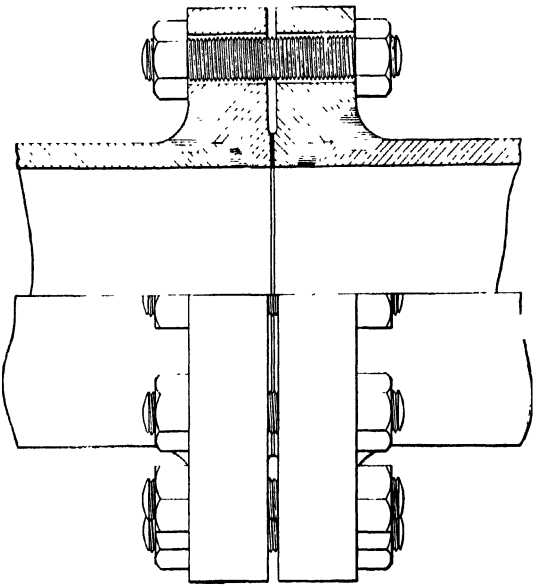


FIG. 109.

When the steam pressure exceeds 350 lbs. per sq. in. and the temperature 750° F., great care must be exercised in choosing the type of flanged connection from pipe to pipe, and pipe to fittings or valves.

The design of pipe flanges for very high-pressure steam lines has naturally received the attention of the British Standards Institution, who in 1932 issued a tentative specification for flanges of pipework and fittings to be used for working pressures from 900 up to 1400 lbs. per sq. in. at temperatures up to 800° F., but extended by a reduction in the working pressure to 900 lbs. per sq. in. to a maximum of 900° F. In issuing this specification the Committee pointed out that the recommendations were in advance of practice and knowledge and the tabulated data were thereupon issued as a *tentative* standard only.

For the very highest pressures there are three forms of welded high-pressure pipe connection which have proved successful in practice. The first was developed in America and is known as the " Sarlun " joint (see Fig. 110). The Sarlun joint is a development of the

" Sargol " joint, which was in effect the old well-known " Van Stone " joint, the only alteration being that the face of the loose flanges was set back to enable the welding to be carried out, but as the collars are fairly thick considerable heat had to be employed in welding them together ; it was soon found that this heat resulted in difficulties and the " Sarlun " joint was evolved to eliminate these troubles. In it the collars are the same as in the Sargol joint, but the collar is turned down circumferentially, thus leaving on the face side of the collar a raised V-shaped circumferential ring. This being thin, requires much less heat in the welding operation. The faces of the collar are scraped and made steam-tight before welding.

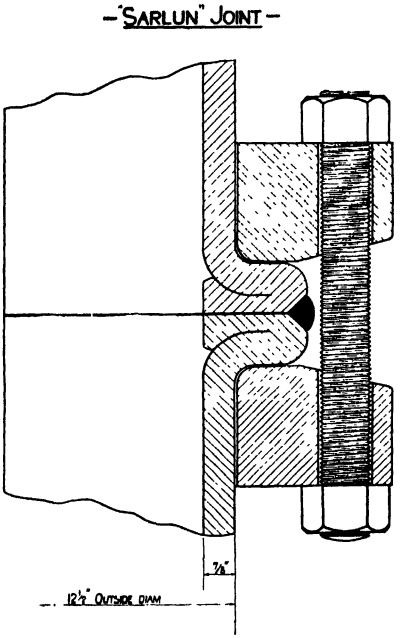


FIG. 110.

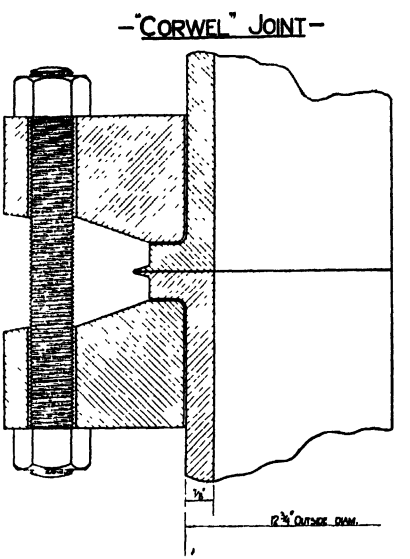


FIG. 111.

The second form of seal-weld joint is the " Corwel," developed in Great Britain (Fig. 111). This joint uses a loose flange of similar shape to the " Sarlun," but the collar is produced by raising a corrugation on the end of the pipe and rolling this back, thus producing a double or folded collar. The face is machined smooth, and a heavy weld is used without difficulty. The bolts used for the Corwel joint are nickel-chrome molybdenum steel and are not formed with head but are screwed fine thread right through. Such bolts in a 16-in. " Corwel " high-pressure high-temperature joint are $1\frac{3}{4}$ ins. diameter, $15\frac{3}{8}$ ins. long, and since there are 20 of these bolts, the total weight of such is $2\frac{1}{4}$ cwt.

Aiton (*Electrical Power Engineer*, Jan., 1933). Messrs. Aiton of

Derby, have kindly supplied me with the following particulars of three recent steam-pipe installations, in all of which seal-weld "Corwel" joints were used :—

(*a*) *Power Station.*—Working pressure, 650 lbs. per sq. in. at 875° F. Pipes, 10½ ins. nominal bore, 0·86 in. thick ; 9 ins. nominal bore, 0·75 in. thick. Maximum stress allowed was 2 tons per sq. in. (including expansion stresses).

(*b*) *Power Station.* –Working pressure, 625 lbs. per sq. in. at 825° F. Pipes, 11 ins. nominal bore, $\frac{45}{64}$ in. min. thickness ; 9 ins. nominal bore, $\frac{19}{32}$ in. min. thickness.

(*c*) *Power Station.*—Working pressure, 550 lbs. per sq. in. at 842° F. Pipes, 15¾ ins. nominal bore, $\frac{45}{64}$ in. thick ; 12¾ ins. nominal bore, $\frac{37}{64}$ in. thick.

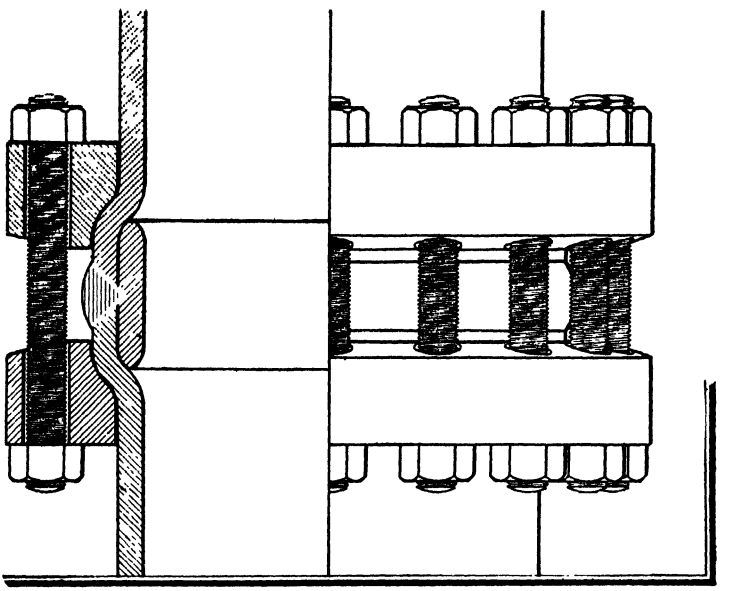


Fig. 112.

The third method of pipe connection, this time by an all-welded joint, is shown in Fig. 112 ; this is known as the Dawson joint and has been developed by Stewarts & Lloyd Ltd. It is in use for pressures of 1900 lbs. per sq. in. at temperatures of 930° F. down to 200 lbs. per sq. in. at 750° F., and can be used with or without guard flanges depending upon the working condition. Being an all-weld joint the bolts and flanges are not required to take any stress, and hence bolts made from special steel are not necessary. When pipes with Dawson joints are connected to flanged valves, a projection on the tube flange of the same dimensions as the pipe is provided. A photograph of the joint is shown in Fig. 113.

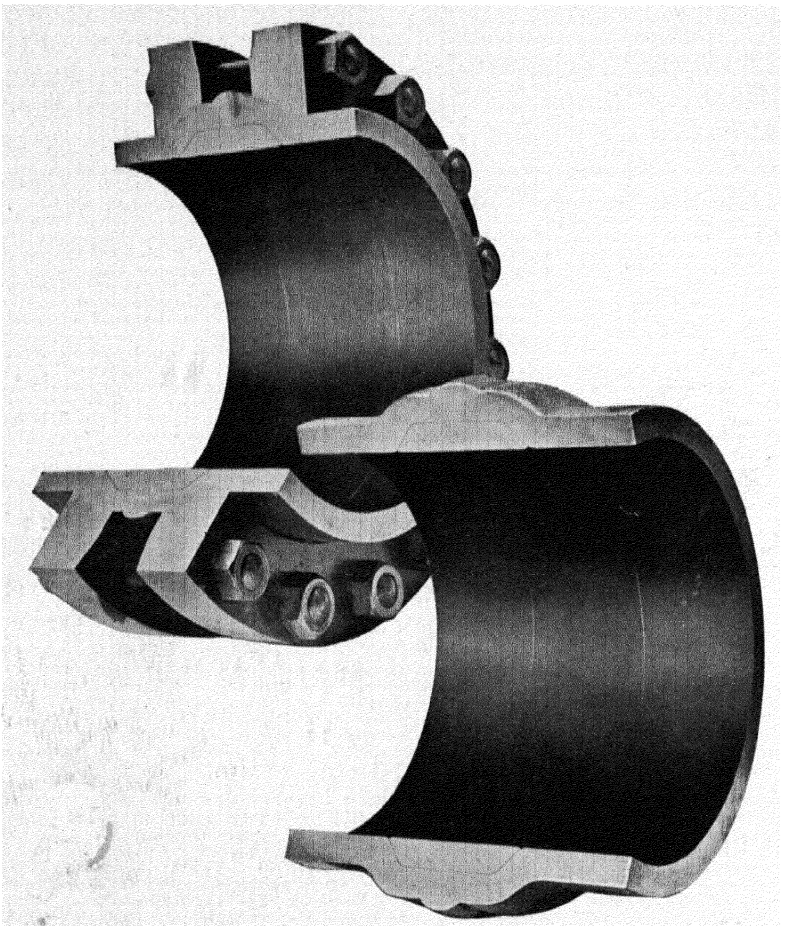


FIG. 113.

[*To face page* 249.

Important large-scale investigations into materials of construction and methods of assembly of high-pressure high-temperature pipework and plant have been carried out in America at the Trenton Channel and Delray power-stations, reported by Thompson and van Duzer.

"*High-Temperature Steam Experience at Detroit.*"

Thompson and van Duzer, *Engineering*, 1933, **136**, 661.

The authors report experiments on two high-pressure high-temperature steam installation, one at the Trenton Channel power-station and one at the Delray power-house No. 3. The first experimental plant at Trenton started up in 1929 comprised a separate oil-fired superheater and piping system designed to operate with steam at 1000° F., and later at 1100° F., and this was operated for two years to give data for the second stage of the experimental work which comprised the installation of a 10,000 kW. steam turbine with necessary equipment for working at 1000° F. The working pressure throughout was limited to pressures not higher than 400 lbs. per sq. in., and it was considered that the higher temperature, without the added complication of very high pressure, would provide the information most desired.

Description of Equipment.—The Trenton equipment comprised an oil-fired superheater supplied with 400 lbs. 700° F. steam from the power-station main header. The superheater was of the radiant type, and was capable of adding 400° F. of superheat to 6000 lbs. of steam per hr. from the initial temperature of 700° F. The high-temperature piping system consisted of a valve, eight flanged joints, and a desuperheater in order that the steam used in the experiments could subsequently be used in the house turbine at 700° F.

The superheater was made of low-carbon steel tubing in the section where the steam temperature did not exceed 800° F., and the remainder of the superheater and the high-pressure piping system were made from stainless steel with analysis C 0·06–0·09, Cr 17–20, Ni 7–10, Si 0·5. The steam piping was $5\frac{1}{2}$ ins. outside diameter with $\frac{3}{8}$-in. thick walls. The loose companion flanges, valve and desuperheater castings were made of similar material to the above, except that the carbon was increased to 0·25 and the silicon to 2·0–2·5 per cent. The flange bolts were made from chrome-tungsten vanadium steel with analysis, as seen in Table 39. The pipe ends were provided with Van Stone Sarlun laps (see Fig. 110), the faces of which were provided with a serrated finish to provide data for gasketed as well as seal-weld joints. All piping joints were constructed to the 600 lbs. A.S.A. standard. The original line has been somewhat modified by the addition of experimental joints of heavier construction.

Numerous gasket materials were tried, and the best was found to be $\frac{1}{32}$-in. Monel metal in plain sheet form.

The authors found little or no change in the physical properties of

the 18–8 alloy after considerable service at Trenton, and hence this material was specified for the pipework, and the hotter portions of the superheater at the Delray turbine installation. The low-carbon 18–8 steel was used for the $8\frac{5}{8}$-in. outside diameter $\frac{1}{2}$-in. thick tube.

Several different classes of low-alloy steels were installed for experimental purposes in both Trenton and Delray installations. Apart from savings in material cost, such low alloys are more readily fabricated. Among the castings tried were 4–6 per cent. Cr 1 per cent. W; 0·5 per cent. Mo; a $5\frac{1}{2}$-in. outside diameter length of 4–6 per cent. Cr 1 per cent. W; a valve body of Hadfields Era 131; medium- and high-carbon calorised steel together with a nickel-chromium molybdenum steel adopted by the turbine manufacturers for all parts of the turbine subjected to high-pressure steam.

A few tubes of medium- and high-carbon calorised steel were installed in the Trenton superheater, and 0·35 C steel tubes coated with aluminium were installed in the middle section of the Delray superheater, together with a like number of coated tubes of 18–8 and 12–14 per cent. chrome-nickel austenitic steels. Metal gaskets were used for all unwelded joints, and the flanges were made of low-chrome nickel steel.

The nickel-chrome molybdenum steel (Table 36-7-8) was used for the turbine throttle valve, the inner and outer high-pressure cylinders and the rotor, and a max-design stress of 5000 lbs. per sq. in. was used in the turbine design.

TABLE 36.

PRINCIPAL PROPERTIES OF IMPORTANT ALLOYS USED IN TRENTON CHANNEL AND DELRAY INSTALLATIONS IN THE "AS RECEIVED" CONDITION.

Alloy No.	Tensile Strength (lbs. per sq. in.).	Yield Point (lbs. per sq. in.).	Elongation (per cent. in 2 ins.).	Reduction of Area (per cent.).	Designation of Material.
1 . .	85,000	25,000	40	40	KA2 Nirosta
2 . .	91,600	—	53 in 8 ins.	59	KA2S
3 . .	90,000	35,000	40	40	KA2B
4 . .	68,000	—	4 in $1\frac{3}{8}$ in.	8	Resistal 2C
5 . .	137,000	118,000	25 in 1 in.	33	Used in turbine construction
6 . .	78,000	45,000	25	40	$\frac{1}{2}$ per cent. Mo
7 . .	140,000	122,000	16	50	4–6 per cent. Cr 1 per cent. W
8 . .	110,000	76,000	32	65	14 per cent. Cr
9 . .	—	—	—	—	Hecla ATVI
10 . .	67,000	40,000	31	45	Era 131
11 . .	225,000	210,000	11	33	Seminole Hard

TABLE 37.

CREEP PROPERTIES—STRESS TO PRODUCE A CREEP OF 1% IN 100,000 HOURS.

Part.	Material.	Temperature.	Stress (lbs.).
Tubes and castings	KA2	1000° F.	15,000
Tubing	KA2S	,,	12,500
Tubing and casting	4 6 Cr 1 W	,,	6,350
Casting	Era 131	,,	5,200
Bolts	Seminole Hard	,,	7,000
Castings	Ni Cr Mo	,,	5,900
Casting	0·5 Mo	,,	7,200
	0·43 C	,,	1,500
	0·42 C	,,	3,500
	0·20 C	,,	3,200

TABLE 38.

Alloy No.	C	Cr	Ni	Mo	W	Mn	Si	P and S
1 . .	0·16 max.	17·0 20·0	8·0 10·0	—	—	0·50	0·25 0·75	0·025 max. —
2 . .	0·06	17·6	9·2	—		0·53	0·57	0·02 max.
3 . .	0·10 0·20	17·0 19·5	8·0 10·0	—		0·65	2·0 2·5	0·025 —
4 . .	0·23	17·5	9·0	—	—	—	1·6	0·03
5 . .	0·31	0·35	3·10	0·34		0·72	0·32	0·06
6 . .	0·25	—	—	0·50	—	0·75	0·36	0·035
7 . .	0·39	5·20	—		1·10	0·46	0·25	0·015
8 . .	0·25	14·28	0·28			0·52	0·34	0·015
9 . .	0·47	11·84	36·72	—		0·24	0·23	0·01
10 . .	0·17	0·24	—	0·84	—	0·71	0·24	—
11* . .	0·45 0·50	1·20 1·45	—	—	1·75 2·25	0·35	—	0·05 —

* Also V—0·20 0·25 per cent.

Some idea of the creep-resistance of these various materials can be gathered from the values of stress required to produce a 1 per cent. creep in 100,000 hrs. as given in Table 37.

Results of both physical and microscopic examinations made on various materials after service from the two installations have shown slight change after service under the experimental conditions, but in no case have the changes been sufficiently serious as to warrant replacement of affected parts. Six different classes of alloys were examined.

Three different sections of 18–8 material removed from the Trenton installation showed evidence of carbide segregation at the grain boundaries; and each successive sample revealed widening of these

boundaries. The physical properties appeared to indicate slow embrittlement, but such changes were not considered by the authors to cause concern as to their continued service. The authors recommend the development of special alloys to avoid the chromium-carbide segregation.

The calorised superheater tubes and headers of medium- and high-carbon steel were removed from the Trenton superheater after 3821 hours' service, of which 3305 hrs. were above 1000° F., and stresses due to all circumstances as high as 3000 lbs. per sq. in. Approximately 10 per cent. of the calorised surface coating had disappeared and the remaining 90 per cent. was quite brittle. The inside of the tubes was coated with 0·04–0·08 thickness of magnetic oxide, and measurements showed creep rates of 2 per cent. per 1000 hours' service.

The Delray calorised and sprayed superheater tubes were not removed for inspection, but the external surface was apparently in quite good condition.

A valve at the outlet of the Trenton superheater made from 0·4–0·6 per cent. Cr 1 per cent. W was removed for examination after 12,995 hrs., 10,818 of which were at a temperature of 1100° F. The valve was 600 lbs. A.S.A. construction, and the test results show that the material of the valve body did not undergo embrittlement, but that the long service at high temperature tended to increase the toughness and ductility. Experience with Nitralloy showed that it is unsuitable for valve parts.

Samples of the nickel-chrome molybdenum steel from the throttle valve of the turbine after 3800 hrs., 1450 of which were at 1000° F., showed but little change in physical properties.

Various bolting materials were tried with varying results. The material which gave the best service was No. 1 in Table 39. Bolts made from this material were heat-treated by oil quench from 1650° F. followed by 1100° F. tempering, and the threads were cut after heat treatment to prevent the formation of cooling cracking the thread roots.

Steel No. 2 was found to be liable to severe embrittlement, and one set of bolts made from material No. 3 required tightening once during 10,891 hrs. of service and showed a drop in impact value of 50 per cent. Steels 4, 5, 6 were found to require frequent tightening to allow for continuous creep. Bolts made from No. 7 were supplied with the turbine and their behaviour was satisfactory.

Pipe Joint Experience at Trenton and Delray.

Many and varied troubles were experienced with pipe jointing, but from experience gained it was found possible to construct two joints which successfully withstood 16,000 hrs. at steam temperatures of 1000° F. The authors state that full weld-joints appear to be the answer to the high-temperature problem.

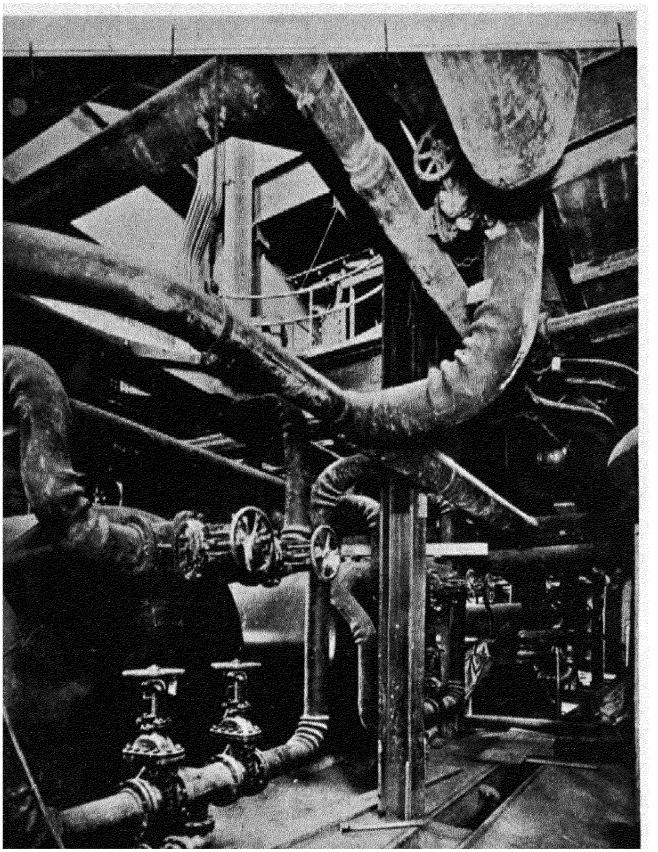


FIG. 114.—View of creased bend in steam pipework (Pittsburg Piping & Equipment Co.).

[*To face page* 253.

The successful 5-in. bolted flange joint was of the Van Stone type with serrated flanges of KA2 material, No. 1 steel bolting material, and $\frac{1}{32}$-in. plain Monel metal gaskets. The bolt stress was limited to 10,000 lbs. per sq. in., and one joint of this type had flanges as 900 lbs. standard but $3\frac{3}{8}$ ins. thick, and the others as 1500 lbs. standard but $4\frac{1}{8}$ ins. thick.

No material dimensional changes were noted in the 8-in. Delray pipe stressed to 6400 lbs. per sq. in., or in any of the fittings, and measurement of a section of $5\frac{1}{2}$ in. outside diameter chrome-tungsten tube after service in Trenton likewise showed no change after 7468 service hours.

TABLE 39

CHEMICAL ANALYSES OF BOLTING MATERIAL.

Steel No.	Trade Name.	C	Cr	Ni	W	Mn	Si	Mo	V	S and P
1 .	Seminole Hard	0·45	1·25		2·0	—	—	—	0·25	Max. 0·05
2 .	Resistal 2C	0·05	19·5	9·9		0·70	2·3	—	—	,, 0·01
3 .	Supertemp.	0·36	0·52	—	0·94	0·90		—		,, 0·03
4 .	1722	0·45	1·40	—	0·8	0·50	0·71		0·28	—
5 .	D1	0·08	1·17		0·97	0·25	0·28		—	—
6 .	SAE 3140	0·4	0·6	1·25	—	0·5–0·8	—		—	Max. 0·05
7 .	Vibrac	0·48	1·28	2·6	—	0·62	0·18	0·59		,, 0·02

In a concluding paragraph, the authors state that the use of steam equipment up to 1000° F. is entirely feasible, but this is qualified by the statement that if such operation demands existing high-priced alloys, it is scarcely workable. Further metallurgical research will no doubt, however, produce durable materials at a much lower cost, when such high temperatures will be justifiable.

Bends, Expansion Bends and Joints.

Bends.—In designing large bends for steam mains three rules should be observed :—(*a*) all bends should be formed on long lengths of tube wherever possible, (*b*) all bends should have at each end a straight portion not less than one and a half pipe diameters, and (*c*) all bends should be of as large radius as possible. In some installations, however, the layout may necessitate the use of bends of short radii, and in such cases creased or corrugated bends may be used (see Figs. 114–5).

It must be realised that creased and corrugated bends cause largely increased pressure drop and their use is not recommended unless the layout renders this imperative. Where bends of still shorter radii are necessary, these can be formed by gusseting, i.e. wedge-shaped pieces are cut from that side of the tube which is to form the inner curve of the bend and the edges of the opening are bevelled. The tube is then bent, forcing the cut edges together, and these are then welded. As an alternative to such gusseted bends cast steel elbows may be employed.

The following data abstracted from a paper by J. A. Aiton (*Proc. Elect. Power Engineers Association*, London, 1933) are of interest in connection with the design of large high-pressure high-temperature bends.

With small radii and very thick bends, the bending process may thin the outside wall of the bend by 30 per cent., and experience shows that to bend a 10-in. diameter pipe $\frac{7}{8}$ in. thick without reducing the thickness by more than 10 per cent., the radius must be not less than 10 ft. Creasing the inner wall (see Fig. 114) makes it possible to bend pipes of the dimensions given to a smaller radius without thinning the outer wall, and such creasing definitely increases the flexibility of the

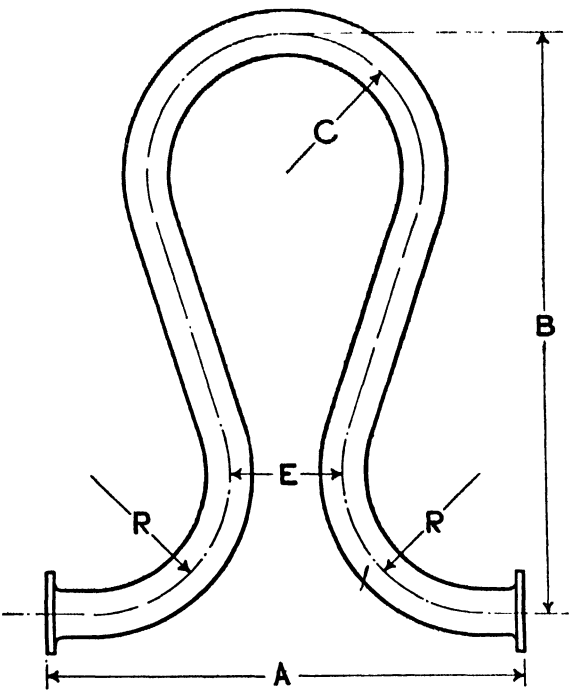


FIG. 116.—Expansion bend.

pipe. Creasing a bend enables it to be made in large diameters. For example, pipes made for reheating steam at pressures from 100 to 150 lbs. per sq. in. and temperatures up to 800° F. can be made in sizes up to 40 ins. and $\frac{1}{2}$ in. thick.

The fully corrugated pipe (see Fig. 115) can be made to smaller radii even than the creased pipe. They are more flexible. No case of corrosion in the walls of the corrugation has come to the notice of Mr. Aiton, who has had very wide experience of this class of work.

Expansion Bends.—Provision for expansion must be made in the design of every steam main, and this is best done by arranging a sufficient number of ordinary bends to allow for all movement. Where

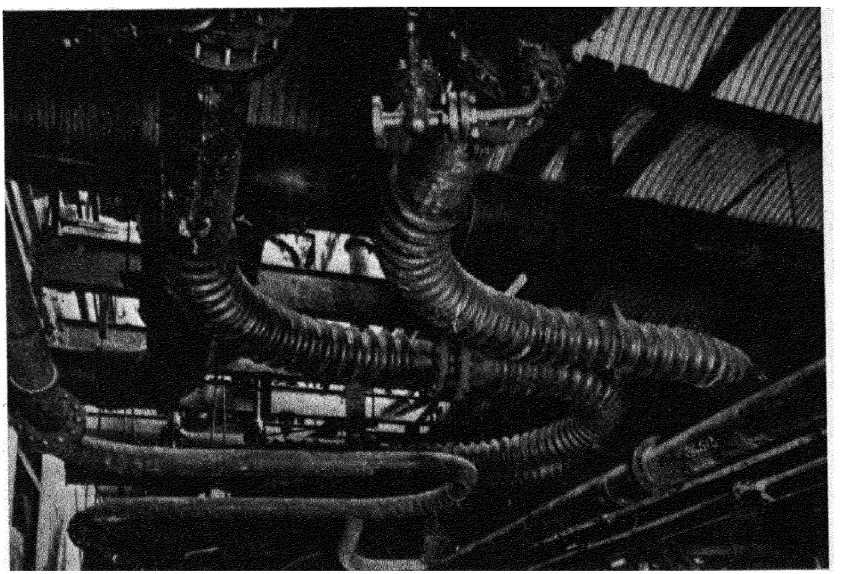


FIG. 115.—View of corrugated bends in steam pipework with Corwel Joints (Aiton & Co., Ltd., Derby).

[*To face page* 254.

it is not possible to do this, expansion bends of the type shown in Fig. 116 may be used. In arranging the pipe movements, care should be taken that branch connections to the main do not cause restriction of such movement, otherwise serious damage to the main may result.

Sliding expansion joints of the stuffing-box type are used where space does not permit of the use of expansion bends, but such joints should only be used for low pressures and temperatures. Great care is necessary in erecting and packing such joints, as leakage from the gland will otherwise result.

Copper expansion bellows are sometimes used, but they are not recommended for pressures higher than 10–20 lbs. per sq. in., or where torsion or excessive movement may possibly arise.

Erection of Expansion Bends and Joints.

To use an expansion bend to the best advantage it is necessary to spring it during erection. In doing this, care must be taken to prevent any movement of the main at the anchors, since this would mean the

TABLE 40.

STANDARD EXPANSION BENDS.

(Stewarts & Lloyds Ltd.).

Outside Diameter of Tube (ins.).	Dimensions.									
	Length.		Height.		Radii.				Width.	
	A		B		C		R		E	
	ft.	ins.	ft.	ins.	ft.	ins.	ft.	ins.	ft.	ins.
1 1/32 1/32	1	10	2	9		6		6		5½
1 1/16 1/16	2	0	3	3		6½		6½		5¾
1 2/32 9/32	2	3	3	8		7		7		7
2⅜	2	10	4	3		9		9		8
3	3	4	4	10		10		10½		9
3½	3	8	5	4	1	0	1	0		10½
4	4	4	5	10	1	3	1	3	1	0
4½	4	8	6	3	1	4	1	4	1	2
5½	5	4	6	10	1	6	1	6	1	4
6½	6	0	7	3	1	9	1	9	1	5
7½	6	8	7	6	2	0	2	0	1	6
8½	7	7	8	2	2	6	2	2	2	1
9½	8	10	9	7	3	0	2	6	2	8
10½	10	5	11	2	3	6	3	0	3	3
11½	12	2	12	10	4	0	3	6	3	10
12½	13	7	14	10	4	6	4	0	4	3

loss of so much of the cold springing and consequently an increase in the stress imposed on the bend in the working condition if it is still to take up the same amount of expansion movement.

Pipe anchors in suitable positions are essential for the satisfactory working of all types of expansion bends or expansion joints, and even where these are not employed anchors are frequently necessary to regulate the movement of the main. In long mains, guides to maintain the alignment are necessary both for expansion joints and expansion bends—for expansion joints because any misalignment will probably cause the joint to jam; for expansion bends because the end load necessary to produce the safe travel of the bend may be greater than the adjacent pipes can supply without themselves bending.

Expansion of Steam Pipes.

Formula for calculating Expansion.—The amount of expansion which will occur on any steam main can be calculated from the formula :—

$$E = KLt$$

where E = amount of expansion, in ins.
L = length of piping under consideration, in ft.
t = maximum temperature variation in ° F.,
and K has one of the following values, depending on the range of temperature.

Range of Temperature (° F.).	K
0 to 500	0·000085
0 to 700	0·000088
0 to 900	0·000095

The total variation in temperature should be determined basing on a minimum temperature appropriate to the local conditions.

For example, assuming a minimum temperature of 60° F. and a maximum temperature of 700° F., the linear expansion per 100 ft. of tube would be,

$$0{\cdot}000088 \times 100 \times (700 - 60) = 5\tfrac{5}{8} \text{ ins.}$$

Range of Temperature (° F.).	Expansion in ins. per 100 ft. of tube.		Range of Temperature (° F.).	Expansion in ins. per 100 ft. of tube.	
	Decimals.	Fractions.		Decimals.	Fractions.
60 to 250	1·6	$1\frac{5}{8}$	60 to 600	4·75	$4\frac{3}{4}$
60 to 300	2·05	2	60 to 650	5·2	$5\frac{1}{4}$
60 to 350	2·5	$2\frac{1}{2}$	60 to 700	5·65	$5\frac{5}{8}$
60 to 400	2·9	$2\frac{7}{8}$	60 to 750	6·55	$6\frac{1}{2}$
60 to 450	3·3	$3\frac{1}{4}$	60 to 800	7·05	7
60 to 500	3·75	$3\frac{3}{4}$	60 to 850	7·5	$7\frac{1}{2}$
60 to 550	4·3	$4\frac{1}{4}$	60 to 900	8·0	8

Branches and Connections to Mains.

For low pressures, i.e. up to 150 lbs. per sq. in., and for pipes below 5 ins. diameter, screwed tees are quite suitable for branch connections. For higher pressures and larger pipes it is usual to take branch connections from flanged tees or from riveted or welded-in branches on the main.

In attaching welded branches most makers cut out the opening in the main or manifold by oxy-acetylene cutter and then shape the contour of the branch piece to the pipe opening. The connection should then be welded with a good fillet. When possible branches should be welded on at right angles to the main, as the large flat surfaces formed at the junction of an angle branch with the main are subject to a much

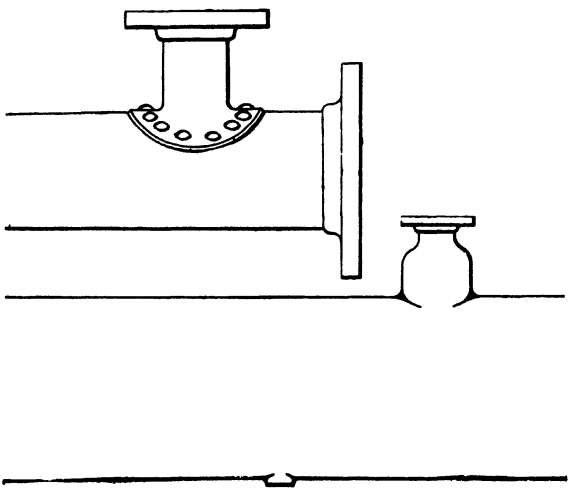


FIG. 117.—Connections to pipe mains.

higher stress than the cylindrical parts. When the branch is very much smaller than the main it is sometimes advantageous to adopt the form shown in Fig. 117.

Bosses welded on are often used in place of branches for small connections to mains. They are either tapped to receive the screwed end of a pipe or tapped for studs for flange connection. (See underside of pipe, Fig. 117.)

If desired and over 10 ins. diameter riveted branches can be used where the pressure and temperature are low. Such branches should be placed near the ends of the main to permit of efficient holding of the rivet-heads while riveting. The riveted branches should be of pressed steel of similar design to boiler nozzles or stand-pipes, and should be of thicker gauge than the standard pipe size so as to allow for thinning in flanges, and give sufficient landing edge for caulking. (See Fig. 117.)

Steam Separators and Receivers.

Complication in separator design is not desirable ; it usually adds little to the efficiency and often causes unnecessary loss of pressure.

Steam separators depend for their powers of extracting water from steam on the following principles :—

(1) Sudden alteration of direction of flow.

(2) Reduction in velocity of flow.

Separators are designed to utilise both of these principles, and the types in Figs. 118 *a*, and *b* differ only in the modification rendered necessary by the different positions of the branches. Separators should have hand holes in the body where the drain branches are not sufficiently large to take their place.

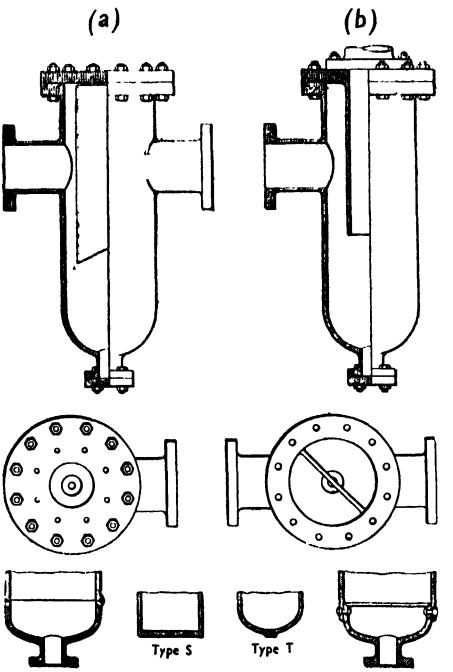


FIG. 118.—Steam separators.

Steam Receivers.—Riveted steam receivers are suitable for steam pressures up to 500 lbs. per sq. in. working pressure at temperatures not over 650° F. The receiver shell is formed from one plate, the longitudinal joint being butted, fitted with double butt-straps, and electro-welded at each end to ensure steam tightness. Each receiver end is made from a single plate pressed to shape in one heat and machined to ensure a good fit in the shell, which is bored out to receive the ends. The ends are of special form, giving the maximum strength combined with a flat large enough to accommodate the usual elliptical manhole

for access to the interior. Stand-pipes for this type of receiver are solid forged, and double riveted to the receiver.

For working pressures above 500 lbs. per sq. in. at temperatures exceeding 650° F. solid forged receivers are recommended. On these the stand-pipes are solid forged and are welded to the receiver.

Steam-Piping Supports.

The supporting of steam-pipes is closely connected with the provision for movement of expansion and contraction, but the supports proper should, as far as possible, permit free movement of the pipes in any direction, and any necessary constraint should be provided by anchors.

Where pipes are subject to vertical movement or to vibration, spring supports should be employed to avoid excessive stresses which might be set up in the pipes by the use of too rigid supports. In designing such supports the selection of springs of the proper strength is of importance. If the springs are too weak they will allow undue vibration to take place, whilst if too rigid they will not relieve the stresses in the pipeline. The spacing of supports is largely determined by the position of floor girders, joints, columns or other structural features, but supports must not be placed too far apart. A general rule is to place supports at intervals of not more than 10 ft. for a $\frac{3}{4}$-in. pipe, the maximum interval increasing with the size to 20 ft. for pipes of 6-in. bore or larger. As far as possible, pipe joints should be placed close to the points of support.

Although in many cases pipelines can be allowed free movement, subject only to constraints imposed by the fixing of their end flanges to the units which they connect, it is sometimes necessary to introduce fixed anchors to minimise the stresses which might otherwise be set up at certain points of the system. The location of anchors must be very carefully considered in relation to the system as a whole.

As auxiliaries to fixed anchors, limiting or guiding anchors are sometimes required to prevent movement in some particular direction or to maintain the correct alignment of the pipes under the loads imposed by expansion.

Drainage of Steam Mains.

The proper drainage of steam pipework and receivers is of the utmost importance, and such drainage should include provision for the immediate removal of the water formed by condensation, and for the water which accumulates in the pipes after steam is shut off the main.

It is to be noted that water will not readily flow against the direction of steam flow even if the pipes are given a steep inclination. A normal steam speed of, say, 100 ft. per sec. is comparable to a wind velocity of

60 m.p.h., which is likely to cause water to back up against the direction of flow of the pipes.

Where possible, the boiler junction valves should be the highest point of the range, otherwise the drainage of a branch steam-pipe to a boiler which is out of action is difficult and the presence of water in this pipe is particularly liable to set up water hammer. If necessary and possible, the boiler junction valve may be raised by inserting a stand-pipe between the boiler and the valve.

To ensure that pipes can be cleared of water before steam is admitted, it is necessary that there be a drain and an efficient steam trap at the lowest part of each section and that there be also means for admitting air to each section, preferably at the highest point.

All drain connections should be of ample bore to prevent choking, and should be made in the mains at such points as at valves of smaller diameter than the main, expansion bends in vertical planes, the foot of each rising bend and all similar positions. It is specially important that branch pipes rising from the main and provided with stop valves next the main should each have a drain connection to prevent water from accumulating when the branch pipe is not in use. The occurrence of such danger-points can often be avoided by slight changes in the design.

To take drain connections from mains either bosses welded to mains, drilled and tapped to take the screwed end of the drain pipe, should be used, or branches welded on and flanged to match the flange on the drainpipe. If more water is expected than could be satisfactorily discharged by a drainpipe connected to the main, a drain pocket of proper size welded to the main, flanged and fitted with a blank flange or with the end closed, as illustrated opposite, should be employed, the blank flange or closed end being fitted to take the drain connection.

Steam Traps.

There are many designs of steam traps on the market, and care should be taken to select the proper type for a particular purpose. Traps may be classified into two main types, viz. lifting and non-lifting. The latter is used when the condensate is discharged at a level lower than the trap and where the discharge of the condensate imposes no back pressure upon the trap. Lifting traps are used to raise the condensate to a level higher than the trap, in which case the trap must frequently be designed for a considerable back pressure.

Every trap should be provided with some means of testing its condition while at work, and with a by-pass to permit of its being removed for repairs. A non-return valve should be fitted on the outlet of the trap, where it discharges into a common condensate main or where the water is to be conveyed to a higher level.

Many manufacturers specialise in the manufacture of all types of steam traps, and when purchasing such appliances the fullest informa-

tion should be given in the specification and enquiry in order that the most suitable type is supplied.

Steam Reducing Valves.

Steam at reduced pressure is frequently required in many departments of a chemical works. It is usual to supply steam at high pressure to the department concerned, and reduce close to the point of use, thereby keeping the steam supply pipe as small as possible.

The principle of most reducing valves is the balancing of a double beat valve by assisting the low-pressure side of the valve by a spring, which can be varied in strength for various reduced pressures. In this way the pressure in the reduced main is automatically controlled, since if the pressure in the reduced side rises beyond that arranged for, the double beat valve closes and steam is not again admitted until the reduced pressure falls.

Relay reducing valves are desirable especially with widely fluctuating loads to prevent hunting of the valve and wide variations in steam pressure.

The protection of pressure vessels connected to reduced pressure mains is dealt with in Chapter VI, page 236.

Flow of Steam in Pipes.

In determining the size of a steam main the known factors are usually the quantity of steam to be conveyed, the initial pressure and temperature, and the length of the main. These are not sufficient definitely to fix the size of the pipe, as the permissible pressure drop or the velocity of flow must first be decided upon. These two factors are interdependent, and both are subject to limits which it is not wise to exceed.

It is not possible to lay down any hard and fast rules on the subject of velocities of steam flow, as so much depends on the circumstances of each individual case. In addition to the velocities being limited by the permissible drop in pressure, there are certain maximum values which should not be exceeded. One of the chief limiting factors is the erosive action of the steam on the valve seats and other similar exposed parts. This action is more pronounced with wet than with superheated steam. The velocity of wet steam should, therefore, not be as high as that of superheated steam. As a guide the following values may be based on :—

For exhaust steam	70–100 ft. per sec.
„ saturated steam	100–130 „ „
„ superheated steam	130–200 „ „

If it is decided to use a definite velocity, the bore of the pipe may be determined from the following formula :—

$$D = 1{\cdot}75\sqrt{\frac{Wv}{V}} \quad . \quad . \quad . \quad . \quad (1)$$

where D = bore of pipe in ins.
W = weight of steam in lbs. per min.
v = mean specific volume of steam in cu. ft. per lb.
V = steam velocity in ft. per sec.

More often, however, it is the permissible pressure drop which is the determining factor. This is generally kept at about 2 per cent. of the initial pressure per 100 ft. of pipe.

If the pressure drop is the determining factor, the following formula will give the size of pipe :—

$$P_1 - P_2 = 0{\cdot}000132\left(1 + \frac{3{\cdot}6}{D}\right)\frac{W^2 L v}{D^5} \quad . \quad . \quad (2)$$

where P_1 = initial pressure in lbs. per sq. in.
P_2 = final pressure, in lbs. per sq. in.
L = equivalent length of pipe, in ft.

The " equivalent length " of the pipe is its actual length with an allowance sufficient to compensate for the additional friction of any fittings in the installation as compared with straight pipe. Judgment must be used to allow the appropriate amount to substitute for each of the usual fittings, based upon the data given on page 271.

Equation (2) can easily be solved by the use of the alignment chart given in Fig. 119. From this any of the unknown quantities can be obtained, provided the others are known. In using the double " v " and " W " scales it is to be noted that the two red or the two black graduations must be read together.

The scales are divided in terms of :—

(1) Specific volume of steam, in cu. ft. per lb.—scale headed " v."
(2) Bore of main, in ins.—scale headed " D."
(3) Weight of steam discharged, in 1 lb. per min.—scale headed " W."
(4) Drop in pressure, in lbs. per 100 ft. run—scale headed " p."

To find the discharge under given conditions, the proper values of p and D are joined by a straight edge, the point where this crosses the line I noted, and this point joined to the proper value of v. The point at which this last line cuts the W scale indicates the weight of the discharge. To find the volume of the discharge this weight has only to be multiplied by the volume per lb.

The same result follows if first of all values of W and v are used to fix a point on line I, this point being joined to the proper value of p to find the value of D. To find the best values of two of the factors v and W or D and p, the other factors being known, join values of the known factors and note where this line cuts line I ; any line through this point cuts the other scales in values satisfying the required conditions, so that by rotating a straight edge about this point the variations of the factors can be studied and the best values selected.

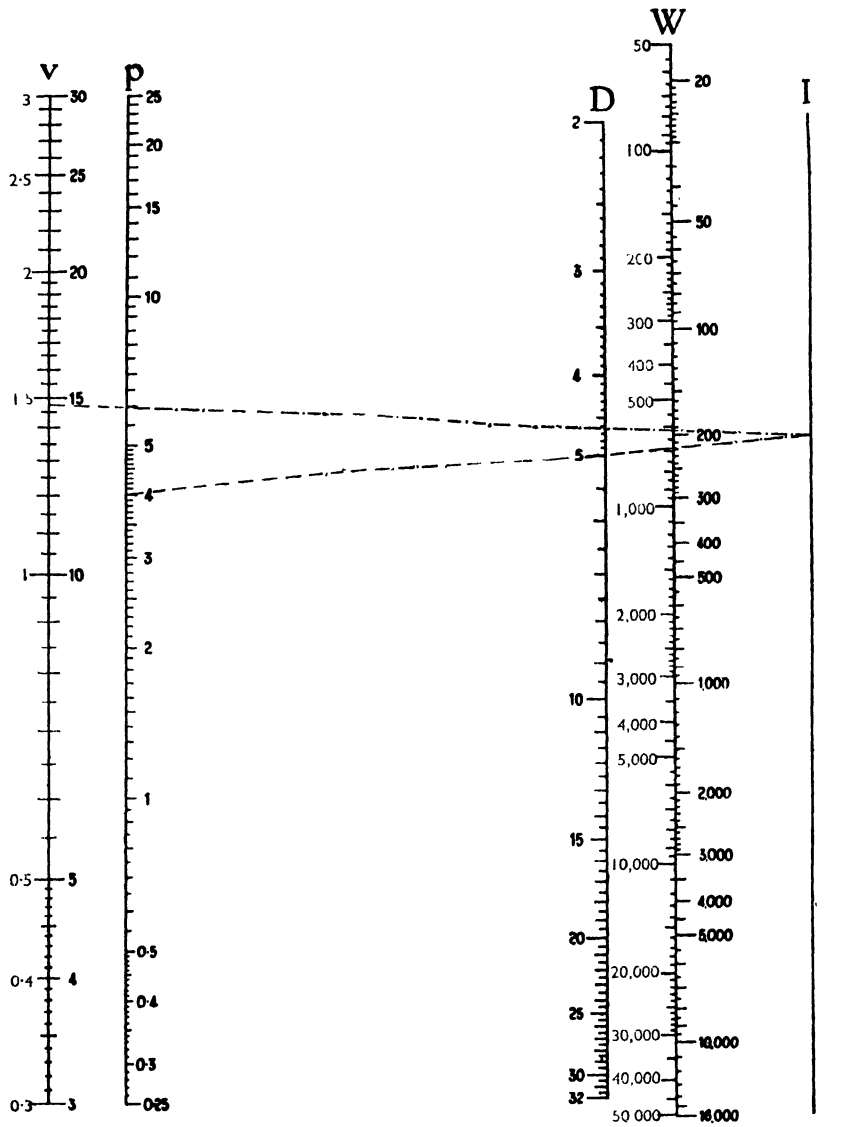


CHART FOR CALCULATING FLOW OF STEAM IN PIPES

FIG. 119.

Examples.

Required to find the flow of steam in a 5-in. main, the working pressure being 385 lbs. per sq. in. (gauge) superheated to 595° F. and the fall of pressure 4 lbs. per 100 ft.

The specific volume corresponding to the given temperature and pressure is, from steam tables, 1·47 cu. ft. per lb. Join 4 on *p* scale to 5 on D scale, note where this line cuts scale I and join this

point to 1·47 on v scale. Where this line cuts scale, W gives the value of the flow—610 lbs. per min.

It will be noted that the same line also gives the discharge for a value of v of 14·70 cu. ft. per lb., say 21 lbs. per sq. in. (gauge), superheated to 440° F. The discharge in this case is 195 lbs. per min. To prevent confusion the two sets of values of v and W are printed in black and red, figures of the same colour being read together.

If, in the above example, the weight discharged per min. is given—610 lbs.—and the bore of the main is to be found, the procedure is reversed and the point found on scale I is joined to point 4 on p scale, cutting scale D at the required value—5-in. bore.

The dotted lines show the above operations. These should not actually be drawn in use.

The velocities corresponding to the above data would be about 110 ft. per sec. and 350 ft. per sec. respectively.

An outstanding example of a large industrial plant necessitating the transmission of steam over long distances is that installed at the Billingham synthetic ammonia and nitrates works of Imperial Chemical Industries (Humphrey, Buist, and Bansall, *Journal I.E.E.*, 1930, **68**, 1233). Briefly, this plant consists of eight three-drum pulverised-fuel boilers, each designed to operate normally at an output of 215,000 lbs. of steam per hour. The normal saturated steam pressure is 715 lbs. per sq. in. abs., but the supply pressure to the high-pressure distributing receiver is 675 lb. per sq. in. abs., the maximum steam temperature being 458° C.; and the steam is supplied to three 12,500 kW. back-pressure turbines exhausting at 290 lbs. per sq. in. abs. and 345° C. into a low-pressure receiver from which it is passed to (*a*) process plant steam mains and (*b*) two 12,500 kW. condensing turbo-alternator sets. From the latter the steam is wholly extracted and is used in four feed-water heaters and in an unusually large quadruple-effect distillation plant which supplies make-up feed water to the boilers. The low-pressure receiver is equipped to act as a desuperheater for any steam passed directly to it through a reducing valve from the high-pressure line, There are altogether seven feed heaters, and the feed temperature at inlet to the Foster steaming economisers is 205° C.

The total steam output of the boilers is 11,900,000 kg. per day, of which 6,930,000 kg., or about 57 per cent., is used for the process plants. About 42 per cent. of this amount—i.e. about 24 per cent. of the total output—cannot be recovered, hence the large capacity of the distillation plant installed. The maximum distance of transmission of steam in this plant is stated to be 1 mile, both for the high-pressure (290 lbs. per sq. in.) steam and for a 30 lb. per sq. in. low-pressure supply. The 290 lbs. per sq. in. process plant steam is utilised in driving non-condensing reciprocating engines and turbines, the

exhaust from which is used for heating purposes in evaporation vats. A number of mixed-pressure turbines serve to maintain a balance between power and heating steam requirements. The sizes of the steam mains are 7, 9, and 10 ins. internal diameter for the 715 lb. per sq. in. lines, and 12½ ins. internal diameter for the 290 lbs. per sq. in. lines ; the insulation consists of 1 in. of asbestos, 2½ ins. of magnesia composition, and a covering of ½ in. of hard-setting cement—a total thickness of 4 ins.

An American plant of considerable interest from the point of view of process steam supply is the Deepwater steam station erected on the east bank of the Delaware river in New Jersey (*Power Plant Engineering*, 1929). This station is run in the joint interests of three large companies, each of which has its own plant in the central building. The first two—which are power supply companies—have cross-compound turbo-alternator condensing units, of 53,600 kW. capacity, supplied from a pair of Babcock and Wilcox boilers (one standard and one reheat), with steam at 1215 lbs. per sq. in. abs. and a temperature of 385° C.

The third company—the Du Pont de Nemours Company—has a high-pressure turbine of 12,500 kW. capacity, identical in size and construction with the high-pressure turbines of the two larger sets. It is also supplied with steam at 1215 lbs. per sq. in. abs. and 385° C. from two standard Babcock and Wilcox boilers, and the whole of the power generated is delivered to the Du Pont Company. At normal load, this turbine exhausts 530,000 lbs. of steam per hour at 400 lbs. per sq. in. abs. into seven single-effect high-pressure evaporators, which in turn provide hourly 400,000 lbs. of steam at 180 lbs. per sq. in. abs. from raw water. This medium-pressure steam is superheated to 227° C. by live-steam reheaters and delivered by two 16-in. mains, 1500 ft. long, to the works of the Du Pont Company. The exhaust steam from the turbine is completely condensed in the, evaporators, and returned directly by centrifugal pumps to the suction of the boiler feed pumps.

The object of this rather unusual arrangement is to avoid the necessity of pumping back from the Du Pont works any condensate that might be available from the process plants. This has the disadvantage of requiring the use of evaporator plant of large capacity, and of reducing considerably the available " Rankine " heat drop of the steam through the reduction of pressure. The latter point is not, however, of great importance if the steam is used wholly for heating purposes. The Du Pont plant is interconnected with the systems of the two other companies. Should the process steam requirements necessitate the turbine working at full load, the excess power generated is supplied to the other electrical systems ; on the other hand, if the steam requirements are low and the electrical power developed in the

turbine in consequence insufficient, the deficiency can be made up from the other power systems. (These notes were taken from an interesting paper by Genève (*Inst. Mech. Eng.*, Advance Proof, June, 1938).)

Pipes and Pipework for other than Steam Services.

The chemical engineer to-day has a wide choice of materials for tubes for handling liquids, gases, etc., used in chemical process work. For example, the range of pipework now manufactured by Accles & Pollock includes materials of construction as given in Tables 41, 42, 43. This firm also manufactures steel capillary tubes with bore as small as 0·004 in. with an outside diameter of $\frac{1}{16}$ in., up to 0·4 mm. hole and 10 mm. outside diameter ; and where thermal conductivity is a requirement these capillary tubes can be obtained with a copper tube drawn tightly over the outside. Accles & Pollock also make tubing in a wide variety of special steels for use in the hydrogenation of coal and oil, the synthesis of ammonia, etc., and for such purposes tubes can be supplied for internal pressure as high as 2000 atms. (30,000 lbs. per sq. in.).

Fig. 120 shows a series of heating batteries made from " Staybrite " steel tubes. Most of the non-ferrous materials suitable for chemical plant are now available in tube form, e.g. copper and copper alloys, aluminium, nickel, Monel metal, silver, lead, etc. In addition, chemical stoneware, hard rubber, fused silicia, and other non-metallic materials including plastics (e.g. Bakelite, Haveg, etc.) are now made into tubes.

In the latter connection the following description of a new plastic will be of interest. This material is based on polyvinyl chloride, and tubes are now made under the trade name " Mipolam," which has the following properties.

Specific gravity	1·38
Tensile strength	600 kg./sq. cm.
Softening point	Martens 67°, Vicat 89° C.
Coefficient of expansion . . .	65×10^{-6} per °C.

It is absolutely resistant to vegetable and mineral oils and alcohol, (it shows but a slight increase (up to 0·5 per cent.) in weight after 6 months' immersion in petrol), acetic acid, sodium carbonate, caustic soda (up to 50 per cent.), nitric acid 30 per cent., hydrochloric acid (30 per cent.), sulphuric acid including concentrated acid at 45° C. It is unsuitable for use with acetone, ether, benzene, cyclohexamone, ethyl acetate, chlorohydrocarbons and nitrating acids. It is non-inflammable.

Tubes in this material can be sawn, filed, turned and drilled with ordinary metal working tools. Since the material becomes plastic above 80° C. it can be softened at any convenient source of heat, and

TABLE 41.

WELDLESS TUBES—CARBON STEELS.

Purposes.	Quality.	Analyses (per cent.).							Physical Properties.			
		Carbon.	Manganese.	Silicon.	Sulphur.	Phosphorus.			Condition.	Tons per sq. in. Yield.	Tons per sq. in. Ultimate.	Elongation (per cent in 2 ins.
For parts not subjected to severe stresses For easy manipulation *Note.*—For case-hardening and welding, order specially	B	0·20 max.	0·80 max.	0·30 max.	0·05 max.	0·05 max.	—	—	—	As drawn	24 min.	27 min.	10
										Blued at 400° C. . .	26 min.	28 min.	15
										Annealed at 650° C .	11 min.	20 min.	40
For case-hardening Also a good steel for oxy-acetylene welding	Special case-hardening steel	0·12 to 0·18	0·50 to 0·80	0·10 to 0·30	0·05 max.	0·05 max.	To Harden.—Carburise at 900° C. and cool in the box. Time depends on depth of casing required. Re-heat to 900° C. and quench in water or oil to refine core. Heat again to 760° C. and quench in water			As drawn	25–28	28–32	10
										Blued at 400° C. . .	28 min.	30 min.	15
										Annealed at 650° C. .	11 min.	20 min.	40
										Welded	15 min.	24 min.	10
										Normalised at 880° C.	13–16	23–26	35
A grade of steel between B quality and A quality	1A	0·20 to 0·30	0·50 to 0·80	0·30 max.	0·05 max.	0·045 max.	—	—	—	As drawn and blued at 400° C.	28–33	32–38	10
										Annealed at 650° C. .	14 min.	24 min.	40
										Normalised at 850° C.	16–20	27–32	32
Harder than B quality For parts where a higher yield point is required after heat treatment—e.g. brazing Can be oxy-acetylene welded	A	0·30 to 0·40	0·80 max	0·40 max	0·04 max.	0·04 max	—	—	—	As drawn	30–35	35–40	10
										Blued at 450° C. . .	30 min.	35 min.	15
										Annealed at 700° C. .	18 min.	28 min.	35
										Normalised at 830° C.	20–26	32–38	28
A hard steel for bushes, etc. Can be hardened in oil To Harden.—Quench in oil from 850° C. and temper to suit degree of hardness required Gives higher yield point than A quality after brazing. etc. Not suitable for welding	K	0·40 min.	0·80 max.	0·40 max	0·05 max.	0·05 max	—	—	—	As drawn	35 min.	40 min.	5
										Blued at 450° C. . .	35 min.	40 min.	10
										Annealed at 750° C. .	23	34 min.	30
										Normalised at 830° C.	25–30	37–42	26
A high carbon steel Can be oil hardened. Not suitable for welding. Care must be exercised to prevent over-heating if used for brazing	No. 11 Carbon	0·50 to 0·60	0·60 max.	0·40 max.	0·04 max.	0·04 max.	—	—	—	Blued at 450° C. . .	40 min.	45 min.	12
										Annealed at 700° C. .	24 min.	35 min.	30
										Normalised at 820° C.	30–33	45–50	25
										Oil quenched from 850° C. . . . . Temp. at 400° C. .	75	80	8

TABLE 42.

Weldless Tubes in Low Alloy Steels.

Purposes.	Quality.	Analyses (per cent.).							Physical Properties—Approximate.			
		Carbon.	Manganese	Silicon.	Sulphur.	Phosphorus.	Nickel.	Chromium.	Molybdenum	Condition.	Tons per sq. in. Yield.	Tons per sq. in. Ultimate.	Elongation (per cent in 2 ins.).
For oil hardening and tempering . . A high-tensile steel, with good ductility	3 per cent. nickel steel	0·40 to 0·48	0·60 max.	0·35 max.	0·04 max.	0·04 max.	2·75 to 3·50	—	—	Blued at 450° C. . . .	45	50	12
										Annealed at 750° C. . .	26	37	26
										Hardened in oil from 830° C. . . . . Tempered at 350° C.	88	95	12
For either air hardening or oil hardening For parts subjected to severe stresses, such as aircraft axles Supplied in the annealed or hardened condition only	Nickel-chrome steel	0·25 to 0·35	0·65 max.	0·35 max.	0·04 max.	0·04 max.	4·0 to 4·5	1·10 to 1·40	—	Annealed	38	50	23
										Air hardened from 850° C. and tempered at 280° C.	78 min.	85 min.	5 min.
A steel having good tensile strength after oxy-acetylene welding	5M manganese steel	0·30 max.	1·5 max.	0·30 max.	0·05 max.	0·05 max.	—	—	—	As drawn and blued at 400° C.	35	40	10
										Annealed	18	28	35
										Welded	25	30	12
										Normalised at 850° C. .	25	40	25
A steel having high tensile strength, and suitable for oil hardening and tempering	8M manganese steel	0·50 max.	1·2 to 1·5	0·30 max	0·05 max.	0·05 max.	—	—	—	As drawn	40	45	10
										Annealed at 750° C. . .	25	39	26
										Quenched in oil from 820° C. . . . . Tempered at 400° C.	80	90	10
An alloy steel giving high tensile values after oxy-acetylene welding Excellent for manipulating, hardening, etc.	Chrome-molybdenum steel	0·25 to 0·35	0·60 max.	0·30 max.	0·04 max.	0·04 max.	—	0·80 to 1·10	0·15 to 0·25	As drawn	35	43	12
										Welded	30	35	6
										Annealed	20	30	35
										Normalised at 920° C. .	40	50	12
										Quenched in water from 900° C. and tempered at 480° C.	60	70	10
Similar to standard chrome molybdenum, but with a higher carbon content. Suitable for oil hardening and tempering where greater toughness is required	High-carbon chrome-molybdenum steel	0·45 to 0·55	0·50 to 0·80	0·30 max.	0·04 max.	0·04 max.	—	0·80 1·10	0·15 to 0·25	As drawn	45	50	10
										Annealed at 720° C. . .	27	38	30
										Normalised at 800° C. .	50	65	10
										Oil hardened from 850° C. Tempered at 320° C.	85	100	5

TABLE 43.

Weldless Tubes in Stainless Steels.

Purposes.	Quality.	Analyses (per cent.).								Physical Properties—Approximate.			
		Carbon.	Manganese.	Silicon.	Sulphur.	Phosphorus.	Chromium.	Nickel.		Condition.	Tons per sq. in. Yield.	Tons per sq. in. Ultimate.	Elongation (per cent in 2 ins.).
A martensitic steel, easy to manipulate Commonly known as "stainless iron"	Chrome stainless steel	0·12 max.	0·50 max.	0·20 max.	0·04 max.	0·04 max.	11 to 14	—	—	As drawn Annealed at 650° C.–700° C. Normalised at 900° C.	30 16	35 26 up to 70 max.	10 35 12
A martensitic steel, harder to manipulate than "stainless iron," but offering greater resistance to corrosion, especially sea water	2-20 stainless steel	0·20 max.	0·80 max.	0·30 max.	0·04 max.	0·04 max	16 to 20	1·5 to 2·0	—	Air hardened and tempered Softened 650° C.	45 33	55 43	8 25
An austenitic steel Can be hardened by cold work only Suitable for manipulating and welding, but must be fully softened after welding	11–15 stainless steel	0·15 max.	0·50 max.	0·25 max.	0·04 max.	0·04 max.	14 to 16	11 to 13	—	As drawn Fully softened	40 15	50 36	10 50
Similar to 8–18 but need not be heat-treated after welding	Austenitic welding stainless steel Firth's F.D.P.	0·20 max.	0·80 max.	0·50 max.	0·04 max.	0·04 max.	17 to 19	7 to 9	Tungsten 1·0 Titanium 1·0	Similar to 8–18. (See below)			
	Brown-Bayley's Weld-Anka	0·20 max.	0·80 max.	1·5 to 2·0	0·04 max.	0·04 max	20	9	—				
An austenitic steel, slightly different in composition from 11–15 This steel work-hardens fairly rapidly More difficult to manipulate than 11–15 Satisfactory for welding, but must be fully softened after welding	8–18 stainless steel	0·15 max.	0·60 max.	0·25 max.	0·04 max.	0·04 max	17 to 19	7 to 9	—	As drawn Fully softened	45 15	55 40	12 50

then moulded as desired. To join successive lengths of Milopam one end of one tube is warmed slightly and then expanded to receive the end of the next tube. The joint is made by a special adhesive. T-pieces, etc., can be made in a similar way (H. Lutz, *Chem. Fabrik.*, 1936 (Sept.), p. 441).

In so far as fabrication of chemical pipework is concerned, in view of the wide variety of materials of construction, and the special nature of most chemical process pipework, it is impossible to give any detailed rules. In regard to large pipework for gases and liquids, the principles given for steam pipework are often applicable. In so far as properties of materials used are concerned the reader is referred to the appropriate chapter earlier in the book.

Graphical Method of determining Pressure Drop and Heat Transfer to Pipes.

R. A. Bayard, *Chem. Met. Eng.*, 1932, **39**, 130.

By the chart (Fig. 121) it is possible to determine the pressure drop for any fluid, either liquid or gas, under conditions of flow, either viscous or turbulent. It also gives, (1) film heat-transfer coefficient for liquids ; (2) optimum size of pipe taking into account both cost of pipe and pumping ; (3) A handy method for converting flow rate in one set of units into flow in another ; (4) equivalent values for specific gravity and density in lbs. per cu. ft. ; (5) gallons (U.S.) per min. and cu. ft. per sec. ; (6) pressure drop in lbs. per sq. in. and ins. of water ; (7) kinematic viscosity and viscosity in centipoises.

Nomenclature.—C = specific heat, k = heat conductivity B.Th.U./hr./sq. ft./° F. per ft. thickness, S = specific gravity (water = 1), Z = viscosity in centipoises relative to water at 68° F.

Pressure Drop in Pipelines.—By the use of equation based on Fanning's formula it is possible to calculate the pressure drop in 100 ft. of pipe (clean and straight) when the pipe diameter, cu. ft. per sec. flowing and viscosity of fluid are known. This has been worked out for the chart by supplying the friction factor of Walker, Lewis and McAdams and graphically solving the equation. The method of using this chart for this purpose is shown by the solid line and the arrows indicate the order in which to pass from step to step. *Problem as example.* Required to find the friction pressure drop per 100 ft. of 2½-in. steel pipe with a flow of oil of 90 gals. per min. Specific gravity of oil 0·8 and viscosity 2·5 centipoises.

Procedure.

(1) Start on bottom line at 90 gals. per min., rise vertically to meet the diagonal line for 2½-in. pipe.

(2) Go horizontally to the right to meet the dashed line for 2½ in.

pipe, then vertically down to base line, read there lineal velocity in pipe = 6·2 ft. per sec.

(3) Extend the horizontal line to the left to meet the kinematic viscosity line the quotient of $\frac{S}{Z} = 0{\cdot}32$. This line is the diagonal through the point of intersection of the vertical specific gravity line 0·8 and the horizontal viscosity line 2·5. Or it is obtained by dividing S by Z.

(4) Rise vertically to the friction curve for steel pipes.

(5) Go horizontally to the right to meet the diagonal density line for a specific gravity of 0·8.

(6) Rise vertically to meet the diagonal line for a 2½-in. pipe.

(7) Go horizontally to the left to meet the diagonal velocity line. Its value 6·02 ft. per sec. was found in step (2).

(8) To determine the final answer rise vertically and read the pressure drop per 100 ft. of pipe on the top line. The quantity is 2·4 lbs. per sq. in.

Pressure drop through fittings allowed for by taking for each fitting an equivalent length of straight pipe. The equivalent (in ft. length) is approximately the pipe diameter in ins. × 2·75 for elbows, 5 for side way of tees, 7·5 for globe valves, 1 for gate valves.

For old piping allowance must be made for condition of the interior.

Optimum Pipe Size.—The three vertical scales in the upper left corner of the chart marked Density, Flow Rate and Pipe Diameter are drawn so that a straight line, through the fluid density and the flow rate in cu. ft. per sec., will pass through the diameter of the most economical pipe size. Calculations for this nomograph are based on cost of pumping and cost of pipe. If previous worked example is taken, the chart shows that a 3-in. pipe should be used instead of a 2½-in. pipe, from the point of view of greatest economy.

Heat-Transfer Coefficients of Fluids in Pipes.—In the design of heat exchangers, it is important to know the pressure drop through the tubes as well as the heat-transfer coefficient. It is desirable to have the solution to both problems on one chart so that the relation between pressure drop and heat-transfer coefficients may be readily noted. The heat-transfer chart uses the same base line as the pressure-drop chart. This can be done because both are a function of the Reynolds number.

The heat-transfer curves marked air, water and oil are the " straight-line curves " of Walker, Lewis and McAdams. The CZ curves which are used for any liquid are based on later data and are not plotted for specific temperature as the others. They make use of the relation found by Morris and Whitman between the Reynolds number and the film coefficient. The method of using the chart for the air, oil and water curves in solving for the heat-transfer coefficient is shown by the arrowed dotted lines. The conditions of the problem are the same

as those postulated above for the pressure-drop solution. In addition, the conductivity k is taken as 0·8.

Procedure.

(1) Same as step (1) for pressure drop.

(2) Omitted.

(3) Same as step (3) for pressure drop.

(4) From the kinematic viscosity line S/Z rise vertically to meet the oil line instead of stopping at the friction curve as in the pressure-drop problem. The heat-transfer lines are readily distinguished from the pressure-drop lines by being started in the opposite direction.

(5) Go horizontally to the right to meet the dashed line for the $2\frac{1}{2}$-in. pipe.

(6) Rise vertically to the heat conductivity line for $k = 0{\cdot}8$.

(7) Go horizontally to the right and read the film coefficient 68 on the right hand vertical scale.

(8) For obtaining the corrected value multiply by the factor $\left(1 + \frac{50}{r}\right)$, where r = ratio of length of straight pipe to inside diameter. For example, in the present problem, the coefficient read is 68. If the length of straight pipe is 18 ft. the correction factor is

$$1 + \frac{50}{18 \times 12 \div 2{\cdot}47} = 1{\cdot}57.$$

Hence $68 \times 1{\cdot}57 = 107$, which is the corrected factor of the coefficient. For fluids other than air, water and oil, the procedure is as above, except that in step (4) the dotted line rises to the appropriate CZ curve. E.g. if specific heat of the oil is 0·5 and viscosity is 2·5, then $CZ = 0{\cdot}5 \times 2{\cdot}5 = 1{\cdot}25$. Rise then from the $\frac{S}{Z}$ line to meet the (CZ = 1·25) curve (interpolated). Then go to the right to the pipe size line and follow through the remaining steps to reach the coefficient on the right-hand scale. For the corrected coefficient multiply by a factor obtained from the table in the upper right corner of the chart. The proper value depends on k and is chosen for either heating or cooling. In this example the coefficient is 58 and the factor for cooling interpolated from the table for $k = 0{\cdot}08$ is 1·79. Hence the corrected coefficient is 104 B.Th.U. per hour per sq. ft. per ° F.

CHAPTER VIII

HEAT INSULATION.

THE heat loss from steam, hot water, and hot liquor pipework, etc., and the loss of refrigeration from refrigerating equipment, depends upon the temperature of the apparatus, the nature of the surrounding atmosphere and the thickness and nature of any covering applied. The requirements of a good non-conducting insulating material include in general :—

(1) Freedom from danger of combustion.
(2) Good non-conducting properties.
(3) Durability under working conditions.
(4) Easily handled and applied to the surface to be lagged.
(5) Light in weight.
(6) Not attractive to vermin.

Few, if any, materials combine all the above desirable features but many closely approach the ideal.

A survey of insulating materials available and suitable for large-scale thermal insulation indicates that the majority of them have but a limited application, and it is by varying combination of these materials that most commercial insulating materials are produced. The range of various insulating materials can be classified according to the working temperature as follows :—

Group 1. *Temperature below* 200° *F.*

Use.	*Materials.*
Refrigeration	Granulated cork and cork board.
Cool-water systems	Wood and wood pulp. Charcoal.
Hot-water systems	Sponge rubber, aluminium foil. 85 per cent. magnesia-asbestos.
Buildings	Wool and hair felts.

Group 2. *Temperature* 200–650° *F.*

Use.	*Materials.*
Boilers and steam Pipes, etc. Steam turbines Hot-air systems Flue gas ducts	85 per cent. magnesia-asbestos and other magnesia compositions, slag wool, spun glass, bonded asbestos and other asbestos products, aluminium foil and other metal foils and sheets. Silicas and clays.

Group 3.	*Temperature* 600–1200° *F.*
Use.	*Materials.*
Superheated steam plant Stoves and ovens Oil Engine Exhausts	Asbestos (up to 850° F.), spun glass (up to 900° F), kieselguhr, aluminium foil, magnesia-kieselguhr-asbestos mixtures. Silicas and clays.

Group 4.	1000° *F. upwards.*
Use.	*Materials.*
Kilns, furnaces, stoves and ovens	Silicas and clays, natural and manufactured in various forms.

Economy of Insulation.

The saving in heat by the various materials suitable for use in a particular problem should be set against the interest upon the capital outlay and consideration of the probable life of the equipment to be insulated. It must be noted that the bulk of any saving of heat by insulation is obtained by the primary thickness applied, and subsequent increments have an increasingly less effect (see Fig. 122).

The following discussion of the fundamentals of heat insulation is based upon a recent paper by Gard (*Jour. Inst. Fuel*, 1937, X, 224).

Thermal Conductivity.

Thermal Conductivity in so far as insulation is concerned is usually expressed in English units as the number of B.Th.U. passing per hr. across 1 sq. ft. of material through a thickness of 1 in. with a difference of temperature of 1° F. between the two faces of the material in question. The thermal conductivity of an insulator is not a constant quantity, but varies, often greatly, with the temperature at which it is considered. It so happens that for all practical purposes the variation of thermal conductivity with temperature closely approximates to a straight-line law, and hence the conductivity coefficient over a given thickness of material may be taken as the arithmetical mean of the coefficient at the temperatures occurring at the two planes which bound the given thickness.

Heat Transmission.

Heat Transmission from an Insulated Pipe.—From mathematical considerations it can be deduced that the following formula will give the heat transmission for a homogeneous cover :—

$$Q = \frac{2\pi K(t_1 - t_2)}{A\left(\log_e \frac{D_2}{D_1}\right)},$$

where Q = the heat transmission per sq. ft. of pipe surface.
K = the coefficient of thermal conductivity of the covering.
t_1 and t_2 = the inner and outer surface temperatures of the covering.
A = the pipe area per ft. run.
D_1 = the outer diameter of the pipe.
D_2 = the outer diameter of the cover.

Where several layers of different conductivity are employed the formula becomes :—

$$Q = \frac{2\pi(t_1 - t_4)}{A\left[\frac{\log_e \frac{D_2}{D_1}}{k_1} + \frac{\log_e \frac{D_3}{D_2}}{k_2} + \frac{\log_e \frac{D_4}{D_3}}{k_3}\right]},$$

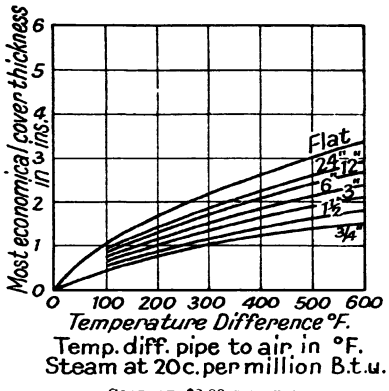
where the successive layers have diameters of D_2, D_3 and D_4 and conductivities of k_1, k_2 and k_3, respectively, and t_4 is the final outer surface temperature.

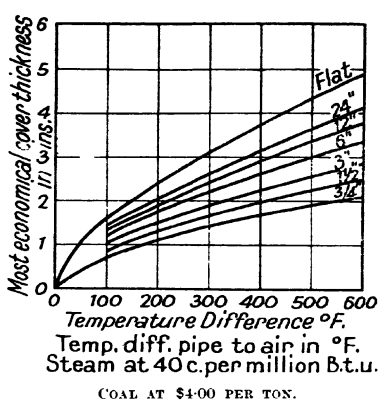
Notes on the Use of the Above.—In the above formulæ t_2 (or t_4) is the temperature of the surface and not that of the surrounding air. All calculations depend upon a knowledge of this temperature ; in fact, as will be shown later, the " external " method of calculation depends entirely upon this. Surface temperature presents the great difficulty of linking up theory with its application, since the basis of all such application is the experimental determination of this value. Surface temperatures for 85 per cent. magnesia on a pipe of 6-in. internal diameter are given in the following table :—

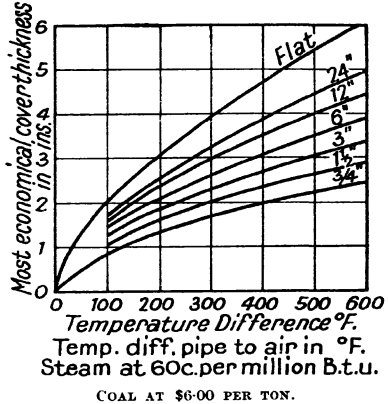
SURFACE TEMPERATURES OF 85 PER CENT. MAGNESIA FOR VARIOUS INTERNAL TEMPERATURES WITH ATMOSPHERIC TEMPERATURE OF 70° F. AND CALM CONDITIONS.

Internal Temp. in ° F.	Thickness of Covering in ins.					
	1 in.	1½ in.	2 ins.	2½ ins.	3 ins.	4 ins.
100	75	74	73	72	72	71
200	91	86	83	80	78½	76
300	107	98	93	88	85	82
400	123	111	102	96	91	87
500	139	123	112	104	98	92
600	155	135	122	112	104	98
700	171	147	132	120	110	102

FIG. 122.—PROPER THICKNESS OF COVERING FOR MAXIMUM NET SAVING. (For Covering by 85 per cent. Magnesia.)







COAL AT $2·00 PER TON.

Size Pipe.	Hot Water 175° F.	Steam (5 lbs.).	Steam (100–200 lbs.).	200 lbs. 150° F. Super-Heat.	200 lbs. 300° F. Super-Heat.
¾"	S	S	S	1¼"	DS
1½"	S	S	S	1½"	DS
3"	S	S	S	1½"	DS
6"	S	S	1¼"	2"	DS
12"	S	S	1½"	2"	DS
24"	S	S	2"	3"	DS
Flat	1"	1½"	2"	3"	3½"

S—Standard thickness.

COAL AT $4·00 PER TON.

Size Pipe.	Hot Water 175° F.	Steam (5 lbs.).	Steam (160–200 lbs.).	200 lbs. 150 F. Super-Heat.	200 lbs. 300° F. Super-Heat.
¾"	S	S	1½"	DS	2"
1½"	S	S	1½"	DS	2"
3"	S	S	DS	DS	3"
6"	S	1¼"	DS	3"	3"
12"	S	1½"	DS	3½"	4"
24"	S	1½"	DS	3½"	4"
Flat	1½"	2"	3"	4"	5"

COAL AT $6·00 PER TON.

Size Pipe.	Hot Water 175° F.	Steam (5 lbs.).	Steam (100–200 lbs.).	200 lbs. 150° F. Super-Heat.	200 lbs. 300° F. Super-Heat.
¾"	S	S	DS	2"	2"
1½"	S	1¼"	DS	2"	3"
3"	S	1½"	DS	3"	3"
6"	1¼"	2"	DS	3"	4"
12"	1½"	2"	DS	4"	4"
24"	1½"	2"	DS	4"	5"
Flat	2"	3"	4"	5"	6"

DS—Double standard thickness.

These curves and tables are taken from paper by Glen D. Bagley, read before the American Society of Mechanical Engineers, December 1918.

These curves and tables give the proper thickness for maximum net saving for different costs of steam and different sizes of pipe. They refer particularly to 85 per cent. Carbonate of Magnesia coverings, but can be used with satisfactory results for any type of pipe covering having approximately the same efficiency as 85 per cent. carbonate of magnesia.

They are based on a period of service of 8760 hrs. per year. If pipes are cold part of the year these curves can still be used, providing the cost of steam is multiplied by the number of hours per year the pipes are hot and divided by 8760. Then take this revised cost of steam and select the set of curves whose steam cost most nearly corresponds. The thicknesses specified are conservative since in arriving at these curves it was assumed that the cost of covering would be list price plus the proper cost of application. The annual fixed charges were figured at 13 per cent. on the investment.

These tables are based on average conditions. In transforming the steam cost to coal cost it has been assumed that 75 per cent. of the cost of steam is coal cost, that 1 lb. of coal will evaporate 7 lbs. of water, and that each pound of steam contains about 1000 B.Th.U. above the feed water temperature.

HOW TO USE THESE TABLES.

Determine your cost of coal, steam pressure and size of pipes; select the table where the coal cost most nearly corresponds to your coal cost. Then select the column where the steam pressure most nearly corresponds to your steam pressure. The thicknesses in this column are the proper thicknesses for the pipe sizes given at the left of the table.

Example.—Cost of coal $3·75, steam pressure 150 lbs., size of pipe 12 in. Select the $4·00 per ton table and the third column headed "Steam at 100–200 lbs." Run down this column to the 12-in. pipe size line and find the proper thickness to be DS (3½ ins.).

External Consideration of Heat Transmission.

Surface Coefficient.—Estimations are often facilitated by the use of arbitrary surface coefficients for various materials. If we define the heat dissipated from a surface in B.Th.U. per sq. ft. of surface per hr. per 1° F., temp. diff., then the heat transfer for still air may be expressed for flat surfaces as

$$Q = \alpha(t_s - t_a)$$

where α = the surface coefficient defined as above.
t_s = the surface temperature in ° F.
t_a = the temperature of the air in ° F.

For a cylinder the expression becomes

$$Q = \alpha \frac{D_2}{D_1} (t_s - t_a),$$

where Q = the heat flow in B.Th.U./sq. ft. of pipe surface/hr.
D_1 = the external diameter of pipe.
D_2 = the external diameter of covering.

The expression represents a relationship only and does not portray the physical effects of conduction and radiation, which are discussed later.

α is a variable, increasing with internal temperature. An advantage of the use of a surface coefficient is that a small error in the assessment of its value influences the result by a much less amount than an error in the estimation of surface temperature. For hot face temperatures between 100° F. and 800° F. the change in α is some 20 per cent. for 85 per cent. magnesia. The surface temperature can be eliminated in the foregoing formulæ by substituting a value derived on the assumption that α is constant. For a particular case the possible error, of course, will be dictated by the limits of variation of α.

Heat Loss by Radiation.—From the results of Dulong and Petit's experiments Stefan proposed the formula :—

$$R = \text{constant} \times T^4,$$

where R = the rate of emission of energy by radiation from a body and T = the absolute temperature of the body.

The transfer of heat by radiation, therefore, between two perfectly black bodies may be expressed by

$$H = E(T_1^4 - T_2^4),$$

where H = the heat radiated/unit area/unit of time.
E = a constant.
T_1 and T_2 = the absolute temperatures of the radiating and receiving surfaces.

When the emissivity of a surface is unity, the radiation is a maximum, under which conditions the value of E is 17×10^{-10} in British units. Only what is known as the "perfectly black" body can radiate or receive radiant energy to this extent. It follows, therefore, that some fraction of this amount is radiated or received by any particular surface, which can be expressed by a ratio e, the emissivity.

Thus we have in the practical case, assuming normal conditions of surroundings :—

$$H_R = e.E(T_s^4 - T_A^4)$$
$$= 17 \times 10^{-10} e(T_s^4 - T_A^4),$$

where H_R = the heat transfer by radiation in B.Th.U/sq. ft./hr.

T_s = the absolute temperature of the surface of the body in ° F.

T_A = the absolute temperature of the surroundings in ° F. (Usually the air temperature.)

For most conditions of surface encountered in insulation work, viz. canvas, hard setting compositions, plaster, cement, brick-work, etc., e has a value of 0·9 irrespective of colour and of paint, with the exception of paints having an aluminium base. Where sheet metal surfaces are involved the value of e is small, particularly for bright or polished surfaces.

For surfaces for which no recent data exist, an approximation may be derived from Peclet's values of emissivity. These cover a large variety of surfaces, among which lamp black is taken as 0·82. The value for lamp black, on which the above formula depends, approaches unity.

In the practical case Peclet's values may be increased in this ratio to give e. From an examination of the formula it will be seen that the radiation of heat depends not only upon the excess temperature of one body over another, but upon the magnitude of the temperatures of the bodies emitting and receiving the radiant heat.

Heat Loss by Convection.—The transfer of heat from a body to the surrounding air or vice versa occurs by direct contact between the two as well as by the radiation process previously referred to. This more direct heat transfer is termed convection. When the hot body is surrounded by still air, the process of transfer is termed "natural" convection. Layers of the surrounding fluid in the immediate vicinity of the surface become heated and movement of the fluid occurs, which assists the process. The extent of the movement is influenced by the size and shape of the body and the presence, or otherwise, of re-entrant portions. The velocity and direction of the engendered currents will be affected by the orientation of the surfaces, since the conditions of air movement will obviously be different for a heated surface facing downwards from those occurring on a

surface facing upwards or in the vertical plane. The estimation therefore of the convection loss is considerably complicated in practice, where every condition of size, shape and orientation may be encountered. Some degree of approximation therefore becomes necessary in practice. When the surfaces under consideration are not surrounded by still air all the factors become different. This condition is termed " forced " convection, since the naturally occurring air currents are replaced by a constant motion of the surrounding fluid, according to the velocity and direction of the disturbance. Under these conditions the estimation of the convection loss becomes more complicated and more difficult to apply to the practical case where all sorts of different circumstances exert an influence. The knowledge of the process of convection in still air has been largely augmented by the work of Griffiths and Davis, and extended by Fishendon and Dufton. Griffiths and Davis showed that the heat loss due to convection varied with the power 1·25 of the temperature difference between the surface and surrounding air.

Thus

$$H_c = C(t_s - t_a)^{1.25},$$

where H_c = the heat loss due to convection in B.Th.U./sq. ft. of exterior surface/hr.

t_s = the surface temperature in ° F.

t_a = the air temperature in ° F.

C = a constant depending upon the linear dimensions and shape of the hot body.

The constant C is a variable, influenced by orientation of the surface and its dimensions. For a given surface its value increases considerably when the dimensions are below about 1 ft.

For larger surfaces it assumes a more constant figure. In practice the important cases are those of the vertical plane and the horizontal cylinder. In the latter the value of C becomes almost constant when the diameter of the cylinder is 8 ins. or over. In insulation practice the diameter of the cylinder considered is, of course, that of the pipe plus the covering.

Values of C for particular cases are as follows :—

Vertical plane surfaces greater than 1 sq. ft. . .	C = 0·32
Horizontal plane surfaces facing upwards . .	C = 0·42
„ „ „ „ downwards . .	C = 0·21
Horizontal cylinders, diameter 8 ins. . . .	C = 0·3

The conditions affecting convection are too complex to express in a general expression so simple as $H_c = C(t_s - t_a)^{1.25}$. A very accurate determination cannot, therefore, be obtained from this equation, but for all practical purposes the agreement is close enough.

Heat Loss by both Radiation and Convection.

Combining the radiation and convection losses, we have :—

$$H_s = H_R + H_C,$$

where H_s = the total heat loss/sq. ft. of exterior surface in B.Th.U./hr.

H_R = the heat loss/sq. ft. by radiation in B.Th.U./hr.

H_C = the heat loss/sq. ft. by convection in B.Th.U./hr.

Then $$H_s = eE(T_s^4 - T_A^4) + C(t_s - t_a)^{1\cdot25}.$$

For a vertical flat surface with cement, composition and similar face, the equation becomes :—

$$H_s = 0\cdot9 \times 17 \times 10^{-10}(T_s^4 - T_A^4) + 0\cdot3(t_s - t_a)^{1\cdot25}$$
$$= 15\cdot3 \times 10^{-10}(T_S^4 - T_A^4) + 0\cdot3(t_s - t_a)^{1\cdot25}$$

It is usual when considering the heat transmission through covered pipes or larger cylinders to express the heat transmitted in units per sq. ft. of bare pipe surface, therefore :—

$$Q = \frac{D_2}{D_1} H_s = \frac{D_2}{D_1}(H_R + H_C),$$

where Q = heat loss in B.Th.U./sq. ft. of pipe surface/hr.

D_2 = the external diameter of covering.

D_1 = the external diameter of pipe.

Hence for the horizontal pipe covering with composition, or canvas surface and external diameter of 8 in. or more :—

$$Q = \frac{D_2}{D_1}[15\cdot3 \times 10^{-10}.(T_S^4 - T_A^4) + 0\cdot3(t_s - t_a)^{1\cdot25}]$$

Practical Insulation Data.

Insulation for Temperatures below 60° F.

In such cases, it is important that the material selected should not be susceptible to moisture absorption, since wherever a temperature appreciably lower than that of the surrounding air is long maintained there is sure to be condensation of moisture upon the cool surface. It is well known that moisture seriously impairs the thermal efficiency of most insulation of the absorbent type. The following table gives the average values of the thermal conductivity of thermally suitable insulations for low-temperature work.

Expanded rubber	0·23	Balsa wood	0·35
Corkboard	0·28	Yellow pine	1·1
Hair felt	0·30	Kapok	0·26
Wool felt	0·47	Slag wool	0·40

Cork is a good insulator, both structurally and thermally, for low-temperature conditions and is widely used in consequence. It

is interesting to note that cork is quite waterproof, and it is practically free from capillarity. Sponge rubber, a comparatively new product to this field, has the advantage of light weight and is thermally very efficient, but it is liable to deterioration if not used in suitable conditions. Other materials frequently used are hair and wool felts, light woods such as Balsa and slag wool.

Cork for insulation is sometimes supplied as granules to fill spaces provided for insulation purposes, but more generally in compressed corkboard form for flat work, and moulded shapes for pipe-work. Corkboard sheets can be obtained in the following standard sizes :— 12 ins. × 36 ins., 18 ins. × 36 ins., 24 ins. × 36 ins., and 36 ins. × 36 ins. The standard thicknesses are 1 ins., 1½ ins., 2 ins., 3 ins., 4 ins. and 6 ins. For pipe insulation moulded products can be obtained made from cork granules compressed and baked in moulds. Such moulded coverings are coated with a heavy asphalt plastic finish, and in cases where such covering must harmonise with surroundings, it is covered with 8-oz. canvas and given a sufficient number of coats of decorative paint.

The following thicknesses of cork insulation are recommended :—

Room Temperature.	*Thickness of Insulation.*
45° F. and over	2 ins.
35 to 45° F.	3 ,,
20 to 35° F.	4 ,,
10 to 20° F.	5 ,,
0 to 10° F.	6 ,,
— 10 to 0° F.	9 ,,

Non-Sweat Pipe Insulation.

It is essential to insulate all cool water and liquor pipes where condensation of moisture from the air will cause unsanitary and unsightly dripping from such pipes. The nature of such insulation will depend largely upon local conditions, but usually a combination of insulating and waterproofing felts is used.

Insulation for Temperatures of 200–650° *F.*

The heat losses from bare pipes and bare flat surfaces within this temperature range for various temperature differences between the hot body and the surrounding air are given in Table 44 (see following page).

For covering boilers, steam pipework and vessels up to about 650° F., a mixture of 85 per cent. magnesia and 15 per cent. long fibre asbestos is satisfactory and if properly applied will give commercial efficiencies of 80–90 per cent. This mixture is usually supplied dry in bags, and the procedure for applying to work is as follows :—

The mixture of magnesia and asbestos is mixed with sufficient

TABLE 44.

B.Th.U. per hour per Linear Foot of Bare Pipe and per Square Foot of Bare Flat Surface at Various Temperature Differences.

For finding losses at temperatures between those shown, the B.Th.U. Differences per degree are given in italic figures between the main columns.

Pipe Size.	Area of Pipe Surface per lin. ft.	Heat Loss in B.Th.U. per lineal ft. per hour. Temperature Differences.																	
		50°		100°		150°		200		250°		300°		350°		400°		450°		500°
½″	0·220	21·5	*0·52**	47·3	*0·64**	79·2	*0·76**	117·3	*0·90**	162·3	*1·06**	215·2	*1·28**	279·1	*1·52**	355·1	*1·93**	451·4	*2·37**	569·8
¾″	0·274	36·8	*0·64*	59·0	*0·79*	98·6	*0·96*	146·8	*1·11*	202·1	*1·33*	268·5	*1·58*	347·6	*1·89*	442·2	*2·40*	562·2	*2·95*	709·7
1″	0·344	33·6	*0·81*	74·0	*1·00*	123·8	*1·19*	183·4	*1·41*	253·7	*1·67*	337·4	*1·98*	436·5	*2·37*	555·2	*3·03*	705·4	*3·69*	891
1¼″	0·435	42·5	*1·01*	93·6	*1·26*	156·6	*1·51*	231·9	*1·78*	320·8	*2·09*	425·4	*2·53*	551·9	*3·00*	702·1	*3·80*	892·6	*4·68*	1126·7
1½″	0·498	48·7	*1·17*	107·2	*1·44*	179·3	*1·72*	265·4	*2·04*	367·3	*2·39*	487	*2·90*	631·8	*3·44*	803·8	*4·36*	1021·9	*5·36*	1289·8
2″	0·622	60·9	*1·46*	133·9	*1·80*	223·9	*2·15*	331·5	*2·54*	458·7	*2·99*	608·3	*3·62*	789·2	*4·29*	1003·9	*5·45*	1276·3	*6·69*	1611
2½″	0·753	73·4	*1·76*	161·6	*2·18*	270·4	*2·60*	400·3	*3·07*	553·9	*3·61*	734·5	*4·37*	952·8	*5·19*	1212·1	*6·58*	1541·1	*8·08*	1945·1
3″	0·917	89·6	*2·15*	197·3	*2·66*	330·1	*3·17*	488·8	*3·75*	676·3	*4·41*	896·8	*5·33*	1163·4	*6·33*	1480	*8·03*	1881·7	*9·87*	2375
3½″	1·047	102·3	*2·46*	225·3	*3·03*	376·9	*3·62*	558·1	*4·28*	772·2	*5·04*	1024	*6·09*	1328·4	*7·23*	1689·9	*9·17*	2148·4	*11·3*	2711·7
4″	1·178	115·1	*2·77*	253·5	*3·41*	424·2	*4·07*	627·9	*4·82*	868·8	*5·67*	1152·1	*6·85*	1494·6	*8·13*	1901·3	*10·3*	2417·3	*12·7*	3051
4½″	1·309	127·9	*3·07*	281·5	*3·79*	470·9	*4·53*	697·2	*5·35*	964·7	*6·29*	1279·2	*7·61*	1659·5	*9·03*	2111·1	*11·05*	2684	*14·1*	3387·7
5″	1·456	142·2	*3·42*	313·1	*4·21*	523·8	*5·03*	775·5	*5·95*	1073	*7·00*	1423	*8·46*	1846	*10·0*	2348·4	*12·7*	2985·7	*15·7*	3768·5
6″	1·734	169·4	*4·05*	371·9	*5·04*	623·9	*6·00*	923·7	*7·09*	1278·1	*8·34*	1694·9	*10·1*	2198·7	*12·0*	2797·1	*15·2*	3556·2	*18·6*	4488·5
7″	2·00	195·0	*4·71*	430·4	*5·79*	720·0	*6·92*	1066·0	*8·19*	1475·6	*9·61*	1956	*11·66*	2539	*13·78*	3228	*17·46*	4101	*21·6*	5180
8″	2·257	220·6	*5·30*	485·7	*6·54*	812·5	*7·81*	1203	*9·23*	1664·5	*10·8*	2207·3	*13·1*	2863·6	*15·6*	3642·8	*19·8*	4631·4	*24·3*	5845·6
9″	2·52	246·0	*5·92*	542	*7·30*	907	*8·72*	1343	*10·34*	1860	*12·1*	2465	*14·7*	3200	*17·4*	4070	*22·0*	5170	*27·2*	6530
10″	2·817	275·4	*6·62*	606·2	*8·16*	1014·1	*9·75*	1501·5	*11·5*	1077·5	*13·6*	2755	*16·4*	3574·1	*19·5*	4546·6	*24·7*	5780·5	*30·3*	7296
11″	3·08	300	*7·26*	663	*8·92*	1109	*10·66*	1642	*12·6*	2272	*14·76*	3010	*17·9*	3905	*21·3*	4972	*26·9*	6315	*33·3*	7980
12″	3·34	326	*7·86*	719	*9·68*	1203	*11·54*	1780	*13·7*	2465	*16·02*	3266	*19·4*	4235	*23·1*	5390	*29·2*	6850	*36·0*	8650
14″ o.d.	3·66	357	*8·59*	786	*10·64*	1318	*12·64*	1950	*15·0*	2700	*17·06*	3580	*21·3*	4645	*25·2*	5905	*31·9*	7500	*39·5*	9475
16″ o.d.	4·19	408	*9·84*	901	*12·2*	1510	*14·5*	2233	*17·2*	3095	*20·1*	4100	*24·4*	5320	*28·9*	6765	*36·5*	8590	*45·2*	10850

Flat Curved or Cylindrical Surfaces.	Heat Loss in B.Th.U. /sq. ft./hr.																			
	97·5	*2·35*	215·2	*2·90*	360·0	*3·46*	533·0	*4·10*	737·8	*4·80*	978·0	*5·83*	1269·4	*6·89*	1614·0	*8·73*	2050·6	*10·8*	2590·0	
	Heat Loss in B.Th.U./sq. ft/degree temperature difference/hr.																			
	1·950		2·152		2·400		2·665		2·951		3·260		3·627		4·035		4·557		5·180	

* Example 2-in. Pipe, 235° Temp. difference. 235° − 200° = 35°; 35° × 2·54 (B.Th.U. per degree) = 88·9 B.Th.U. 331·5 + 88·9 = 420·4 B.Th.U. loss at 235° Temp. difference.

water to bring the material to the consistency of stiff mortar. The surface to be covered should be warm, and the first coat of the covering should be applied not more than $\frac{1}{4}$–$\frac{3}{8}$ in. thick. This coat should be allowed to dry before applying the second, which should be not more than $\frac{1}{2}$ in. thick, and so on. The final coat should be trowelled to a smooth surface. The covering should then be protected by a layer of hard-setting asbestos cement, and if in exposed situations a final stitched covering of high-grade 8-oz. smooth canvas. The canvas should then be painted with two or three coats of best varnish, preferably light in colour. If outdoors the varnish should be of the waterproof type. The composition of hard-setting cement varies widely with the manufacturers, but the majority are composed of asbestos fibre and kieselguhr, with clay binder.

All flanged steam-pipe joints should be covered with easily removable magnesia-asbestos lined non-corrosive metal boxes, arranged so that the metal sheathing does not come into contact with the hot pipe.

The foregoing 85 per cent. magnesive covering can also be applied in sectional form, which can be applied immediately to a cold pipe. Such covering sections can usually be obtained in the following forms :—

(1) Sections covered with canvas securing band.

(2) Sections without canvas and bands.

(3) Sections covered with waterproof cloth and bands.

To apply (1), the brass securing bands are removed, the section placed round the pipe and the canvas overlap then secured with an adhesive composition. The canvas can then be covered as desired. (2) is placed round the pipe, secured with wire, and finished off with $\frac{1}{2}$ in. or more of hard-setting cement. (3) is applied as (1) and is used for outdoor insulation.

The thickness of 85 per cent. magnesia covering normally applied to saturated steam pipework is given in the table below.

THICKNESS OF 85 PER CENT. MAGNESIA USUALLY APPLIED.

Temperature of Pipe Surface (° F.).	Diameter of Pipes.			
	Up to 2 ins.	2½ to 5 ins.	6 to 18 ins.	Flat Surfaces.
	ins.	ins.	ins.	ins.
200	¾–1	1–1¼	1½–1¾	1½–1¾
220–350	1–1¼	1½–1¾	2–2¼	2–2¼
350–650	1¼–1½	2–2½	2½–2¾	2½–2¾

Note.—⅜ in. to ½ in. layer of hard-setting cement is usually applied over the 85 per cent. magnesia. The non-conducting properties of the layer of hard-setting cement are not usually taken into account in computing the efficiency of the covering. (See also Fig. 122; Bagley, *Am. Soc. M.E.*, 1918.)

Glass silk is now frequently used as a heat insulator for temperatures up to 900° F., and I am indebted to Chance Bros. of Glasgow, the makers of this material, for the following data :—the material consists of long fine threads or fibres of glass which are very flexible and can be made up into various forms suitable for use as heat insulation. The following tests of conductivity on this material were made by the National Physical Laboratory.

TABLE 45.

THERMAL CONDUCTIVITY AND EFFICIENCY OF GLASS SILK.

(Q) for Glass Silk, in thicknesses of ¾ in., 1 in., 1½ in. and 2 ins. for temperatures ranging from 150° F. to 800° F. The efficiencies (E) are also stated.

Thicknesses.	¾-in. G.S.		1-in. G.S.		1½-in. G.S.		2-in. G.S.	
Temperature (° F.).	Q	E	Q	E	Q	E	Q	E
150	25	85·0	22	86·7	18	89·7	12	91·7
200	46	85·1	40	86·9	30	89·9	23	92·0
250	70	85·2	60	87·0	45	90·1	36	92·2
300	94	85·3	82	87·1	64	90·2	49	92·5
350	123	85·8	107	87·5	84	90·6	64	92·8
400	152	86·3	132	88·0	103	91·0	79	93·0
450	183	86·7	163	88·5	125	91·3	95	93·3
500	220	87·2	194	89·0	150	91·7	115	93·5
550	260	87·8	228	89·5	178	92·1	135	93·8
600	302	88·5	265	90·0	207	92·5	158	94·0
650	348	89·0	307	90·5	238	93·0	181	94·3
700	397	89·5	350	91·0	271	93·4	207	94·5
750	449	89·9	400	91·3	306	93·6	235	94·8
800		—	448	91·5	343	93·8	264	95·0

The Heat Losses (Q) are given in terms of B.Th.U. per sq. ft. of pipe surface per hour, assuming an atmospheric temperature of 70° F.

Glass silk is non-hygroscopic, is incombustible, is chemically inert, and is unaffected by vermin.

It is supplied in various forms as follows :—

(1) *Ravelled.*—In this form it is used for packing into enclosed spaces such as engine casings, dryer casings, etc.

(2) *Sheets* are supplied for covering large surfaces such as tanks, large pipes, etc., and are built up to the required thickness and secured by wire or straps so as to be close against the surface to be insulated.

(3) *Mattresses* are made up to special order and comprise glass silk enclosed in wire netting, asbestos cloth, etc., and are

suitable for positions where it is necessary to remove frequently the covering and have it available for replacement immediately.

(4) *Strips.*—This form is designed for use in covering pipes, and the thicknesses recommended for general use are :—

Pipe Outside Diameter.	Below 250° F.	250 - 350° F.	350 - 450° F.	450 - 550° F.	550 - 650° F.
	in.	in.	in.	in.	ins.
Below 1½ in. .	½	¾	¾	1	1¼
1½ in. to 4½ ins.	¾	¾	1	1¼	1½
5 ins. to 9 ins. .	¾	1	1¼	1½	1¾
10 ins. and larger	1	1¼	1½	1¾	2

For higher temperatures each case should be separately considered.

Method of Applying Strip to Pipes.—The strip is wound diagonally round the pipe, each lap lying close to the pipe. Each successive layer, if more than one layer is used, should be wound on it in opposite directions to avoid any gaps, and the whole sewed by wire. The covering can be finished by sewing canvas around it, or using millboard, or if a plastic paint is preferred, wire netting about ½-in. mesh should be bound tightly round the glass silk and a layer of hard-setting cement trowelled over. Fig. 123 shows high-pressure boiler drums, headers, and superheated steam pipes insulated with glass silk at a large Scottish Power Station.

Insulation for Temperatures 650–1000° F.

Above 650° F. magnesia should not be used alone as an insulating material, but in conjunction with an underlayer of high-temperature material, the thickness of which is so arranged as to bring down the temperature at the surface of the magnesia to 650° F. or below.

For superheated steam temperatures of 500–1200° F. the Philip Carey Co. of Lockland, Cincinnati, have developed an underlayer consisting of compounds of silica, magnesia, calcium and alumina with high-grade asbestos, and this is used in conjunction with an outer layer of 85 per cent. magnesia.

The Chemical and Insulating Co. of Darlington have developed " Dextramite " as the underlayer in high-temperature pipe insulation work up to 2000° F., and at a temperature of 1832° F. the heat loss per 1 in. thickness per sq. ft. per hr. per °F. was found to be 0·85 B.Th.U.

As an example of the thickness of some of these special materials used as underlayers the Keasbey & Mattison Co. of Ambler, Pa., recommend the thicknesses of their Hy-Temp underlayer as given in Table 46 below.

TABLE 46.

Nominal Pipe Sizes (ins.).	Temperature.					
	600–699° F.		700–799° F.		800–1000° F.	
	Thickness of Insulation (ins.).					
	Hy-Temp.	85 per cent. Magnesia.	Hy-Temp.	85 per cent. Magnesia.	Hy-Temp.	85 per cent. Magnesia.
* 1½ and smaller	Single layer only of Hy-Temp, 2 ins. thick					
2	1¼	1½	1¼	2	1 9/16	1½
2½	1 5/16	1½	1 5/16	2	1 13/16	1½
3	1 9/16	1½	1 9/16	2	2 1/16	1½
3½	1 5/16	1½	1 5/16	2	1 13/16	1½
4	1 9/16	1½	1 9/16	2	2 1/16	1½
4½	1 5/16	1½	1 5/16	2	1 13/16	2
5 and larger	1½	1½	1½	2	2	2

* All insulation on pipes 1½ in. and smaller shall be single layer of Hy-Temp Pipe Insulation.

High-Temperature Insulation for Temperatures above 1000° *F.*

Such insulation is used in connection with stoves, ovens, combustion chambers and the like, and the materials available are the silicas and clays, either in natural or manufactured form.

The usual and most convenient form is the insulating brick used in conjunction with special insulating mortar of similar composition. It is highly desirable that the joints should be as few and as thin as possible, and since such insulating bricks are very porous, they should be well wetted before use to avoid drawing the water away from the mortar too quickly.

The selection of suitable materials for insulating furnaces, kilns, etc., is often more complicated than insulation for lower temperatures in connection with steam plant because in furnaces and kilns the insulation must often form part of the structure and is called upon to take part of the stress of the structure. Hence, although low thermal conductivity is still important, mechanical strength is often the decisive factor, and in addition some degree of refractoriness is essential.

It is important to note that insulating bricks should not be confused with refractory bricks, as the function of these is entirely different. The refractory should take the direct shock of the flame and abrasive action of dust, whereas the insulating brick should be regarded as functioning purely as a heat insulator.)

In dealing with the insulation of high-temperature furnaces it is necessary closely to consider the temperature gradients through the walls in relation to the softening temperature of the refractory. Con-

sidering a case where the internal temperature is approaching the softening point of the refractory, with no insulation this will only take effect through a small thickness of the fire brick, since the temperature gradient is steep owing to the relatively high conductivity. When, however, the refractory is backed by insulation the temperature gradient becomes much less steep and the whole thickness of the fire-brick lining is raised to a temperature more nearly approaching that of the inside face. Hence the softening effect spreads through a greater thickness of the brick. Then it is advisable to employ a higher-grade refractory. Consideration, therefore, should be given to the refractory and the insulator as a whole, although their respective functions are independent. For example, a high-grade refractory plus an insulating course will usually result in a higher thermal efficiency than a greater thickness of low-grade refractory without insulation.

It is, unfortunately, an established fact that as refractoriness and mechanical strength in insulating bricks increases the efficiency falls; thus it is necessary, when very high temperatures are being dealt with, to employ more than one grade of insulating brick to obtain the greater efficiency.

A number of investigators have published equations covering combined radiation and convection from heated surfaces at varying temperatures, to air at a constant temperature. The curve for still air shown in Fig. 124 is based on Stefan and Boltzman's law, while the curves for moving air are from equations by Langmuir.* Tests made at the Research Laboratory of the Johns Manville Corporation indicate that the Stefan and Boltzman curve may be used for any ordinary dull surface, such as steel plate, fire brick, red brick, or insulation. The position of the surface has not sufficient effect to make it necessary to take this into consideration for ordinary purposes, and the curves may be used for either horizontal or vertical surfaces.

Radiation losses rise rapidly with rise in temperature, and it is consequently increasingly important to reduce heat losses at the higher temperatures. For instance, on reference to Curve A in Fig. 124, it will be noted that a furnace wall at a temperature of 200° F. under still air conditions will be dissipating 270 B.Th.U. per sq. ft. per hr., while at 400° F. the loss will be 1110 B.Th.U., or more than four times as great.

The air velocity on the outside of a wall has a very great effect on the amount of heat which will be lost from the wall at a definite outside surface temperature. The effect of air velocity is to decrease the thickness, and consequently the resistance, of the air film on the outside of the wall, and the outside surface temperature will be correspondingly reduced. But, as the heat flow by conduction through the wall increases in approximately direct proportion to the temperature difference between inner and outer surfaces, a wall exposed to moving

* *Tran. American Electro-Chemical Society*, **23**.

air, while it will be at a lower temperature than if the air were still, will actually be losing a greater amount of heat.

The magnitude of the effect of air velocity on heat transfer from surface to air at various outside surface temperatures is shown in Curves B, C, D and E in Fig. 124, all of which are based on Langmuir's equations. For example, a furnace casing at an outside surface temperature of 400° F. under still air conditions (Curve A) will be losing 1110 B.Th.U. per sq. ft. per hr., while with an air velocity of 400 ft. per min., corresponding to a wind of 4·5 m.p.h. (Curve B), a casing at the same outside temperature will be losing 1760 B.Th.U. per sq. ft. per hr., or an increase of about 60 per cent. At higher air velocities the difference is correspondingly greater.

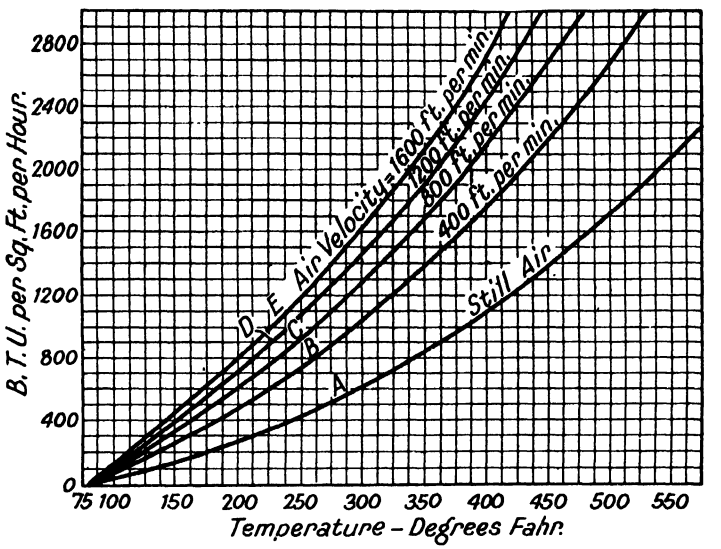


FIG. 124.—Loss from heated surfaces by radiation and convection at various air velocities and different temperatures.

The relative thermal conductivities of fire brick, red brick and representative high-temperature insulating materials are shown in Fig. 125, all conductivities being based upon *mean* temperature of test specimens. The lines showing the conductivities of red brick and fire brick illustrate the rapid rate of increase as the temperature increases. When it is realised that the super-refractories now in quite general use in many high-temperature processes have conductivities many times higher than that of fire-clay brick, the importance of backing refractory materials with insulation can be readily understood.

It will be noted that fire-clay brick transmits an average of about ten times as much heat as the insulating materials in Fig. 125. The low conductivity of these insulating materials, which are prepared from

diatomaceous silica, is due to the fact that they contain a volume of as much as 85 per cent. of minute air cells and an enormous number of enclosing surfaces which effectively interrupt the transfer of heat. Being practically pure silica (SiO_2), the material has a high melting point, 2930° F. The insulating brick shown for temperatures up to

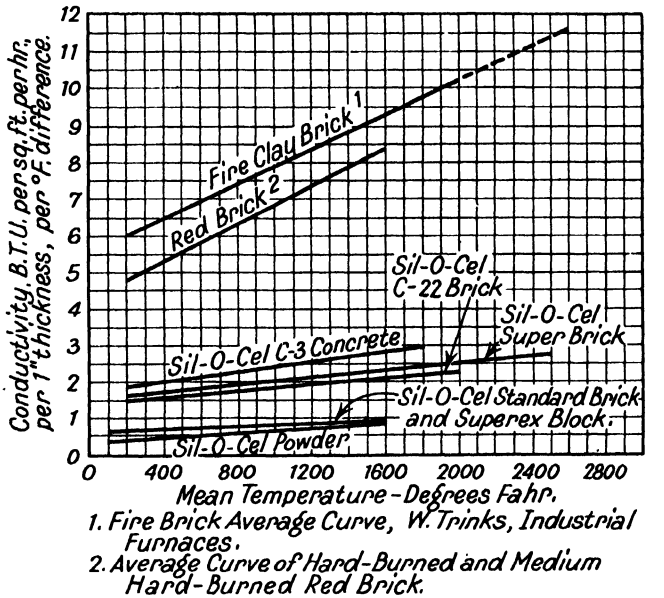


FIG. 125.

1600° F. is cut from the natural "rock," diatomaceous silica, and beyond drying, is not treated in any way. The block insulation is composed of the same material and asbestos fibre. Bricks for temperatures up to 2000° and 2500° are diatomaceous silica that has been ground, pugged, pressed and fired in kilns.

Thickness of Insulation.

The thickness of insulation which should be used for best results depends largely upon the method of heating employed. In coal and oil-fired equipment, where in most cases the cost of heat is relatively low, from 4½ to 9 ins. of insulation is usually used. Gas-fired equipment is usually more heavily insulated; and where electricity is used as the source of heat as much as 20 ins. of insulating material is often used. Naturally, the higher the cost of generating the heat, the more money can be economically invested in insulation to keep the heat within the equipment for productive work.

I am indebted to the Johns Manville Corporation for the following

notes in connection with the calculations involved in the use of their insulating bricks.

Method of Determining Heat Loss through Walls.

The formula for heat flow through walls composed of two or more materials of varying conductivities follows :—

$$Q = \frac{t_1 - t_2}{\frac{x_1}{k_1} + \frac{x_2}{k_2} + \text{etc.},}$$

where Q = quantity of heat conducted in B.Th.U./sq. ft./hr.
t_1 = temperature of the *hotter* surface (° F.).
t_2 = temperature of the *cooler* surface (° F.).
x_1, x_2 = thickness in ins. of each course of material.
k_1, k_2 = conductivity of each material in B.Th.U./sq. ft./hr./in. thick/° F. difference in temperature.

As will be noted in the following description of this method, both outside and inside surface resistances are disregarded as far as the formula itself is concerned ; excepting that the curve, Fig. 124, is used to correct for outside surface temperature. Inside surface temperature is considered to be the same as that of the air or gas within the equipment.

Problem.—Find the heat loss in B.Th.U. per sq. ft. per hr. through a wall composed of 9 ins. of fire brick, 4½ ins. Sil-O-Cel Standard Brick, and 8 ins. of red brick, with an inside temperature of 1800° F.

In figuring the heat loss through a wall, the first step necessary is to estimate the approximate temperature gradient through the wall, so that the conductivities (k) of the materials may be estimated. A convenient method of determining approximate temperature gradient is to convert all materials in the wall to the basis of approximate equivalent thickness of fire brick. The average conductivity of fire brick is about 9 B.Th.U. Therefore an insulating material with a conductivity of 0·9 would be equivalent to 10 ins. of fire brick per in. of insulation. The following rough averages may be used for this purpose, for the different materials shown in Fig. 125.

Material.	*Equivalent Fire Brick Thickness per in.*	
Sil-O-Cel powder	16·0	Factors based on average temperatures encountered in actual operation for each material. The average temperature to which the materials are subjected in service is lower for insulating material than for refractories.
Sil-O-Cel standard brick	13·0	
Superex block	13·0	
Sil-O-Cel C–22 brick	5·5	
Sil-O-Cel C–3 concrete	4·5	
Red brick	1·5	

A wall, therefore, with 9 ins. of fire brick, 4½ ins. of Sil-O-Cel Standard Brick, and 8 ins. of red brick would have a resistance of 9 + 58·5 + 12, or 79½ units of equivalent fire-brick thickness. In other words, the proportional part of the total temperature drop through each material in the wall is represented by the following fractions :— $\frac{9}{79{\cdot}5}$ through the fire brick, $\frac{58{\cdot}5}{79{\cdot}5}$ through the insulation, and $\frac{12}{79{\cdot}5}$ through the red brick.

For this preliminary step of the calculation (estimating approximate temperature gradient) outside surface temperature may be assumed to be 200° F., as this is close enough to the average for conditions ordinarily encountered.

If we have an inside surface temperature of 1800° F., therefore, the total drop will be 1600° (1800 − 200) and the approximate temperature gradient is as follows :—

Temperature Drop through (° F.)	Temp. Hot Face of Material.	Temp. Cold Face of Material.	Mean Temp. each Material.
Fire brick $1600 \times \frac{9}{79{\cdot}5} = 181°$ . . .	1800°	1619°	1710°
Sil-O-Cel brick $1600 \times \frac{58{\cdot}5}{79{\cdot}5} = 1177°$.	1619°	442°	1030°
Red brick $1600 \times \frac{12}{79{\cdot}5} = 242°$ . . .	442°	200°	321°

The conductivities of the materials at their respective *mean* temperatures are then obtained from Fig. 125, and a trial calculation made as follows :—

$$Q = \frac{1800 - 200}{\frac{9}{9{\cdot}6} + \frac{4{\cdot}5}{0{\cdot}80} + \frac{8}{5{\cdot}00}} = 196 \text{ B.Th.U./sq. ft./hr.}$$

This preliminary calculation is made only for the purpose of forecasting the approximate outside temperature and temperature gradient through the wall. From the above, these figures can be obtained very closely.

The approximate outside temperature is obtained by reference to Fig. 124. For a B.Th.U. loss of 196 the outside temperature is found to be 171° (with surrounding air temperature of 80° F.*), which gives a total temperature drop of 1629° F.

The temperature drop through each material will be in proportion

* *Note.*—Where air temperatures are other than 80° F., the outside surface temperature will be correspondingly higher or lower than that indicated by the curve.

to the proportional resistance of each material. In this case the total resistance between surfaces was 8·162, made up as follows :—

Fire brick	$\frac{9}{9{\cdot}6} = 0{\cdot}937$
Sil-O-Cel	$\frac{4{\cdot}5}{0{\cdot}80} = 5{\cdot}625$
Red brick	$\frac{8}{5{\cdot}00} = 1{\cdot}600$
Total resistance	8·162

The temperature drop through each material is, therefore :—

Temperature Drop through (° F.)	Temp. Hot Face of Material.	Temp. Cold Face of Material.	Mean Temp. each Material.
Fire brick $\frac{0{\cdot}937}{8{\cdot}162} \times 1629 - 187°$ . . .	1800°	1613°	1706°
Sil-O-Cel $\frac{5{\cdot}625}{8{\cdot}162} \times 1629 - 1123°$ . .	1613°	490°	1051°
Red brick $\frac{1{\cdot}600}{8{\cdot}162} \times 1629 = 319°$ . . .	490°	171°	330°

We are now ready to make our first definite calculation for heat loss, using 171° F. as outside surface temperature t_2, and using conductivities for the materials at their above mean temperatures from Fig. 125. (In this particular case it was not necessary to change the conductivity of the materials as used in the trial calculation.)

$$Q = \frac{1800 - 171}{\frac{9}{9{\cdot}6} + \frac{4{\cdot}5}{0{\cdot}8} + \frac{8}{5{\cdot}00}} = 200 \text{ B.Th.U./sq. ft./hr.}$$

Curve A in Fig. 124 is then again referred to and a point plotted for the outside temperature used and the B.Th.U. loss secured ; in this case 171° F., and 200 B.Th.U. If the point falls on the curve no other calculation is required. This will not generally be true, however. In this particular case it will be found that the trial calculation gives a point slightly above the line, indicating that the temperature of 171° F. was low. Another calculation should then be made using an exterior temperature which will give a point on the opposite side of the curve to that of the first point. In this instance a temperature 9° higher will be sufficient, or 180° F.

$$\frac{1800 - 180}{\frac{9}{9{\cdot}6} + \frac{4{\cdot}5}{0{\cdot}8} + \frac{8}{5{\cdot}00}} = 199 \text{ B.Th.U./sq. ft./hr.}$$

A point for this temperature and B.Th.U. loss (180° F. and 199 B.Th.U.) is then plotted on Fig. 124, and a line drawn from this point to the point corresponding to 171° F. and 200 B.Th.U. secured in the preceding calculation. The point where this line intersects the curve gives the true B.Th.U. loss and outside temperature; in this case 199·5 B.Th.U. for heat loss and 175° F. for outside surface temperature.

In cases where the first trial does not come so close to the actual B.Th.U. loss for the temperature chosen, a correspondingly greater difference in outside temperature should be used for the second calculation so that the second point secured will be on the opposite side of the curve. If, due to a miscalculation, both points should fall on the same side of the curve, the line can be extended to intersect the curve, provided the point closest to the curve is not more than about 20° away.

Calculation for Temperature Gradient.

The temperature gradient through the wall can now be calculated, using the method previously described. The total resistance is 8·162, made up as follows :—

Fire brick	$\frac{9}{9·6} = 0·937$
Sil-O-Cel	$\frac{4·5}{0·8} = 5·625$
Red brick	$\frac{8}{5·00} = 1·600$
Total resistance	8·162

The temperature gradient, therefore, is :—

Temperature Drop through (° F.)	Temp. Hot Face of Material.	Temp. Cold Face of Material.	Mean Temp. each Material.
Fire brick $\frac{0·937}{8·162} \times 1625 = 187°$ . . .	1800°	1613°	1707°
Sil-O-Cel $\frac{5·625}{8·162} \times 1625 = 1120°$ . .	1613°	493°	1053°
Red brick $\frac{1·600}{8·162} \times 1625 = 318°$ . . .	493°	175°	334°

CHAPTER IX.

STEAM PLANT FOR CHEMICAL WORKS.

THE essential requirement of a chemical works steam plant is reliability, since in a great number of cases the rate and quality of production depends upon a steady supply of process steam at a given minimum pressure.

Modern types of both shell and water tube boilers show equal thermal efficiency when under proper control, and the final choice of the kind of boiler plant for new installation depends largely upon the quantity of steam required and site limitations, and to a lesser degree upon kind of fuels available, the quality of the feed water and the kind of labour available for stoking and maintenance. In general, the water tube boiler has a great advantage in respect of output for a given site area and in the maximum pressure for which this type of boiler can be constructed. The advantages of the shell type boiler are in general lower maintenance cost, greater thermal storage capacity, ability to work with feed water quite unfit for use in water tube boilers, and lesser degree of skill necessary for both stoking and maintenance. The maximum working pressure for a shell type boiler is about 275 lbs. per sq. in., whereas the water tube type is now regularly built for pressures up to 1400 lbs. per sq. in. and in a few special cases to 3000 lbs. per sq. in.

The average steam pressure in chemical works to-day does not exceed 200 lbs. per sq. in., but of recent years the centralisation of manufacture brought about by amalgamation of chemical interest has led to marked developments in the use of considerably higher steam pressures in connection with large combined power and process steam plants. This tendency is increasing rapidly, and in view of the growing importance of such combined steam power plants this subject is dealt with at some length later in this chapter.

The cost of steam raising is often an important factor in determining the cost of the final product, and the relative importance of the various items governing the cost of steam generation will be seen in Table 47, which was drawn up by Reece and Samuels from data supplied by the subsidiary companies of Imperial Chemical Industries Ltd. (*Trans. Inst. Chem. Eng.*, 1934, **12**, 144).

If capital and depreciation charges and certain unimportant

handling charges are omitted, it will be noted that the fuel cost varies between 70–90 per cent. of the total cost of steam raising. Hence it is of the utmost importance to ensure that the steam boiler plant is maintained at the highest possible efficiency, and that the most economical kind of fuel is used. The former depends upon good maintenance and close control of combustion, and the latter upon careful and regular trials of all suitable fuels which are available.

Combined Plants for the Generation of Power and Process Steam.

In the majority of chemical works it is often economical to instal combined power and process steam plant, as by this means the maximum energy can be derived from the process steam by expanding it to do useful work in an engine down to the process pressure.

The process steam power generator is usually either a back-pressure engine or turbine, or a pass-out engine or turbine. The question as to which type is the most suitable for a particular installation cannot be answered in a general way, as each case must be decided upon its own merits and frequently practical considerations, such as site limitations and nature of existing plant, have a great influence upon the final choice. In general, it may be stated that the advantages which the turbine offers as an ordinary condensing unit for large sizes (1000 kW. and upwards) are retained when adapted for exhaust steam utilisation, whereas the reciprocating engine of either the high-speed vertical or horizontal uniflow type is the more effective in the smaller sizes. The scope is enlarged in favour of the reciprocator, when direct coupling for rope or belt drive is desirable.

It is to be noted that the turbine, particularly of the back-pressure type, has a great advantage over the reciprocator where space limitations exist. Further, reciprocators are not satisfactory with superheated steam above 550° F., whereas turbines can deal satisfactorily with steam entering at 850° F. and even higher in special cases. It is necessary to lubricate the cylinders of reciprocators when using superheated steam, and in cases where oil in the exhaust is undesirable, it is necessary to instal suitable oil-eliminating equipment, whereas the exhaust from turbines is oil free. When using saturated steam, however, reciprocators can be designed to work quite satisfactorily without cylinder lubrication.

Apart from these considerations, the decision in favour of one or other of the types of prime mover available will also be influenced by the relative efficiency and economy in steam consumption of otherwise suitable designs. The fundamental economics of combined power and process plants will therefore now be considered, and to simplify the text in the remainder of this chapter the word " engine "

TABLE 47.

	A	B	C	D	E	F	G	H	I
Annual output of steam in tons	347,500	201,316	71,752	54,650	90,748	109,107	130,224	46,400	83,365
Annual fuel consumption in tons	40,300	26,145	9,567	7,920	13,138	12,500	10,432 554,000,000 cu. ft. gas 9,552 coke breeze	6,960	10,972
Number of boilers installed	4 at 22,000 lbs. 2 at 60,000 lbs.	8 at 14,000 lbs. —	2 at 10,000 lbs. 1 at 13,000 lbs.	2 at 7,000 lbs. —	4 at 25,000 lbs. —	2 at 25,000 lbs. —	4 at 23,000 lbs. —	6 at 12,600 lbs. —	3 at 7,000 lbs. 2 at 10,000 lbs.
Number of boilers working normally	3 at 18,700 lbs. 1 at 51,000 lbs.	5 at 14,000 lbs. —	2 at 10,000 lbs. 1 at 10,000 lbs.	2 at 7,000 lbs. —	2 at 25,000 lbs. (summer) 3 at 25,000 lbs. (winter)	2 at 17,000 lbs. —	3 at 23,000 lbs. —	3 at 12,000 lbs. —	2 at 7,000 lbs. 2 at 10,000 lbs.
Normal evaporation in lbs. per hr.	107,100	70,000	33,000	14,000	62,500	34,000	69,000	36,000	34,000
Economisers	Yes On large boilers	Yes	No	Yes	Yes	Yes	No	Yes	No
Steam pressure at stop valve, lbs. per sq. in.	180	180	165	120	200	200	185	200	150
Superheat pressure at stop valve ° F.	120	100	140	230	212	312	140	100	150
Feed temperature ° F.	193	265	117	59	150	110	160	180	180
Class of fuel used	Fifeshire washed singles	Ayrshire washed singles	Lancashire washed slack	—	—	—	—	—	Washed smalls
Calorific value of coal as fired in B.Th.U. per lb.	12,300	12,300	12,480	11,700	12,000	11,500	12,000	11,000	11,200
Calorific value of gas as fired in B.Th.U. per cu. ft.	—	—	—	—	—	—	526	—	—
Calorific value of coke breeze as fired in B.Th.U. per lb.	—	—	—	—	—	—	10,500	—	—
Number of men in boiler-house per shift	2	2	2	1	1	2	1⅓	2 men and 1 boy (day) 1 man (night)	1½
	d.	d.	d.	d.	d.	d.	d.	d.	d.
Maintenance: Brickwork material	0·021	0·327	0·092	0·066		0·0488	0·252	0·28	0·0663
Labour	0·038		0·0608			0·1220		0·87	0·0144
Fitters, etc.	0·282	0·234	0·337	0·154	8·40*	0·1100	0·227		
Electricians	0·008		0·0122	0·114		—		0·09	0·2247
Repairs and stores	0·379		0·599			—			
Total for maintenance	0·728	0·561	1·101	0·334	8·40*	0·2808	0·479	1·24	0·435
Boiler cleaning	0·177	0·142	1·01	0·303	0·405	0·2098	—	1·55	0·7253
Water treatment charges	—	—	0·647	0·571	0·334	0·3000	—	0·05	0·403
Sundries	0·006	0·024	0·514	—	0·226	0·0342	—	0·60	—
Fuel	18·600	24·200	26·300	36·720	20·32	27·5000	22·880	30·00	27·800
Labour on shifts	0·502	1·120	2·980	2·482	1·220	3·0252	1·314	3·07	1·594
Total cost per ton of steam at boiler stop valve excluding all capital and depreciation charges, traction costs, trimming and all handling of fuel and ash except from bunkers or storage dump	d. 20·013	d. 26·047	d. 32·555	d. 38·410	d. 30·905	d. 31·35	d. 24·673	d. 36·51	d. 30·957
Cost per ton of coal in shillings	s. 13·350	s. 15·5	s. 16·25	s. 20·56	s. 11·70	s. 20·08	s. 8·47	s. 16·70	s. 17·6
Maintenance per ton of coal	d. 6·280	d. 4·325	d. 8·27	d. 2·31	d. —	d. 2·46	d. 2·13	d. 8·261	d. 3·304
Maintenance per ton of coal on a 10,000 B.Th.U. per lb. value	d. 5·1	d. 3·51	d. 6·62	d. 1·975	d. —	d. 2·14	d. 1·775	d. 7·51	d. 2·95

* 7 men for coal and ash included.

will be used to denote both reciprocator and turbine unless expressly stated to the contrary.

Economics of Combined Power and Process Plants.

The Willans Line.—Reference to steam tables will show that the heat carried by a pound of dry steam increases but slowly with increasing pressure. For example, a change of pressure in the case of unit weight of steam from 100 to 200 lbs. per sq. in. results in only 1 per cent. increase in the heat content. It is clear, therefore, that, for most practical purposes, the heat supplied to a steam engine is proportional to the steam supply, and hence the weight of the steam supplied to an engine should be directly proportional to the output therefrom.

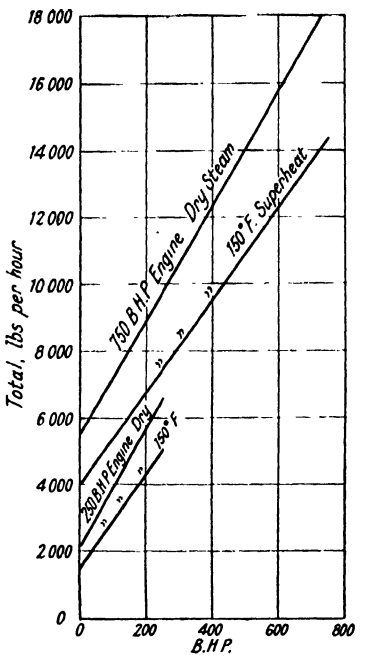


FIG. 126.—Willans Lines Belliss and Morcom engines.

Willans (*Proc. Inst. C.E.*, 1893, CXIV, 2) found that if the total steam used by an engine in lbs. per hr. is plotted against the indicated horse-power developed, the points so found lie on a straight line, the equation of which can be represented by the expression,

$$Q = a + (b \times \text{I.H.P.})$$

where Q is the total quantity of steam per hour and a and b are constants found for any particular engine by experiment. It is to be noted that such a law only holds good if the power of the engine is controlled by throttling, i.e. by a throttle governor. This straight-line law is known as " Willans Law " and is of considerable interest in dealing with process steam problems. The " Willans Lines " for two high-speed back-pressure engines by Belliss and Morcom are seen in Fig. 126. Particulars of the engines and the steam conditions are given in the figure.

Fig. 127 shows diagrammatically a factory installation in which steam is produced exclusively for process purposes in a low-pressure boiler K, supplying process steam directly to the apparatus, h_1, h_2, etc., through the distributing system H. For power supply this factory is equipped with independent motive power, such as a Diesel engine, or an electric motor or motors supplied with current from an outside source.

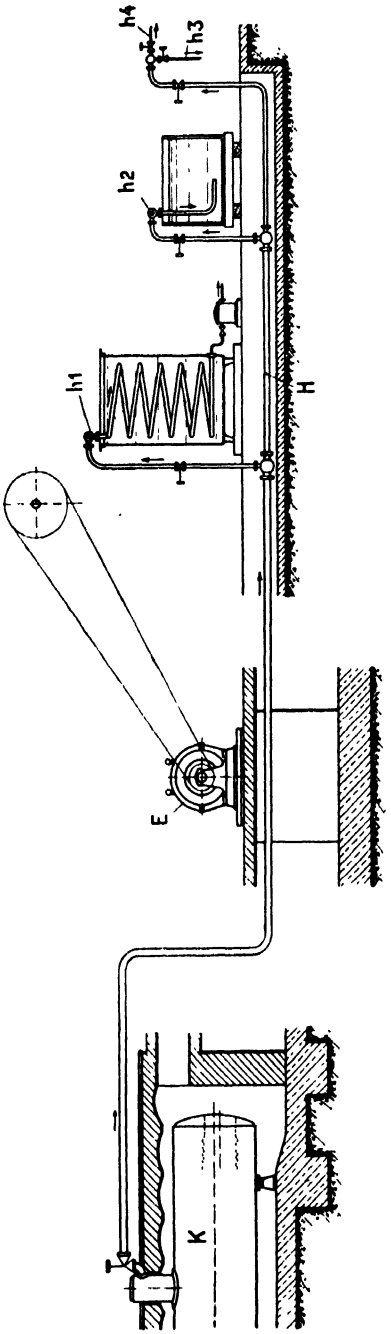


FIG. 127.—Diagram of a plant using low-pressure heating steam direct from boiler.

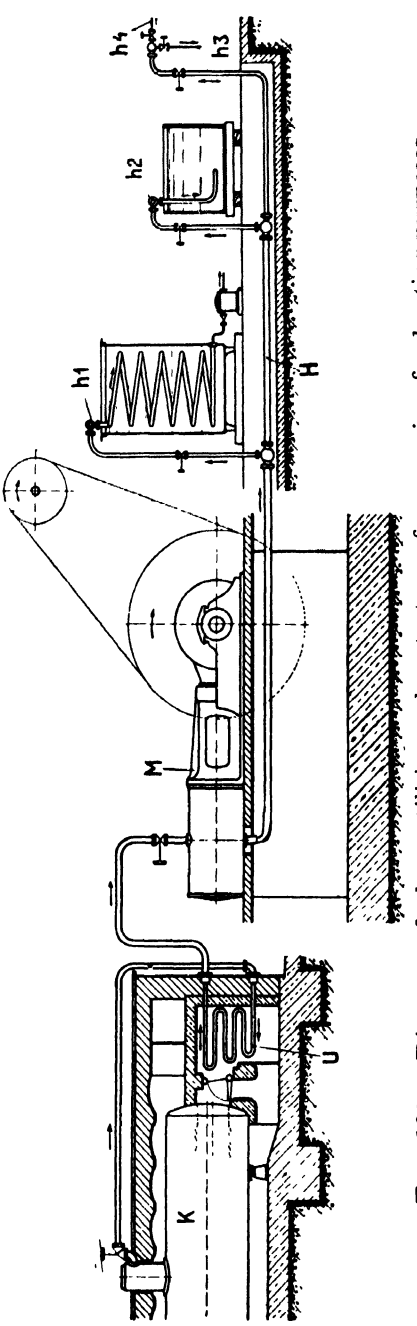


FIG. 128.—Diagram of plant utilising exhaust steam from engine for heating purposes.

On the other hand, in the works depicted in Fig. 128, the superheated steam from the boiler K passes to a back-pressure engine M driving the factory, and the exhaust from this engine is fed into the process steam main.

Assuming that in both cases similar steam conditions in the process steam main are to be obtained, it is clear that in the second factory the steam must be raised in the boiler to a higher pressure and temperature than in the factory shown in Fig. 127, as, for the engine to perform mechanical work, it is imperative that a certain drop in pressure and temperature should be available.

Since this higher pressure and temperature of the steam is only obtainable by the introduction of a larger " heat quantity " into the process or, in other words, by burning more fuel under the boiler, the question arises whether the gain in mechanical power justifies this extra consumption of fuel.

If, for example, the works shown in Fig. 127 requires saturated steam for process purposes at a gauge pressure of 2 atm., or 29·4 lbs. per sq. in., 1174 B.Th.U. (inclusive of the heat contained in the boiler feed) must be supplied to the boiler for each pound of steam raised, whereas, if in the factory in Fig. 128 a boiler pressure of 14 atms., or 206 lbs. per sq. in., is decided upon and the steam is superheated to a total temperature of 550° F., this boiler would require 1300 B.Th.U., i.e. 126 B.Th.U. more per pound of steam to be raised, or 10·7 per cent. more fuel.

From this it follows that for raising high-pressure superheated steam, such as is required for exhaust steam utilisation as diagrammatically shown in Fig. 128, only a little more fuel is consumed as compared with an installation using low-pressure heating steam direct from boilers (see curves, Fig. 129).

Dealing now with the amount of mechanical power which can be produced by the steam, every heat engine requires theoretically the same amount of heat, i.e. 2538 B.Th.U. per h.p.-hr. The theoretical output obtainable therefore with steam power plant can be easily derived from the amount of heat it consumes, i.e. from the difference of heat contained in 1 lb. of steam at the inlet and outlet of the cylinder (heat drop).

In the previous example we have seen that steam with a gauge pressure of 206 lbs. per sq. in., at a temperature of 550° F., enters the engine M with a heat content of 1300 B.Th.U. per lb. It exhausts with a pressure of 29·4 lbs. per sq. in. and in this case in a practically saturated state, with a heat content of 1174 calories, so that about 126 B.Th.U. are used up. In the case of a small engine (say 300 I.H.P.) about 10 per cent. of this amount represents heat losses, and the remainder, i.e. 113 B.Th.U., is converted into mechanical energy. The steam consumption of this engine therefore works out to

$\frac{2538}{113}$ = about 22 lbs. per I.H.P.-hr., or, in other words, for every 2200 lbs. of heating steam required per hour in the works, 100 I.H.P. can be produced in a back-pressure engine, and by reference to the foregoing it will be seen that *this motive power, in addition to the required*

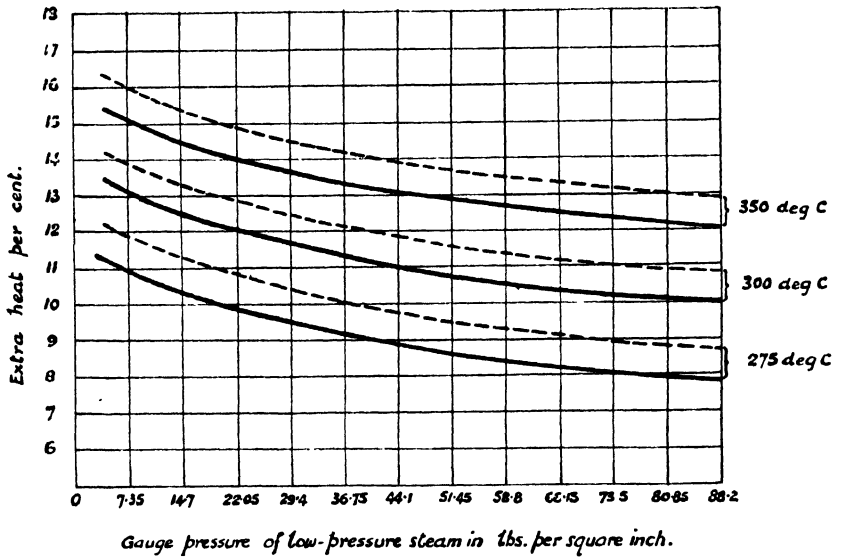


FIG. 129.—Extra heat required to generate superheated steam at 147 lbs./sq. in. or 265 lbs./sq. in. over the amount required to raise saturated steam at low pressure. Full lines are for 265, dotted lines for 147 lbs./sq. in.

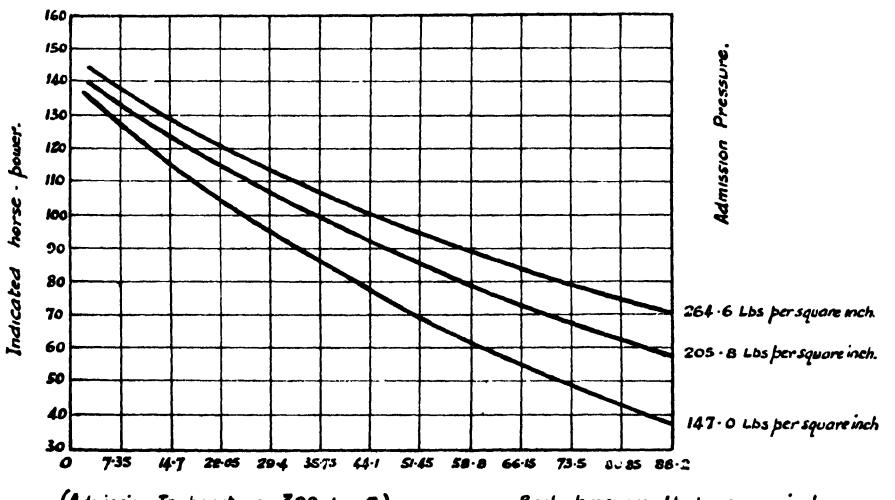


FIG. 130.—Indicated H.P. obtainable from a back-pressure engine per 2200 lbs. of steam per hour.

amount of heating steam, is obtained at the expense of only 10 *per cent. more fuel than would be necessary to raise the same amount of heating steam as low-pressure steam from boilers.*

From these considerations it becomes at once evident that the larger the available heat drop in the engine the smaller will be the steam consumption and consequently the greater the power to be derived from the same quantity of steam. Now, the available heat drop is governed by the amount of superheat and the pressure drop between inlet and exhaust, whereby it is not so much the admission

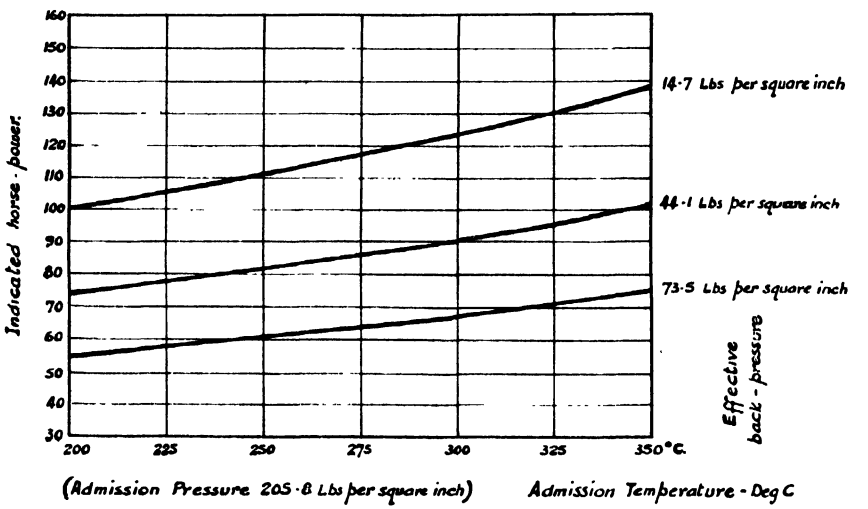


FIG. 131.—Indicated horse power obtainable from a back-pressure engine per 2200 lbs. of steam per hour.

pressure which has the decisive influence, as the amount of the initial superheat together with the numeral value of the exhaust pressure. This can be seen from curves, Figs. 130 and 131, which clearly demonstrate the importance of a high superheat and a low back-pressure. By referring to Figs. 129 and 130 and paying due regard to the increased first cost of a boiler plant if constructed for a higher pressure, it will be possible to choose the admission pressure best suited to any required pressure of the heating steam.

The Back-Pressure Engine—Field of Application.

The requirements for power and heating steam are in most factories subject to heavy fluctuations. With a works arranged as Fig. 128 it may be possible that, at times when the heating steam requirements exceed, say, 2200 lbs. per hr., the power demand falls below 100 h.p., during which periods a supplementary supply of heating steam direct from boilers becomes necessary.

In well-arranged installations, as shown in Fig. 132, this is effected automatically on the following principle: with increased heating steam demand and insufficient exhaust supply from the engine M, the pressure in the heating main H tends to fall, and the automatic steam-reducing valve will consequently permit live steam from the main K to be by-passed through the pipe L and reducing valve D into the heating main H. As soon as the pressure H is restored to normal again, the reducing valve will automatically close. A check valve R prevents steam flowing back from the main H into the engine and valves G serve the purpose of isolating various sections of the piping in case of need.

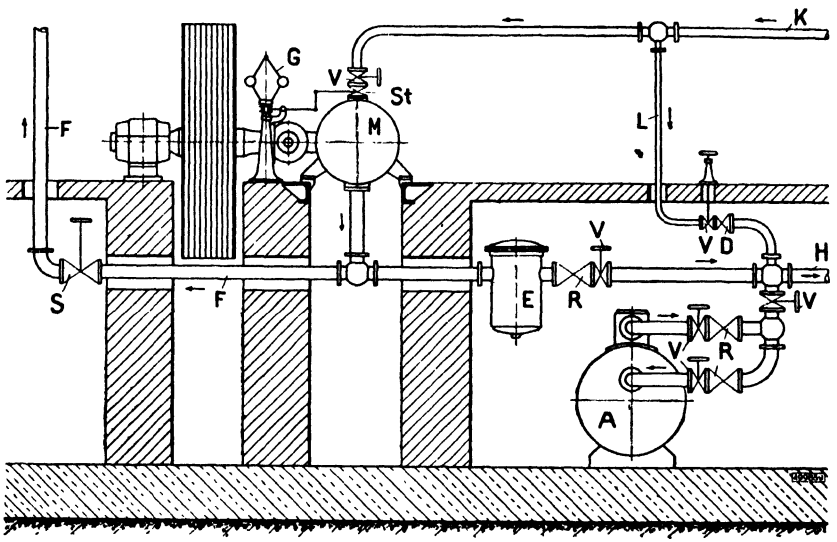


FIG. 132.—Diagrammatic arrangement of a back-pressure engine working with utilisation of exhaust steam.

If, on the other hand, the factory load exceeds at times 100 h.p., while the process steam demand remains at, say, 2200 lbs. per hr. or becomes less, the engine would supply more process steam than could be absorbed by the process apparatus. This excess of steam would have to be released to the atmosphere through pipe F and safety valve S, which is paramount to a thermal loss and adversely affects the economy of the installation.

This is one reason why the number of cases in which the pure back-pressure engine can be applied is limited; its use is restricted to installations in which, during the greater part of the year, the demand for process steam exceeds the amount of steam required for power production.

It is to be noted, however, that in instances where the engine supplies an excess of steam during comparatively short periods only,

this steam, instead of being released to the atmosphere, can be led into a *steam accumulator* "*A*." In such an accumulator, which generally consists of a closed vessel carefully insulated to prevent heat losses, a large quantity of water is stored, and the entering steam when coming into contact with this water condenses at the prevailing pressure and corresponding saturation temperature. As soon as a pressure drop occurs in the heating system, a portion of the hot water re-evaporates, and by this means it becomes possible to store heat, which in times of increased demand is liberated, the amount varying with the permissible pressure fluctuations in the system. There are several methods of making use of steam accumulators in heating systems, depending on the requirements of the works. Accumulators are particularly suitable where larger quantities of hot water are required for manufacturing purposes.

In all cases where, during prolonged periods, less than the whole of the exhaust steam from a back-pressure engine can be made use of for heating or process work and where no other power source is available, the back-pressure engine must give way to an engine arranged for intermediate steam extraction, i.e. an extraction engine (see p. 305 for discussion of the principles of extraction or pass-out engines).

Fig. 133 shows two 800 B.H.P. Sulzer back-pressure single-cylinder steam engines, supplied with steam at 285 lbs. per sq. in. and exhausting at 85 lbs. per sq. in. Fig. 134 shows a 1000 kW. geared back-pressure turbine by W. H. Allen of Bedford, the technical particulars of which are as follows :—

Normal full load output	1000 kW.
Overload capacity	25 per cent. for 2 hours.
Turbine speed	5500 r.p.m.
Generator speed	600 r.p.m.
Steam pressure at stop valve	145 lbs./super to 445° F.
Exhaust back-pressure	90 lbs./sq. in.
Steam quantity at overload	181,000 lbs./hr.

The turbine comprises a single 24-in. Rateau wheel, with 18-in. bore inlet and 20-in. bore exhaust pipe, and from the illustration it will be noted that the turbine is provided with an oil-operated automatic nozzle control valve. In the case of turbines generating power, and either of the back-pressure or pass-out type, and where only a relatively small pressure drop is available, it is of paramount importance to avoid excessive pressure drop by throttling. Hence in the machine under consideration, a system of automatic nozzle control valves is arranged. A small group of fixed nozzles is under the control of the main throttle valve, which on nearing the limit of its travel operates a pilot valve supplying oil in succession to the piston-operated automatic nozzle control valves which uncover in

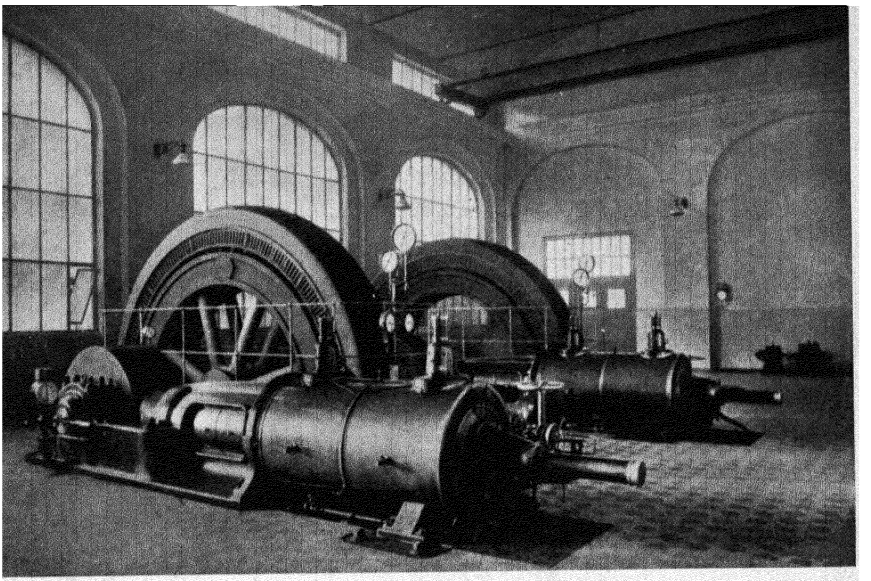


FIG. 133.—Sulzer back-pressure steam engines.

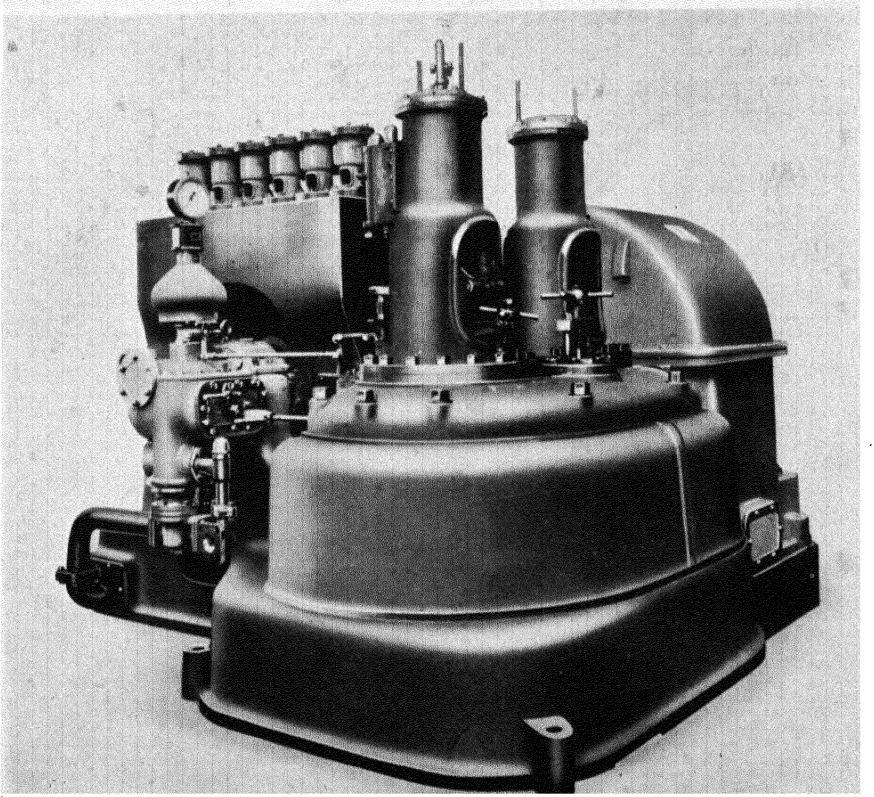


FIG. 134.—1000 kW. geared back-pressure turbine by W. H. Allen & Sons, Bedford.

[*To face page* 304.

succession small arcs of high-pressure nozzles, and by this means for any flow of steam the area of high-pressure nozzle is maintained in correct adjustment automatically by the turbine speed governor.

Pass-Out Engines.

In this method of obtaining power and process steam the engine is run permanently in connection with a condenser, and the desired amount of process steam is withdrawn at the required pressure from one or more intermediate pressure receivers in the case of a reciprocator, or one or more points in the staging of a turbine. The pass-out type of plant is desirable in cases where the power demand is such that the amount of steam required to generate power is normally in excess of that required for process work.

Pass-Out or Extraction Steam Reciprocators.

An extraction reciprocator is a compound engine in which the high-pressure steam expands in the high-pressure cylinder (C_1, Fig. 135) to the required process pressure. The pressure in the steam receiver P, represents the process pressure, and the process steam main is coupled to this receiver.

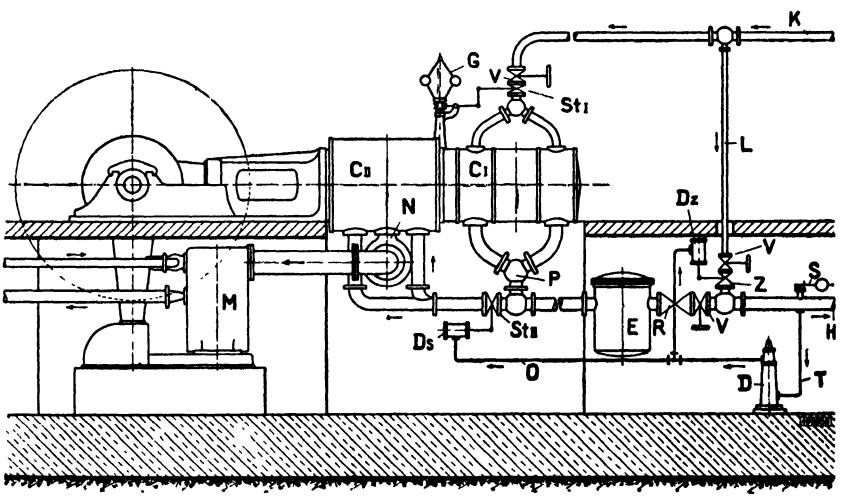


FIG. 135.—Diagrammatic arrangement of compound engine working with steam extraction.

A feature of this type of plant is its adaptability to widely varying service conditions At times of maximum process steam demand only a sufficient minimum of steam is passed into the low-pressure cylinder to prevent it running dry, and hence the greater part of the power load is carried by the high-pressure cylinder, which in effect runs as a back-pressure engine.

If, however, no process steam is required, then the whole of the steam passes through the engine to generate power. In a back-pressure engine it has already been stated that it is possible to regulate *either* the power output *or* the quantity of steam exhausted. In a pass-out or extractor engine, however, it is possible to vary *both* the power output and quantity of steam exhausted within quite wide limits. For this purpose the valve gear and hence the power output of each steam cylinder is influenced by its own governor, that regulating the high-pressure cylinder valve gear being an ordinary speed type governor (St_1, Fig. 135) and that regulating the low-pressure cylinder being a pressure regulator D, D*s*.

If a prevailing state of equilibrium on the engine is disturbed for any reason, the following takes place. An increase in the heating steam demand, with load remaining constant, tends to reduce the pressure in the main H, as a result of which the pressure regulator D, D*s*, which is connected with H through a small steampipe T, curtails the steam admission to the low-pressure cylinder. By this operation the bulk of the increased heating steam demand is provided for. The reduced steam admission to the low-pressure cylinder now causes a reduction in the output and a retardation of the engine speed. This is counteracted by the speed governor G, which increases automatically the high-pressure cut-off through device St_1 to such an extent that not only is the pressure in the receiver P and pipe H re-established again, but also the speed of the engine brought back to normal and the combined output of low-pressure and high-pressure cylinders amounts exactly to the same figure as prevailed at the beginning of the regulating process.

The functions of the various regulating members are reversed or take place in opposite sequence if the heating demand is reduced, or if, with extraction remaining constant, the power requirements increase or decrease.

Unfortunately, with an extraction engine the steam conditions become somewhat too involved to demonstrate the economy in a manner equally simple to that shown earlier for the pure back-pressure engine, but diagram, Fig. 136, gives a fair idea as to the utilisation of heat in this type of engine. The total hourly steam quantity D introduced may be considered as subdivided into two parts, one of which, D_I, represents to some scale the amount extracted per hour from the receiver. Its utilisation in the high-pressure cylinder follows the principle shown earlier, i.e. the power developed corresponds to an amount in heat Wv_I, which on an average is about 10 per cent. of the heat quantity introduced into the engine.

The second part D_{II} of the total amount of steam D admitted, is that which is not extracted but passes from the high-pressure into the low-pressure cylinder and is condensed after having performed

mechanical work in both cylinders. The amount of heat Wv_{III} thus converted into mechanical work is comparatively small (on an average about 20 per cent. of W_{II}), and the amount of heat lost in the condenser Wk comparatively large. It is therefore evident that the thermal efficiency of the engine will increase, the greater the amount of steam extracted, until finally, when the minimum of steam is passing into the low-pressure cylinder and condenser, the economy of the back-pressure engine is approached.

To arrive at the steam consumption per B.H.P.-hour we have to deal first with the steam quantity D_{II} and, further, with a steam quantity which, while being raised to the admission pressure and temperature, would absorb the equivalent of the heat Wv_{I}, used up in the high-pressure cylinder for power production. These two quantities represent with a reasonably large extraction a very low steam con-

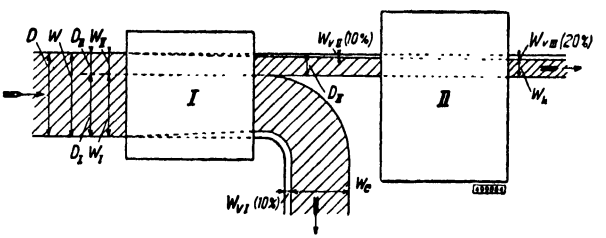


FIG. 136.—Diagram showing heat account of a compound engine working with steam extraction.

I = High-pressure cylinder.
II = Low-pressure cylinder.
D = Total steam admitted.
D_I = Steam extracted.
D_{II} = Steam passing to condenser.
W = Total heat in *D*.
W_I = Total heat in D_I on admission to H.P. cylinder.
W_{II} = Total heat in D_{II} on admission to L.P. cylinder.
We = Heat remaining in D_I on leaving H.P. cylinder.
Wv_I = Heat equivalent of work done by D_I in H.P. cylinder.
Wv_{II} = Heat equivalent of work done by D_{II} in H.P. cylinder.
Wv_{III} = Heat equivalent of work done by D_{II} in both cylinders.
Wk = Heat passing to condenser.

sumption (Fig. 138). That portion of the steam quantity D which supplies the heat content, We, of the extracted steam quantity, must, of course, not be booked to the account of power production and is therefore not to be considered when estimating the specific steam consumption of the engine.

The adaptability of the extraction steam engine is clearly demonstrated in the characteristics given in Fig. 137. This example is taken from a Sulzer 600 B.H.P. engine built for a normal extraction of 8800 lbs. at a pressure of 29·4 lbs. per sq. in., superheated steam being supplied to the high-pressure cylinder at a pressure of 176·4 lbs. per sq. in. The point of intersection of the curve marked 600 B.H.P. with the straight line marked E = 8,800 lbs. per hr., corresponds to the normal working conditions of the engine. From the abscissæ the corresponding steam consumption reads 11,440 lbs. per hr., of which amount, according to the ordinate scale, about 2,640 lbs. pass through the low-pressure cylinder into the condenser. The cut-offs

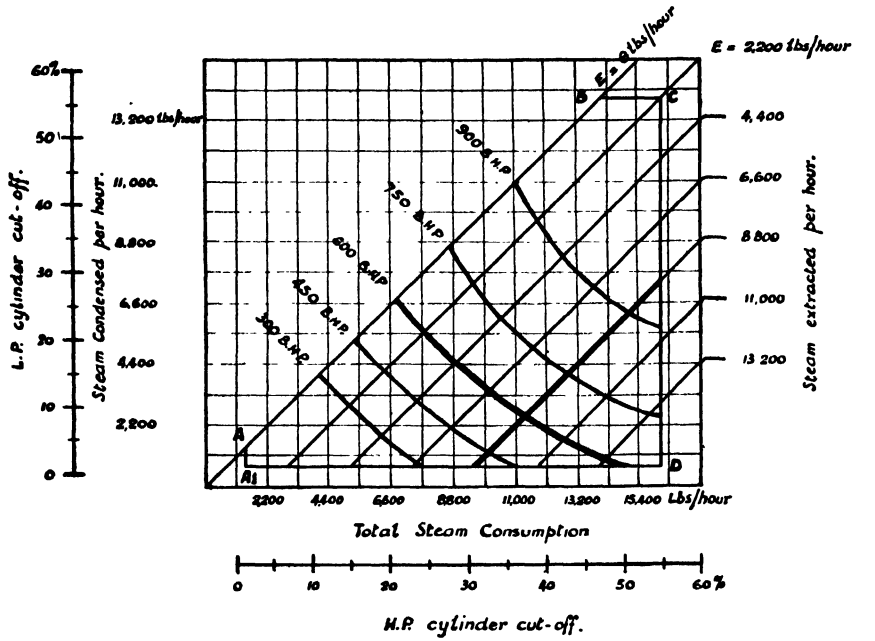


FIG. 137.—**Characteristics** and steam consumption of an extraction steam engine.

on the high-pressure and low-pressure cylinders, which will hereby be set by the speed governor and pressure regulator, amount to about 37 per cent. and 9 per cent. respectively.

For all perfomances within the area of the polygon A, B, C, D, A_1, the engine will—without using additional live steam—be able to cope automatically with all conditions as to power and heating steam

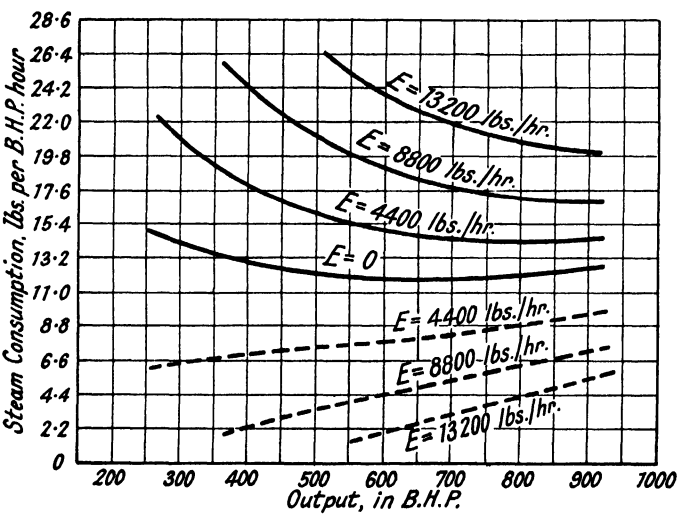


FIG. 138.—E = Steam Extracted per hour.

demand. If, however, more heating steam is required than can be extracted from the receiver at a given output, or in other words, if the point of intersection between output curve and extraction line falls outside this area, the steam pressure regulator D, Dz, automatically opens a by-pass valve Z (Fig. 135), supplementing the steam quantity extracted from the receiver by live steam from the boiler main K through pipe L.

The steam consumptions of this engine under varying service conditions are shown in Fig. 138, the curve marked E = O giving the steam consumption per B.H.P. per hour without extraction. The full curves lying above this line represent the steam consumptions per B.H.P. per hour for differing amounts of extracted steam E, based on the total steam introduced into the high-pressure cylinder, while the dotted curves below indicate the consumptions exclusively for power production, based on the steam quantity passing through the low-pressure cylinder into the condenser.

Pass-Out Steam Turbines.

The pass-out turbine consists of two sections, high-pressure and low-pressure, usually within one casing and forming a single unit. Between the two sections the branch to process mains is provided and the low-pressure section exhausts to a condenser. A sensitive governor controls the admission of the steam to the nozzles of the high-pressure section, this governor maintaining a constant speed of the set for any electrical load or process steam quantity demanded, within the capacity of the plant. A separate governor is provided to control the admission of steam to the low-pressure section. Thus the whole of the steam passes through the high-pressure section and is subsequently divided, part passing to the process or heating main and part through the low-pressure section to the condenser.

As in the case of the pass-out reciprocator, an important characteristic of the combined governing system for pass-out turbines is that it ensures the fullest possible use of the process steam for power generation, i.e. steam is passed to the condenser only when the process steam quantity in demand is insufficient to meet the electrical load. On the other hand, no steam is by-passed direct to the process main unless the process steam quantity in demand is greater than that necessary to meet the electrical load.

In operation, if the demand for process steam increases, the pressure in the process main tends to fall and, assuming the electrical load to be constant, the pass-out governor restricts the admission of steam to the low-pressure section and thus maintains the process pressure. At the same time the main governor automatically compensates for the loss of power due to the reduction in the steam quantity passing to the low-pressure section and a condition of stability

is established. If, on the other hand, the process steam demand is reduced the pass-out governor admits more steam to the low-pressure section and the main governor restricts the inlet steam quantity.

For varying electrical (or mechanical) loads with varying process steam quantities, not necessarily related to each other and such as occur under industrial conditions, it will be seen that the quantities of steam passing through the high- and low-pressure sections may each vary over a wide range.

Each section must, however, be designed for a definite steam quantity, and whatever method of governing may be adopted the efficiency of the section will suffer when the steam quantity passing differs widely from the design quantity.

It is, therefore, necessary, for pass-out turbines, to select most carefully the design conditions that will provide the best efficiency over a period of normal working. To specify that the turbine should develop the full electrical load with no pass-out steam, when such a contingency is extremely remote, results in loss of efficiency to no useful purpose, as such a course would entail designing the low-pressure section for a much greater steam quantity than would normally be used. In other words, the low-pressure section would be running underloaded over long periods. On the other hand, to specify that the turbine should develop full load on pass-out steam only, when the average quantity of process steam in normal use is far below the quantity necessary for this load, will again result in inefficient operation due to underloading of the blading in the high-pressure section.

With full particulars of the process steam and electrical load demands existing and anticipated at his disposal, the turbine designer is the better able to arrive at design conditions most appropriate to the needs of any particular installation.

It should be noted that under all operating conditions it is necessary to pass a small amount of steam through the low-pressure section to the condenser, as otherwise windage and friction of the blading and discs in this section would cause excessive temperatures to be reached. A small constant flow of steam provides sufficient cooling.

Methods of Low-Pressure Steam Control.

There are two principal methods of controlling the admission of steam to the low-pressure section which differ radically in their method of operation and efficiency. These are throttle control and nozzle control. The throttle-control method of governing entails passing the whole of the steam which enters the low-pressure section through a valve, the opening of which is controlled by a pressure regulator, usually through the medium of an oil relay system.

As a result, when little steam is passing into the low-pressure

section, very considerable throttling loss takes place at this point and a portion of the available heat drop in this section is lost, the steam entering the low-pressure nozzles at a considerably reduced pressure.

The nozzle-control method of regulating the admission of steam to the low-pressure section consists essentially of a disc with ports, which moves over the nozzles admitting steam to this section and regulates the area of nozzles in operation in proportion to the steam quantity passing.

High-Pressure Steam Control.

In turbines of the pass-out type it is equally important to avoid throttling losses in the high-pressure section. In such turbines the quantity of steam admitted to the high-pressure section may vary much more than in straight condensing units. For instance, if the full demand for process steam coincides with a large electrical demand, the steam quantity entering the turbine will be very large, whereas with a small electrical load, and little or no pass-out demand, the quantity will be very small. It is on this account very necessary to ensure that the method of control of steam admission should be such that throttling losses are reduced to a minimum.

This can be effected by one form or another of nozzle control, in which the number of nozzles in use at any time is not greater than is necessary for the steam quantity passing.

Use of the Mollier Diagram in the Evaluation of Combined Power and Process Plants.

This subject will be discussed mainly from the point of view of the pass-out turbine.

The most convenient means of examining this matter is by the use of the well-known Mollier diagram or chart, the portion of such a chart which concerns this problem being shown in Fig. 139. On the vertical scale is shown the heat content of the steam in B.Th.U. corresponding to any steam pressure and superheat, so that by noting the point of intersection of the lines of constant pressure and superheat the difference in heat content of steam at various conditions can be readily ascertained.

From this chart it will be seen that steam at 30 lbs. per sq. in. g. (44·7 lbs. per sq. in. abs.) with 50° F. superheat has a heat content of 1200 B.Th.U. (from water at 32° F.), such a point being indicated at X, whereas steam at 185·3 lbs. per sq. in. g. (200 lbs. per sq. in. abs.) with 200° F. superheat is indicated by point A and has a heat content of 1316 B.Th.U., corresponding to an additional fuel expenditure of about 10 per cent.

The Mollier chart can be employed to indicate the changes that

take place during expansion from 185·3 lbs. g. 200° F. to 30 lbs. g., and so assist appreciation of the design and operating characteristics of the pass-out type of turbine.

For this purpose it should be noted that the abscissæ of the chart represent entropy which corresponds to the ratio

$$\frac{\text{Heat Content}}{\text{Absolute temperature °F.}}$$

(the absolute temperature being $t°$ F. + 460), and has the significance that if the steam were expanded adiabatically in a perfect turbine,

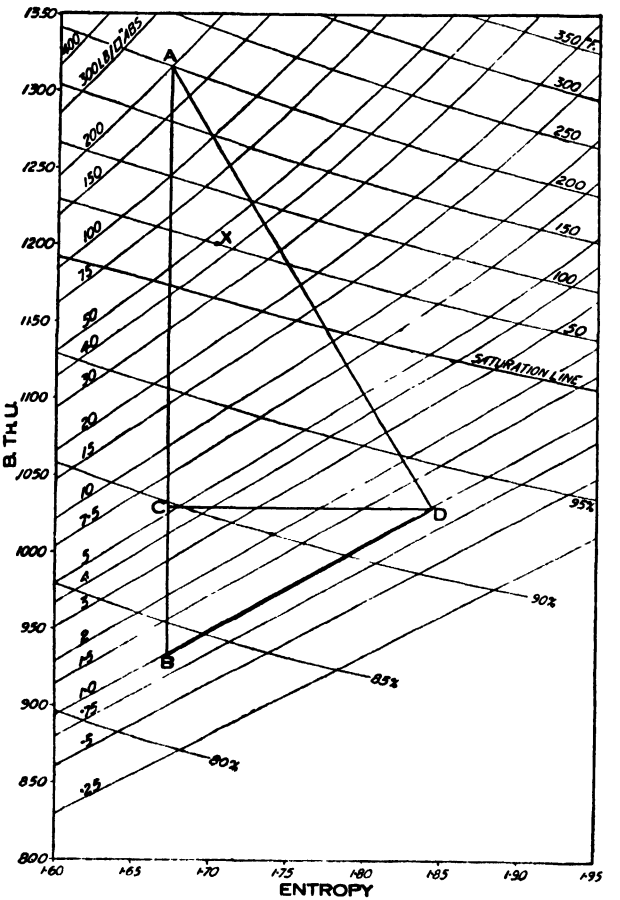


FIG. 139.

the entropy would remain constant; that is, a vertical line on the chart from the point corresponding to the initial high conditions would show the exact state of the steam at different stages of its expansion.

Thus, taking steam at 185·3 lbs. g. 200° F. and expanding to 28 ins. vacuum (0·982 lbs. per sq. in. abs.), the steam in a perfect turbine would

follow the line AB. The chart shows that between these points the heat content of the steam would drop from 1316 B.Th.U to 934 B.Th.U. —a drop of 382 B.Th.U. This last figure is of great importance as it shows the quantity of heat units that for these initial and final conditions is available for conversion into work.

In an actual turbine, however, certain losses inevitably occur which consist chiefly of internal steam friction and eddy losses resulting in the generation of heat, which is returned to the steam as the expansion proceeds so that the net rate of heat loss is reduced. The steam at early stages in the expansion will, therefore, possess a higher degree of superheat and in its final state will contain a smaller percentage of free moisture than would be the condition if there were no losses, as in adiabatic expansion.

Again referring to the Mollier diagram, the conditions applying to the expansion of steam from 185·3 lbs. gauge (200 lbs. abs.) 200° F. down to 28 ins. vacuum in a high-pressure type turbine of, say, 75 per cent. thermodynamic efficiency are shown in Fig. 139.

On the vertical line AB to the exhaust pressure line of 0·982 lbs. abs. the point C is taken such that AC = 0·75 AB and a horizontal line drawn from this point to the point D lying on the exhaust pressure line. The line AD will then closely represent the condition of the steam at intermediate points of its expansion and the point D its final state at which it will contain 7 per cent. moisture, whereas in a perfect turbine with no reheat the percentage would be 16·3 per cent.

Heat due to internal losses and returned to that portion of the steam which passes to the condenser is carried away by the circulating water and constitutes a heat loss to the system. The reheat in the steam passed out for process is, however, available for the process purposes and is, therefore, not a loss to the system as a whole. It does not follow, however, that the efficiency with which power is generated from the process steam is of secondary importance, since it must be realised that the quantity of process steam used in any installation is not unlimited, and for any given quantity the higher the thermodynamic efficiency and the initial steam conditions and the lower the pass-out pressure adopted, the greater will be the power generated.

A typical Mollier diagram for a pass-out turbine with throttle control of the low-pressure section is shown in Fig. 140 for different loads on this section.

The line AB shows the heat drop available in the high-pressure section down to 30 lbs. per sq. in. g., and assuming for purposes of illustration an efficiency of 75 per cent., the line AD shows the state of the steam during its expansion to the pass-out pressure, and the point D lying on the 30 lbs. pressure line shows its state at the pass-out, where it will be seen that the steam retains about 70° F. of superheat.

Even with the low-pressure section fully loaded, a small throttling loss takes place through the control valve. This is represented on the diagram by the horizontal line DE, corresponding to a pressure drop of, say, 2 lbs. per sq. in. The line EF represents the available heat drop, and the line EH the expansion of the steam in the low-pressure section of the turbine, the point H lying on the design exhaust pressure line corresponding to, say, 28 in. vacuum.

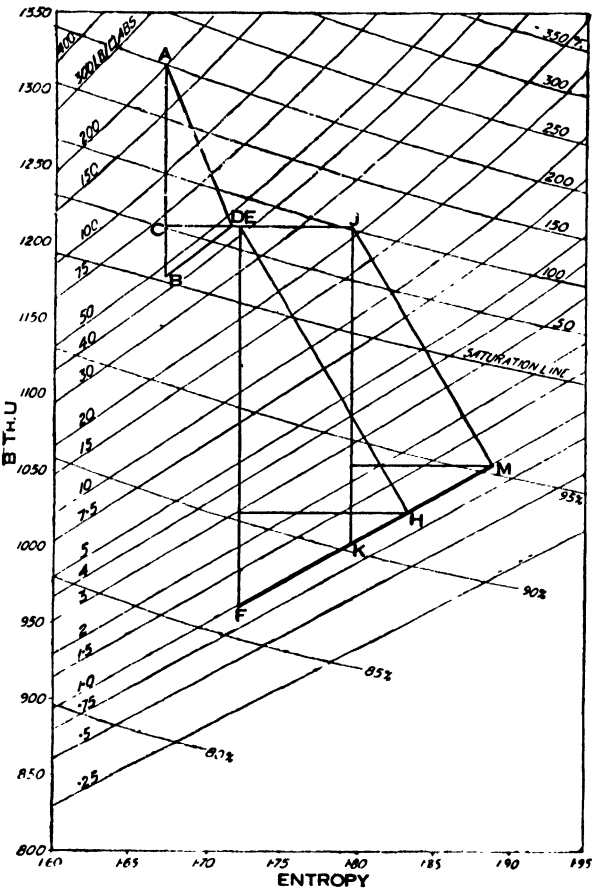


FIG. 140.

If, however, the steam quantity passing through this section is reduced to say one-half, due perhaps to a decrease in electrical load or to an increase in the pass-out quantity, the throttling loss through the control valve will be large and as represented by the horizontal line DJ, the absolute pressures at E and J being proportional to the steam quantities passing in each instance. The available heat drop in the low-pressure section will be reduced to JK, the amount lost by

throttling is EF-JK, and the point M shows the state of the steam entering the condenser.

A characteristic Mollier diagram for the two sections of a pass-out turbine with nozzle control of the low-pressure section is shown in Fig. 141, the line DF representing the available heat drop in this section for all conditions of loading and DH the changes that occur to the steam in its expansion to the point H.

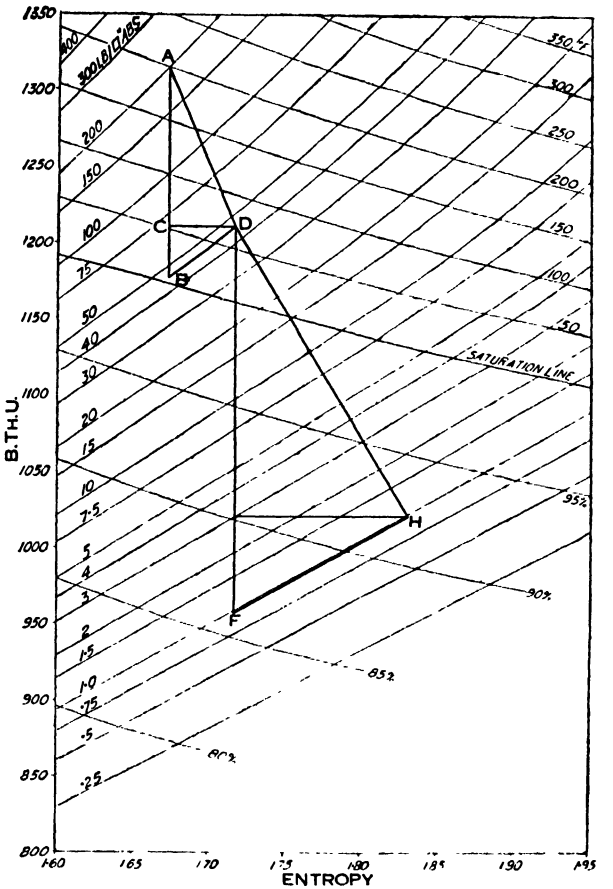


FIG. 141.

It will be seen that with this arrangement which is employed there is no throttling loss. The full pass-out pressure exists in front of the nozzles for all conditions of loading and for partial loads the available heat drop in this section is considerably higher than with throttle-control method.

The relative efficiency of these two methods of control is illustrated in Fig. 142, which shows the characteristic change in efficiency that

occurs with different loadings of the low-pressure section, the actual efficiencies shown being of the order which would obtain in this section of a small turbine.

It must be noted that the Mollier diagram shows the behaviour of each pound of steam and takes no cognisance of the quantity actually

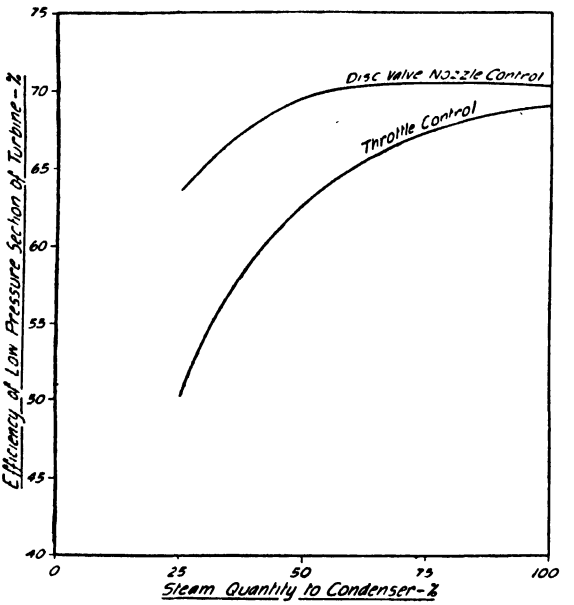


FIG. 142.

in use. Also in the foregoing examples it has been assumed for simplicity that the vacuum remains constant for all loadings of the low-pressure section. Actually the vacuum would improve at lighter loads, provided, of course, that constant quantity of cooling water is used in the condenser.

Power Available from Process Steam.

Summarising the foregoing, it is possible to show in a chart the power that can be generated by the expansion of the process steam from various initial steam conditions down to various pass-out pressures. Such a chart is shown in Fig. 143, in which the power available is shown for convenience in terms of each 10,000 lbs. of process steam. This chart serves to emphasise the importance of keeping the process pressure as low as possible.

It should be realised that the heat units transferred to the process are derived almost entirely from the latent heat of the steam and not from the sensible heat. From the table of temperature and latent heat of saturated steam at various pass-out pressures given below it will be seen that the latent heat is lower at the higher pressures,

and notwithstanding an increase in sensible heat, that the total heat contents do not appreciably vary over the range of pass-out pressures shown.

Steam Pressure (lbs. per sq. in. g.)							
0	5	10	15	20	30	40	50
Saturation Temperature (° F.)							
212	228	240	250	259	274	287	297
Latent Heat (B.Th.U. per lb.)							
970	959	951	944	938	927	918	910
Total Heat (B.Th.U. per lb.)							
1150	1156	1160	1164	1166	1171	1175	1178

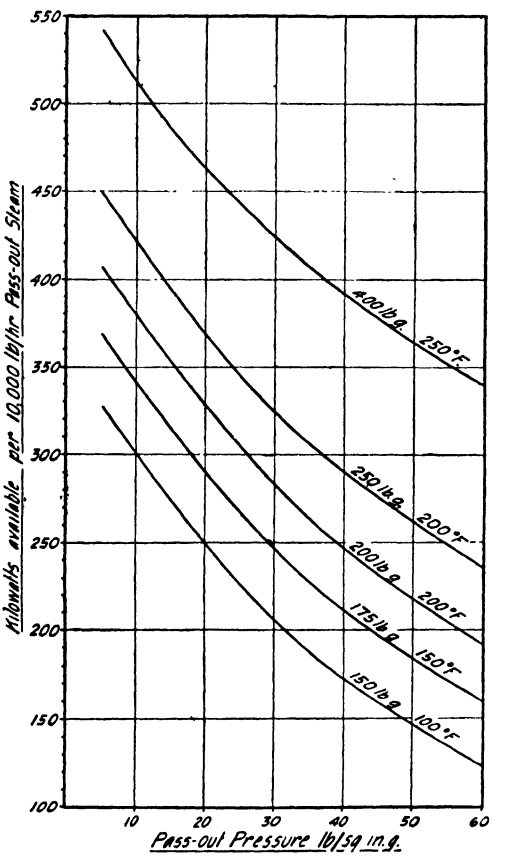


Fig. 143.

The real limiting factor determining the choice of the pass-out pressure is almost always the temperature of the process, and the pressure used should only be slightly above that which corresponds

to this minimum temperature. Referring to Fig. 143, it will be noted that with initial steam conditions of 200 lbs. per sq. in. 200° F. and a pass-out pressure of 40 lbs. per sq. in. gauge each 10,000 lbs. of steam would generate approximately 245 kW. By reducing the pass-out pressure to 20 lbs. per sq. in. the same quantity would generate 327 kW., or about 33 per cent. greater output. Thus, the lower the process pressure the less is the steam to the condenser, and the greater the saving in fuel consumption.

Initial Steam Conditions.

In an entirely new installation where it is possible to fix the most suitable initial conditions, the question of the initial steam pressure should be most carefully considered.

From a purely thermodynamic point of view, the higher the pressure adopted the higher will be the efficiency, but with smaller plant the use of extreme pressures should be undertaken with caution and only after fully considering the difficulties that must be met. Failure to realise these difficulties has occasionally been attended with disappointing results, and it must be realised that because of these difficulties the cost of the plant required to enable the full thermodynamic advantages of high-steam pressure to be realised may, in the case of small units, become disproportionate.

In regard to steam temperature it is advisable to select a degree of superheat that will result in a small amount of superheat being present in the steam after expansion to the heater process pressure, but on the other hand the superheat should not be so high that the process steam still retains a considerable degree of superheat at the heaters and so renders difficult their temperature control. If conditions are chosen to provide a pass-out steam superheat of about 50° F. the steam should, in most instances, reach the heaters in a dry state but without excessive superheat.

The diagram shown in Fig. 144 indicates the degree of initial superheat that will result in about 50° F. superheat being present in the pass-out steam for various initial and pass-out pressures.

For example, if a boiler pressure of 400 lbs. per sq. in. and a pass-out pressure of 20 lbs. per sq. in. are selected, the chart indicates that in order that the pass-out steam will possess 50° F. superheat, the initial superheat should be about 250° F.

Although a pass-out steam superheat of 50° F. has been suggested as suitable for a large proportion of pass-out installations, there are many instances where the exceptional layout of the plant warrants a different degree of pass-out steam superheat and each case requires individual consideration.

It may be assumed for all practical purposes that within limits a change of initial superheat will result in the pass-out superheat being

changed by an approximately equal amount, so that if the pass-out superheat is required to be raised or lowered, it is only necessary to increase or decrease the initial superheat by the same amount. It is, therefore, possible to fix approximately the initial superheat for any pass-out steam superheat by means of the chart, it being merely necessary to assume a final superheat of 50° F. as a preliminary step, and after arriving at the corresponding initial superheat to increase

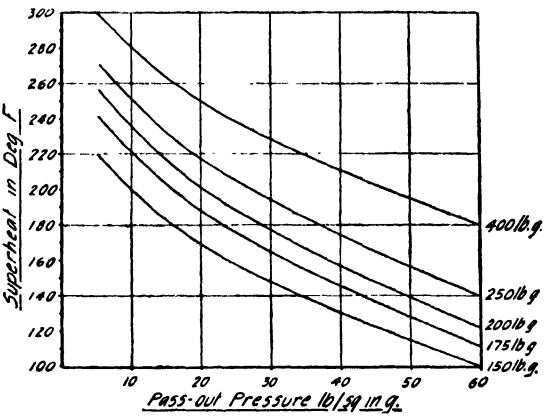


FIG. 144.

or decrease this superheat by the amount that the selected pass-out steam superheat exceeds or is less than 50° F. For example, for pressures of 250 lbs. per sq. in. and 40 lbs. per sq. in. and a final superheat of 100° F. the initial superheat would be 174° F. + 50° F., or 224° F. It should be borne in mind that the performance data given in curves of Figs. 143 and 144 are approximate only and are subject to some variation depending on size and other considerations.

Allocation of Fuel Costs in Combined Power and Process Plants.

In factories where combined power and process steam plant is used, it is frequently required, for departmental costing purposes, to allocate correctly the true fuel costs of power and process steam. This cannot be done by the mere measurement of steam quantities, but must be considered on the basis of actual heat used for the two purposes.

It is obvious that any steam condensed in the condenser of a pass-out turbine or engine must be debited to " power," and similarly, any steam passed to process from the boilers, through the medium of a reducing valve, must be debited to " process." The difficulty is to allocate the proportion of the pass-out steam cost to be debited to " power " and " process " respectively.

Before showing a simple method of computing such costs it is

necessary to bear in mind what really happens to the process steam in its passage through the turbine. In the first place, a number of heat units are converted directly into power and the steam loses heat on this account. Then again, the steam is deprived of a small amount of heat on account of radiation and bearing and gland losses. But as already explained, of the total losses which occur in the turbine, the great proportion is that represented by internal steam friction and eddy loss, and this loss in the high-pressure section of a pass-out turbine is returned to the steam as heat and is present as heat in the pass-out

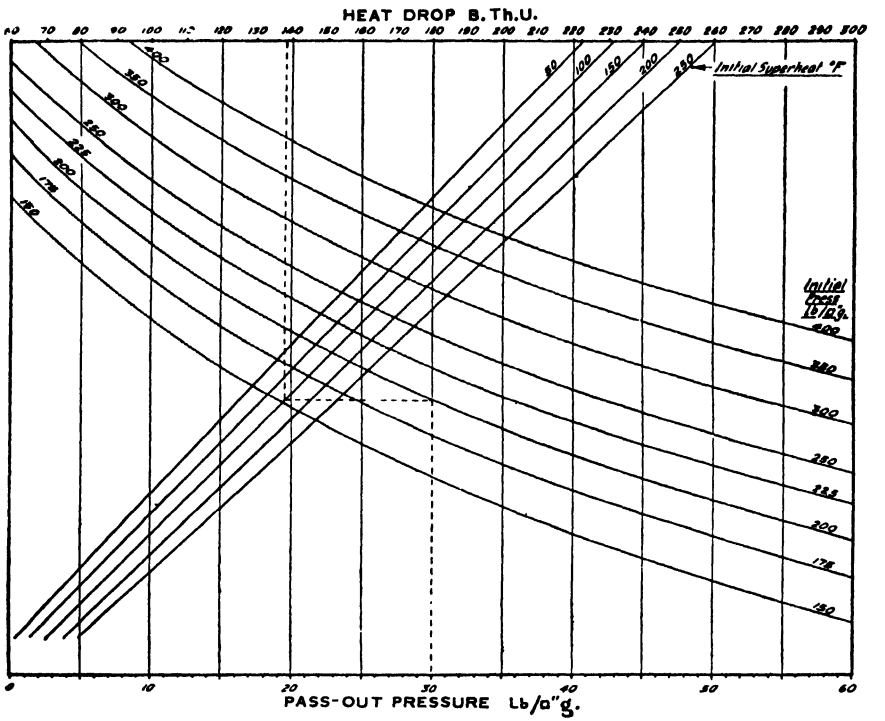


FIG. 145.

steam. This recoverable loss, in the case of large plant, may be 20 per cent. or less of the total turbine heat drop, but for small plant it would be more reasonable to take a value of about 25 per cent., particularly as the plant would operate for part of the time on partial loads.

In this problem the simplest way to make allowance for the recoverable loss is to assume that 75 per cent. of the adiabatic or theoretical heat drop of the process steam should be debited to "power," the balance of 25 per cent. being debited to "process." The adiabatic heat drop is readily obtainable from the chart shown in Fig. 145, for any set of steam conditions in the manner indicated below, this chart

being easier to apply than the Mollier chart, whilst sufficiently accurate for all practical purposes. To read the diagram, first note the point of intersection of the initial pressure line (gauge) with the vertical line of pass-out pressure, and from this point draw a horizontal line to meet the line of initial superheat, then from this second point of intersection read off, vertically above, the heat drop in British Thermal Units.

In the case of an installation employing a single pass-out pressure it is now possible to allocate the fuel cost in proportion to the heat actually used, as follows :—

Let W	= total steam generated	lbs. weekly.
P	= total pass-out steam	lbs. weekly.
C	= steam condensed in power plant	lbs. weekly.
R	= steam supplied through reducing valve	lbs. weekly.
T	= total coal consumption	tons weekly.
L	= cost of coal	£ per ton.
a	= total heat per lb. steam as generated corrected to hotwell temperature	B.Th.U.
c	= net pass-out steam heat drop in turbine (total heat drop $\times$ 0·75)	B.Th.U.

$$\text{Then Fuel Cost for Power in £ per week} = \frac{\left(\frac{c}{a} \times \text{P}\right) + \text{C}}{\text{W}} \times \text{TL}$$

$$\text{and Fuel Cost for Process in £ per week} = \frac{\left(\frac{a - c}{a} \times \text{P}\right) + \text{R}}{\text{W}} \times \text{TL}$$

Example.

Initial steam pressure	200 lbs. per sq. in. g.
Total temperature	538° F.
Superheat	150° F.
Pass-out pressure	30 lbs. per sq. in. g.
Total coal consumption	200 tons weekly.
Cost of coal	16s. per ton.
Total steam generated	3,000,000 lbs. weekly.
Total pass-out steam	2,200,000 lbs. weekly.
Total steam condensed in condenser plant	500,000 lbs. weekly.
Total steam supplied through reducing valve	300,000 lbs. weekly.
Hotwell temperature	93° F.
Total heat in inlet steam (from steam tables or Mollier chart) corrected to hotwell temperature	1230 B.Th.U. per lb.
Total heat drop in pass-out steam (from diagram, Fig. 145).	138 B.Th.U. per lb.
Net heat drop in pass-out steam (138 $\times$ 0·75).	103·5 B.Th.U. per lb.

$$\text{Weekly Fuel Cost for Power} = \frac{\left(\frac{103{\cdot}5}{1230} \times 2{,}200{,}000\right) + 500{,}000}{3{,}000{,}000} \times \frac{16}{20} \times 200$$

$$= £36{\cdot}5.$$

$$\text{Weekly Fuel Cost for Process} = \frac{\left(\frac{1126{\cdot}5}{1230} \times 2{,}200{,}000\right) + 300{,}000}{3{,}000{,}000} \times \frac{16}{20} \times 200$$

$$= £123{\cdot}5.$$

Double Pass-Out Systems.

In installations where process or heating steam is used at two different pressures, B_1 and B_2, the same method can be used to allocate the fuel cost of each supply and of power.

If C_1 and C_2 are the *net* heat drops of the pass-out pressures respectively, P_1 and P_2 the respective pass-out quantities in lbs. weekly, and R_1 and R_2 the quantities supplied to the two systems through reducing valves in lbs. weekly, W.C.T. and L being as given previously, then :—

$$\text{Fuel Cost for Power} = \frac{\left(\frac{c_1}{a} \times P_1\right) + \left(\frac{c_2}{a} \times P_2\right) + C}{W} \times \text{TL in £ weekly.}$$

$$\text{Fuel Cost for Steam Supply at Pressure } B_1 = \frac{\left(\frac{a - c_1}{a} + P_1\right) + R_1}{W} \times \text{TL in £ weekly.}$$

$$\text{Fuel Cost for Steam Supply at Pressure } B_2 = \frac{\left(\frac{a - c_2}{a} \times P_2\right) + R_2}{W} \times \text{TL in £ weekly.}$$

The above method is probably sufficiently accurate for general purposes, particularly in the case of plant of medium capacity in which the turbine internal loss is actually of the order of 25 per cent. as assumed. It must be stated that the above method deals with fuel cost only, and it does not necessarily follow that other charges should be proportionally allocated.

In the foregoing approximate method of allocating fuel costs to power and process steam respectively it will be noted that the actual power generated by process steam is not directly involved. It can, however, be computed when the total process steam quantity and the thermodynamic efficiency of the high-pressure section of the turbine are known.

For instance, in the example given, and assuming a gear and generator loss of 7 per cent. (total) and a thermodynamic efficiency of 75 per cent., the power generated by 2,200,000 lbs. of process steam would be :—

$$\frac{2200000 \times 138 \times 0{\cdot}75 \times 0{\cdot}93}{3420}$$

$$= 62{,}000 \text{ kW. hr. weekly.}$$

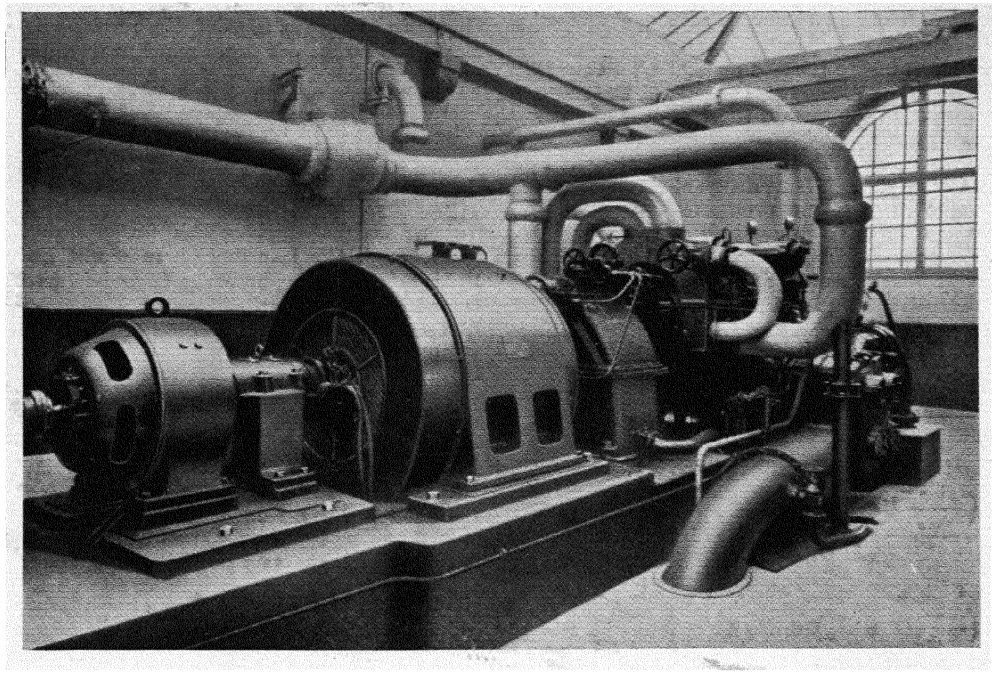


FIG. 146.—2000 kW. self-contained pass-out turbine by Metropolitan Vickers Electrical Co., Ltd.

[*To face page* 323.

Relative Fuel Costs.

Although the information may not be of direct use, it is interesting, however, to arrive at the relative fuel costs of the power generated by process steam and by steam passing through the entire turbine to the condenser. These relative fuel costs are inversely proportional to the thermal efficiency of the two methods.

The thermal efficiency obtaining for process steam is virtually 100 per cent., as practically the whole of the internal loss in the high-pressure section is returned to the steam, and is of direct value. For steam passing to the condenser the thermal efficiency is represented by the ratio :—

$$\frac{\text{Heat Units per lb. of steam converted into work.}}{\text{Total Heat Units per lb. of steam as generated.}}$$

The total heat per lb. as generated may be taken from a Mollier chart or from steam tables, and corrected for the hotwell temperature. The value of heat units per lb. of steam converted to useful work is the adiabatic heat drop corrected for turbine efficiency or the net heat drop, e.g. A.C. in Fig. 140.

For example, with the conditions stated above and assuming a vacuum of 28 ins., the relative fuel expenditure would be :—

By process steam . . . . . 1.

By condensed steam . . . . . $\frac{1230}{375 \times 0{\cdot}75} = 4{\cdot}38.$

In other words, for these conditions each kilowatt hour generated by process steam involves a fuel expenditure of about only 22·8 per cent. of that necessary under condensing conditions.

A large 2000 kW. self-contained pass-out turbine by Metropolitan Vickers is seen in Fig. 146.

Fig. 147 shows a condensing double extraction turbine by the Westinghouse Electric & Manufacturing Company. It is of 2000 kW. capacity and designed for steam supply at 275 lbs. per sq. in. (saturated), vacuum 27·5 ins. and extraction at 45 & 5 lbs. per sq. in.

A diagrammatic sketch showing a recent double pass-out turbine installation by Belliss and Morcom is seen in Fig. 148. The conditions are—Initial steam pressure 140 lbs. per. sq. in., temperature 500° F. Maximum quantity of steam supplied to turbine 34,000 lbs. per hr. Maximum pass-out per hour, 17,000 lbs. at 35 lbs. and 10,000 lbs. at 3 lbs., vacuum 28·5 ins. The Willans lines for this turbine are seen in Fig. 149. The apportioning arrangement is such in that, instead of the whole of the steam being taken out of the machine and a portion returned, the turbine only passes out what is actually demanded for process work, and the remainder goes through a control or " gate " stage or stages. By this means the available energy from the pass-out

to the pass-in, which is often considerable, is partly recovered in useful work.

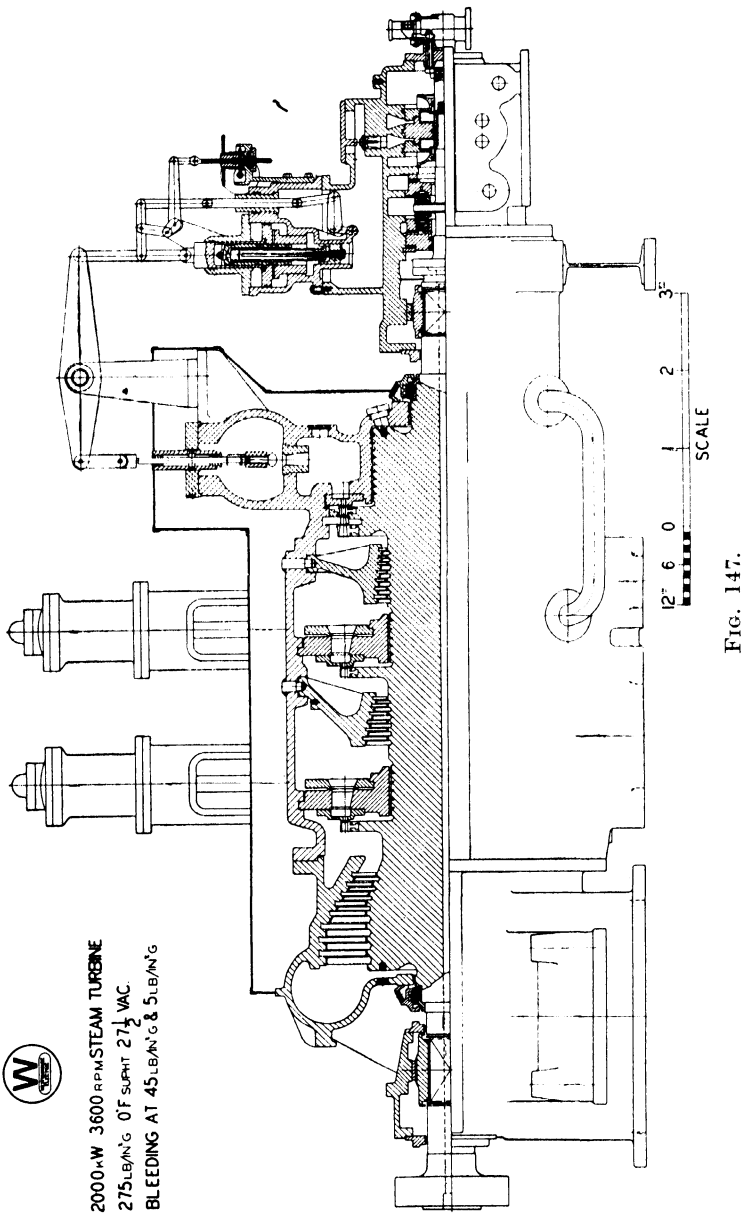


FIG. 147.

As an example of the use of the diagram Fig. 149, take the load as 625 kW. and the pass-out quantities per hour as 15,000 lbs. at 35 lbs. and 8,000 lbs. at 3 lbs. pressure.

Starting at the point A, which is 15,000 lbs. on the 35 lbs. all

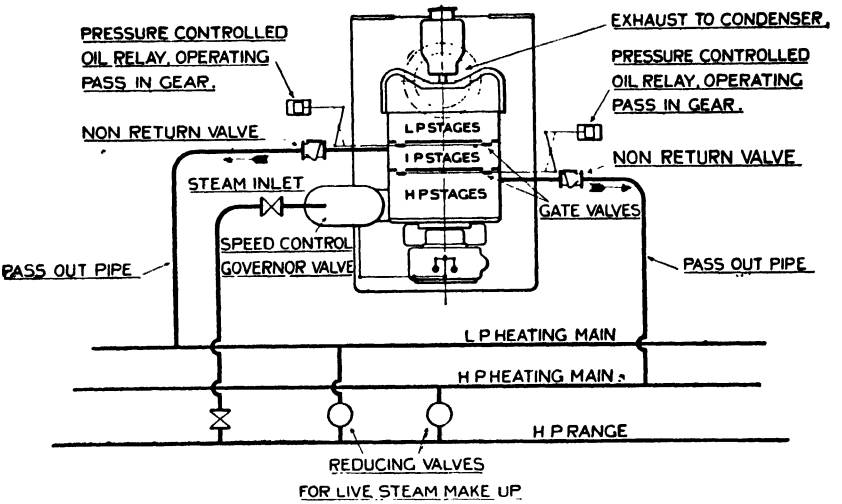


FIG. 148.—Diagrammatic arrangement of steam turbine with double pass-out (Belliss & Morcom, Ltd.).

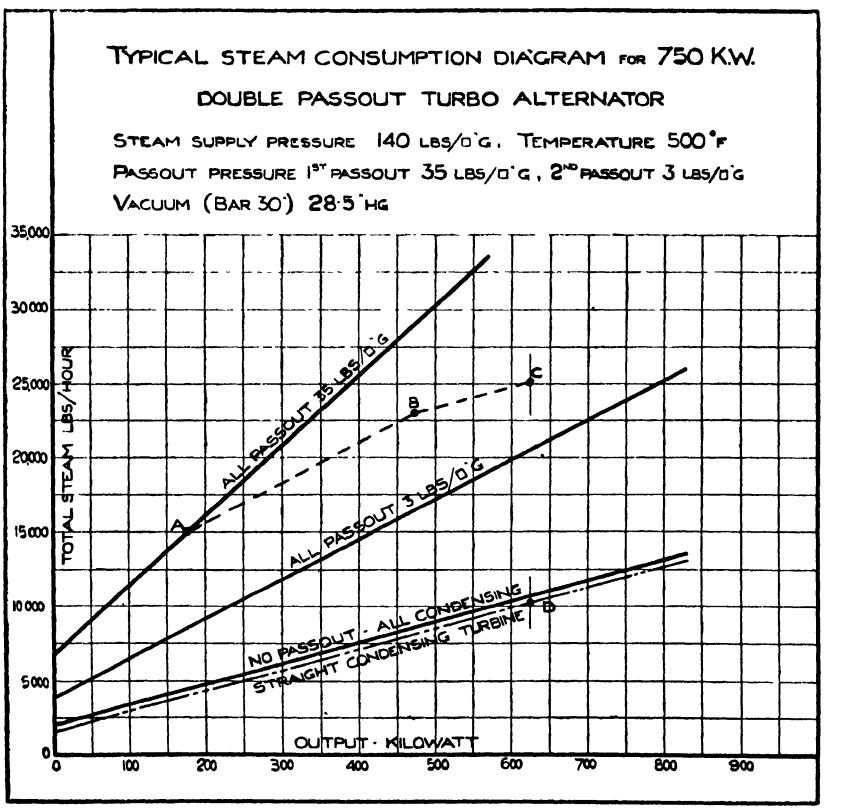


FIG. 149.—Details of performance of double pass-out turbine by Belliss & Morcom, Ltd.

pass-out line, draw a line AB parallel to the 3 lbs. all pass-cut line up to (15,000 and 8,000), i.e. 23,000 lbs., which is at point B. Draw BC. parallel to the all condensing line until the load ordinate (625 kW) is reached, i.e. at point C.

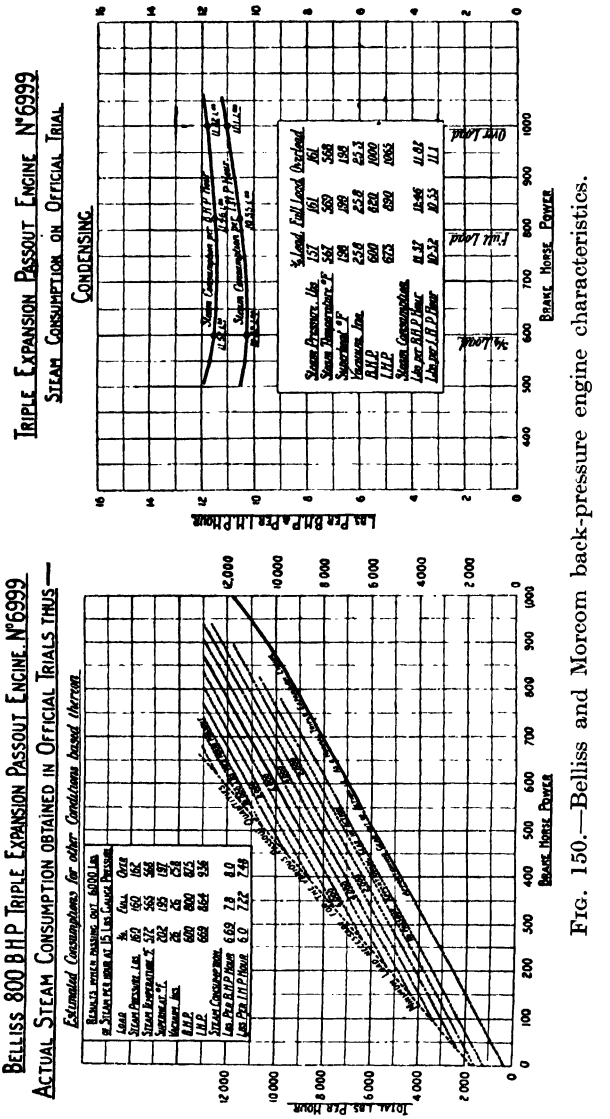


Fig. 150.—Belliss and Morcom back-pressure engine characteristics.

Thus under above condition the total steam consumption for both power and process steam will be 25,100 lbs., of which 23,000 lbs. will be passed out to the process. Had the power been generated in a fully condensing turbine the consumption of steam at 625 kW.

would be 10,200 lbs. (see point D in Fig. 149), and the process steam required would still be 23,000 lbs. Therefore under independent conditions the total steam required would be 33,200 lbs. or 8,100 lbs. per hr. more than if the combined system employing a pass-out turbine is employed. The combined system, therefore, shows an economy of 24 per cent. over independent systems of power and steam supply, without taking into account capital charges, including installation and building costs.

Fig. 150 shows particulars of an interesting 800/1000 B.H.P. triple expansion engine by Belliss and Morcom, Ltd. The engine speed is 300 R.P.M. and the steam supply is at 160 lbs. per sq. in. superheated 200° F. It is arranged for combined electric and rope drive to pass out up to 6,000 lbs. steam per hour at 15 lbs. per sq. in., the L.P. cylinder exhausting to 26 in. vacuum. Allowing for the steam passed out, the consumption of steam per I.H.P. at full load and 6,000 lbs. extraction is 7·22 lbs., and at $\frac{3}{4}$ load 6 lbs. per I.H.P. When operating entirely condensing, the steam consumption at the most economical load is 10·32 lbs. per I.H.P. hour.

CHAPTER X.

EVAPORATORS.

Flow of Fluids—Heat Transfer—Evaporators.

Introductory.—A large number of chemical engineering operations involve the transfer of heat from one body or fluid to another, and hence the laws governing heat transfer are of considerable importance in the design of such equipment.

Many unit operations necessitate the transfer of heat through tubes, and before discussing the laws of heat transfer it is proposed to deal briefly with the principles of the flow of fluids.

Flow of Fluids in Tubes.—The flow of fluids in tubes is influenced by the *viscosity* of the fluid, and by the nature of the flow, i.e. whether the flow is *turbulent* or streamline (viscous). *Viscosity* is defined as that property of fluids whereby they resist an instantaneous change of shape, or rearrangement of their molecules.

Absolute Viscosity (symbol μ) is defined as the force required to move a plane surface of the fluid of 1 sq. cm. in area, parallel to another plane surface of the fluid at 1 cm. distance from the first The *unit* of viscosity is the poise, which is equivalent to 1 dyne-cm. per sec. per sq. cm. The *centipoise* (= 0·01 poise) is used frequently in practical fluid flow calculations. (Note that the viscosity of water at 68° F. is 1 centipoise.) To convert viscosity as measured in poises to English units, use the followiug relationship :

1 poise = 100 centipoises = 0·0672 lbs. mass per ft. per sec. = 0·0672 poundal per sec per sq. ft. = 0·00209 lbs. force per sec. per sq. ft.

Kinematic Viscosity (symbol y) is the ratio of absolute viscosity μ to the density ρ of the fluid, and it can be determined from viscosimeter readings directly by the use of table below (t = time of flow, secs.)

EQUATIONS FOR CONVERTING VISCOSIMETER READINGS TO KINEMATIC VISCOSITY

Viscosimeter.	Metric Units. y = sq. cm./sec.	English Units. y = sq. ft./sec.
Saybolt Universal	$y = 0{\cdot}0022t - \left(\frac{1{\cdot}8}{t}\right)$	$y = 0{\cdot}00000237t - \left(\frac{0{\cdot}00194}{t}\right)$
Engler . . .	$y = 0{\cdot}00147t - \left(\frac{3{\cdot}74}{t}\right)$	$y = 0{\cdot}00000158t - \left(\frac{0{\cdot}00403}{t}\right)$
Redwood . . .	$y = 0{\cdot}0026t - \left(\frac{1{\cdot}72}{t}\right)$	$y = 0{\cdot}00000280t - \left(\frac{0{\cdot}00185}{t}\right)$

Relative Viscosity (symbol Z) is the ratio of the absolute viscosity of a fluid to that of water.

Density of a Fluid (ρ) is defined as the mass per unit volume.

Streamline (Viscous) and Turbulent Flow in Pipes.—The flow of fluids in pipes may be either streamline (viscous) or turbulent, depending upon the value of the average velocity of the fluid through the pipe. In practice nearly all fluid flow problems are concerned with flow under turbulent conditions, because viscous flow is only possible with very low velocities. The work of Professor Osborne Reynolds is the basis of our modern conception of fluid flow. In 1874 he showed that the *critical velocity*, which is defined as that velocity at which the flow changes from viscous to turbulent, varies directly as the absolute viscosity of the fluid, and inversely on the tube diameter and the fluid density; the ratio $\frac{DV\rho}{\mu}$ is known as the Reynolds' number, where D is the diameter of the pipe and V the velocity of the fluid. Note that Reynolds' number is dimensionless, and that any *homogeneous* set of units will give the same value for Reynolds' number. The particular value of Reynolds' number at which the transition from viscous to turbulent flow occurs is called the *Critical Reynolds' Number.* An exact value cannot be given for all cases, but from many tests this value is known to vary between 2000–3000 under ordinary conditions.

Heat Transfer Problems in chemical engineering involve a study of the friction due to the flow of fluids in pipes, as well as the laws of heat transfer. In the case of heavy oil flowing in pipes under *viscous flow* conditions, the following formula is often used (Poiseuille's Law).

$$h = \frac{32ulV}{gD^2}$$

where h = loss of head in feet = $\frac{(P_1 - P_2)}{\rho}$ lbs./sq. in.

P_1 and P_2 = higher and lower pressures respectively lbs. sq. in.;
μ = absolute viscosity poundal/sec./sq. ft.
= 1488 centipoises;
ρ = density lbs./cu. ft.;
D = dia. of pipe in feet;
g = 32·2;
l = length feet;
V = velocity feet/sec.

The above formula indicates that for streamline flow in horizontal pipes the pressure drop varies directly on the absolute viscosity, average velocity and length of pipe, and inversely as the square of the pipe diameter.

For the solution of practical problems involving pressure drop in pipes in turbulent flow, the chart devised by Bayard (Fig. 121, page 270) will be found most useful. (For *steam pipes* the pressure is given in the alignment chart on page 263.)

The Principles of Heat Transfer.—Heat may flow by one or more of three methods—conduction, convection and radiation. In the design of evaporation and heat exchangers, wherein usually one fluid is contained within a nest of tubes and the other fluid surrounds the tubes, the transfer of heat take place mainly by conduction, *accompanied* by convection. Assuming a steady state and homogeneous material, the transfer of heat by *conduction* from one point to another is

(*a*) Proportional to the thermal conductivity of the material.
(*b*) Proportional to the difference in temperature between the two points.
(*c*) Proportional to the area through which heat flow takes place.
(*d*) Inversely proportional to the distance between the two points.

The following equation formulates the above principle :—

$$Q = \frac{\lambda A(t_1 - t_2)}{L} \quad . \quad . \quad . \quad . \quad (1)$$

where Q = heat flow in B.Th.U./hr.,
λ = thermal conductivity (B.Th.U./ft./sq. ft./° F./hr.),
A = area of path (sq. ft.),
t_1 = higher temperature (° F.),
t_2 = lower temperature (° F.),
L = length of path in ft.

See Table 48 for values of λ for some common constructional materials and liquids.

The above equation may perhaps be more effectively expressed as :—

$$\text{Rate of heat flow} = \frac{\text{Driving force}}{\text{Resistance}} \quad . \quad . \quad . \quad (2)$$

This method of expressing the flow of heat by conduction will assist to form a mental picture of the process by analogy with Ohm's law for the flow of electricity.

In chemical engineering problems it is very seldom that the flow of heat can be expressed so simply as in equation (1). In nearly every case the conditions are such that the heat flow must take place through several layers of materials of different thermal conductivities, and hence by analogy with electric currents the resistance to the flow of heat is additive and can be expressed

$$Q = \frac{\Delta t}{\frac{L_1}{\lambda_1 A_1} + \frac{L_2}{\lambda_2 A_2} + \frac{L_3}{\lambda_3 A_3}} \quad . \quad . \quad . \quad (3)$$

Since in most cases the areas of the resistances are equal, then

$$Q = A\Delta t \frac{1}{\frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2} + \frac{L_3}{\lambda_3}} \quad . \quad . \quad . \quad (4)$$

I am indebted to Professor W. L. Badger, Professor of Chemical Engineering, University of Michigan, and the Swenson Evaporator Co., of Harvey, Illinois, for permission to quote at length from the recent publication of the latter Company, "Heat Transfer and Crystallisation."

Flow of Fluids in Pipes in Relation to Heat Transfer.

It has already been shown that fluids such as water, oil, air, steam, etc., may flow under two entirely different sets of conditions. The first is viscous or straight-line flow in which all the particles are moving in straight lines parallel to the tube wall and in which there is no mixing or cross motion of the molecules. Such viscous flow may be pictured as a series of concentric cylinders slipping over each other, the centre one moving the fastest, and the other moving more and more slowly until the cylinder next to the tube wall is practically stationary. The second type of fluid flow is known as turbulent flow, in which the particles are moving along the tube and mixing rapidly as they progress.

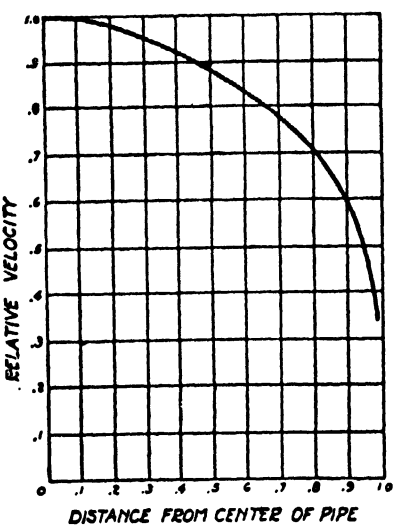


FIG. 151.—Distribution of fluid velocity in turbulent flow.

Viscous flow changes to turbulent flow at a definite velocity known as the critical velocity. Fig. 151 shows the relative velocity with turbulent flow at various cross-sections of a pipe, and it is clear from the curve that somewhere very near the wall of the tube, even under turbulent flow conditions, the velocity will fall below the critical, and a stagnant layer adjacent to the tube wall can then be conceived. The actual existence of this stagnant film has been demonstrated many times, and its properties have the most important effect not only on heat flow, but on a large number of other operations in chemical processes.

Now it is to be noted that heat can only pass through the slow moving film of the stagnant layer by pure conduction, and as liquids and gases are but poor conductors of heat, the rate of heat transfer in actual practical equipment involving heat transfer by fluid flow

is very much less than the value found by simple substitution in equation (1).

As a practical illustration of the resistance of such stagnant films, take the case of a copper tube, thickness 0·065 in. with a difference of 1° F. between its inner and outer walls, and steam on one side of the tube and water on the other. If there were no stagnant films on both sides of the tube the heat flow per hour by equation (1) would be

$$Q = \frac{220 \times 1 \times 1}{\frac{0{\cdot}065}{12}} = 40{,}600 \text{ B.Th.U.}$$

Assuming that there is a stagnant film of water and condensed steam each 0·01 in. thick (and it is to be noted that such thicknesses are often met with in practice), then the problem becomes one of thermal resistance in series and may be solved by equation (4), substituting

$A = 1$ sq. ft.,

$\Delta t = 1°$ F.,

$L_1 = \frac{0{\cdot}01}{12} = 0{\cdot}00083$ ft. (condensate film),

$L_2 = \frac{0{\cdot}065}{12} = 0{\cdot}0054$ ft. (copper tube wall),

$L_3 = \frac{0{\cdot}01}{12} = 0{\cdot}00083$ ft. (water film),

$\lambda_1 = 0{\cdot}417$ (conductivity of water at 212° F.),

$\lambda_3 =$ *do.*,

$\lambda_2 = 222$ (conductivity of copper).

Substituting in equation (4) and solving

$$Q = 1 \times 1 \times \frac{1}{0{\cdot}00199 + 0{\cdot}00002 + 0{\cdot}00199}$$

$$= 410 \text{ B.Th.U./hr.}$$

This is one-hundredth of the heat flow possible if no stagnant film were present, and illustrates the importance of reducing the stagnant layer to the lowest practicable figure. The value of this practical comparison lies not in the numerical answer, but in the fact that it demonstrates that the assumption of a stagnant film of gas or liquid against a tube wall definitely accounts for the low rates of heat transfer found in many types of equipment of the heat exchanger type.

Further, this example demonstrates that if heat is flowing from one fluid to another through a metal wall, the thermal conductivity of the metal has usually but little effect upon the rate of heat transfer. There are, however, some few exceptions to this general conclusion and which are dealt with later in this chapter.

It is evident then that in considering the transfer of heat from one fluid to another through a separating wall there will be at least three resistances, i.e. the two stagnant films and the wall itself. In practice the measurement and control of film thickness is very difficult, and hence indirect methods must be found to express the effect of such films upon heat transfer. By methods to be discussed later in this chapter, values may be computed for $\frac{\lambda_1}{L_1}$ or $\frac{\lambda_3}{L_3}$. Such a value is called a *film coefficient* and is represented by h with various distinguishing subscripts, and given such values for the film coefficient equation (4) becomes

$$Q = A(t_1 - t_2)\frac{1}{\frac{1}{h_1} + \frac{L_2}{\lambda_2} + \frac{1}{h_3}} \quad . \quad . \quad . \quad (5)$$

The fraction

$$\frac{1}{\frac{1}{h_1} + \frac{L_2}{\lambda_2} + \frac{1}{h_3}}$$

is numerically equal to the amount of heat flowing through the combined resistances in B.Th.U. per sq. ft. per hr. per ° F. *overall* temperature drop. This in practice is called the overall heat transfer coefficient and is usually represented by U.

The general equation of heat transfer then becomes

$$Q = UA\Delta t \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Thick-Walled Tubes.—The above discussion is based on the assumption that the area of all the parts of the paths of heat transfer are constant. For tubes which are thick walled, by substituting the film coefficients h_1 and h_3 in equation (3) we get

$$Q = \frac{\Delta t}{\frac{1}{h_1A_1} + \frac{L_2}{\lambda_2A_2} + \frac{1}{h_3A_3}} \quad . \quad . \quad . \quad (7)$$

To define A_2, the mean area of the metal wall, the following procedure is adopted. It may be shown that when heat is flowing through a thick-walled tube the true mean radius to be used in heat-flow calculations is given by

$$r_m = \frac{r_1 - r_2}{\log_e \frac{r_1}{r_2}} \quad . \quad . \quad . \quad . \quad (8)$$

where r_m is the mean radius, r_1 the outside radius, and r_2 inside radius, A_2 should be calculated upon the value of r_m so found.

In the calculation of commercial heat transfer equipment, especially with thick-walled tubes, the question often arises as to whether the inside, outside, or mean surface of the tube should be used as a

basis for calculation. It is possible in most cases to make simplifications sufficiently accurate for all practical purposes on the following lines :—

As has already been noted, the middle term of the denominator of equation (7) is too small in nearly all cases to be of much practical significance, and the numerical results depend on the two other terms involving the film coefficients. If h_1 and h_3 are of the same order of magnitude the full form of equation (7) should be used. On the other hand, if one of the film coefficients is very small compared with the other, then the value of the overall coefficient U will approach the value of the smaller film coefficient. Consequently if h_1 is small compared with h_3, then the term involving h_1 is the term which largely determines the value of U ; hence A_1 is the significant area, and from this follows the important practical rule. The area of the film with the smaller coefficient controls the problem, and hence if the film coefficient on the inside of the tube is low the inside surface should be used in calculation, and vice versa.

Mechanism of Heat Flow from Fluid through Pipes.

It has been demonstrated that the stagnant films on the surfaces of the dividing walls of equipment offer the most important resistance to the flow of heat, and hence it is essential that the magnitude of these resistances be determined as accurately as possible. Viscous flow through pipework is rarely met with in practice, and hence the discussion will be confined to turbulent flow.

The degree of turbulence existing in any practical example is obviously important. A particle of fluid moving in an erratic way along a tube will frequently impinge upon the stagnant film adjoining the tube wall, and will therefore distort this film and tear off a part to mix with the remainder of the flowing fluid. The greater the velocity of flow, the more frequently will such disturbance of the stagnant film occur and hence the thinner will be the average thickness of the film.

The more viscous the fluid the less will be the number of times a particle will collide with the film, and for a given velocity the stagnant film will be thicker than in the case of a less viscous fluid. The heavier the fluid, the more energy a given particle will have when it strikes the wall, and the thinner will be the stagnant film.

Examples of the application of high turbulence to increase heat transmission by reduction of the stagnant film are : (1) the La Mont boiler, wherein the water is forced at high velocity through nests of water tubes, and (2) the Velox steam generator in which both flue gases and water are circulated at high velocity. In the latter case in one section of the boiler the flue gases travel at a speed of 900 ft. per sec. as against an average speed in Lancashire boiler flues of 10–30 ft. per sec. A third example is the Cochran " Sinuflo " boiler, which is of the

economic type, and is filled with sinuous return smoke tubes through which the flue gases are drawn at high velocity by means of an induced draught fan. All the above designs show materially higher heat transmission rates when compared with ordinary natural circulation boilers. Naturally such highly turbulent flow necessitates power for the fluid pumps, but the gain in high heat transmission rate is much in excess of the power requirements.

Another method of securing high turbulence in pipe heat exchangers is by fitting gills or fins to the pipes. In this way a greater surface is exposed but also a greater degree of turbulence results. An interesting example in this connection is the increasing use of gilled or finned tube economisers for boiler plants, wherein for a decade the plain tube type has been used almost exclusively. Another example of gilled tubes is in air heater design where high heat transmission rates are secured by finning of the heating battery tubes.

Coefficients of Heat Transfer of Stagnant Films.

The aim of investigations in this field has been to find some commercial method of calculating the thermal resistance of the stagnant film, and data are available for the following conditions :—

(1) Fluids inside Clean Circular Pipes and Turbulent Flow.

The Dittus and Boelter equation for this case is

$$\frac{hD}{k} = 0{\cdot}0225\left(\frac{DG}{Z}\right)^{0{\cdot}8}\left(\frac{CZ}{k}\right)^{0{\cdot}4}, \quad . \quad . \quad . \quad (9)$$

where h = film coefficient in B.Th.U./sq. ft./° F./hr.,
D = inside diameter of pipe in ft.,
k = thermal conductivity of stagnant fluid in B.Th.U./sq. ft./hr./° F.,
G = mass velocity in lbs./sq. ft. of cross-sectional area of pipe per hr.,
Z = viscosity in units consistent with above (equal to centipoises × 2·42),
C = specific heat (in case of gases at constant pressure).

Some of these units are not usual, but it is to be noted that this system has the advantage that the constants in the equation are independent of the particular set of units chosen, and any consistent set of units may be used. Thus the constant in the above equation will be unchanged if all these quantities are expressed in terms of inches, pounds, seconds and ° F. ; or metres, kilograms, hours and ° C.

Petroleum oils, through a part of the range, do not seem to obey the Dittus and Boelter equation. In heating oils Morris and Whitman* recommend the use of the equation

$$\frac{hd}{k}\Big/\left(\frac{CZ}{k}\right)^{0{\cdot}37} = f\left(\frac{DG}{Z}\right) \quad (10)$$

* *Ind. Eng. Chem.*, 1928, **20**, 234–40.

where the numerical value of the left-hand side of the equation is taken from Fig. 152. For values of $\frac{DG}{Z}$ greater than 7000 this group coincides with the Dittus and Boelter equation given before. For values between 2100 and 7000 the plot should be used. This gives the heat transfer coefficient when heat is flowing from the metal wall to the oil. When cooling oils—that is, when heat is flowing from the oil to the metal wall values of h 25 per cent. lower than those

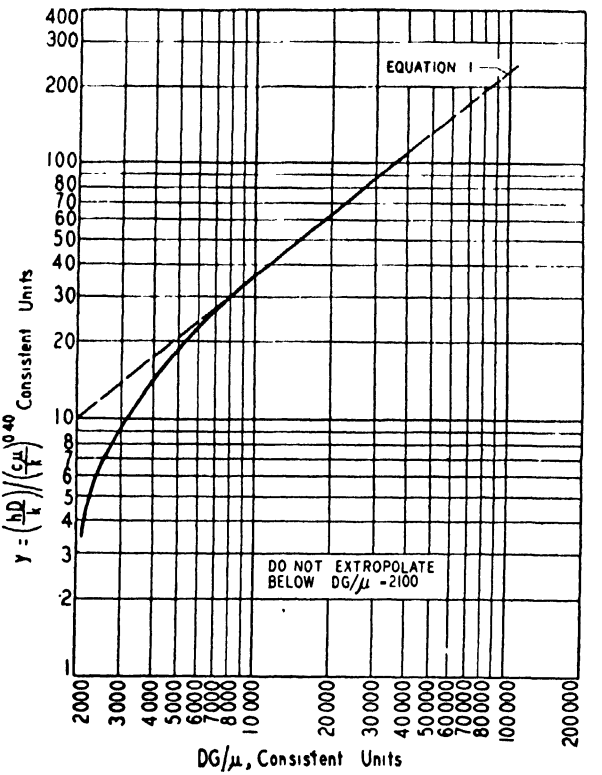


FIG. 152.

given by the plot should be used. This is probably due to a wide difference between the temperature of the oil film on the tube and the temperature of the oil in the tube.

The density of most fluids handled in practice is easily determined by hydrometer readings, and for calculations made in cases where a sample is not available a large amount of such data will be found in Volume III of the "International Critical Tables." The density of water at various temperatures is given in Table 49. The density of most gases may be calculated with sufficient accuracy for heat transfer met by the usual gas laws. It is convenient to note that

the density of any gas at 60° F. and 30 ins. mercury is given by $\frac{M}{378}$ where M = molecular weight. (The corresponding factor for 0° C. and 760 mm. is 359.)

The viscosity of liquids and solutions changes rapidly with changes in temperature, and always in the direction of lower viscosity at the

TABLE 48.

THERMAL CONDUCTIVITIES.

(*a*) METALS.

Material.	Experimental Temperature Range (° F.).	λ
Aluminium	32–212	118
Brass, yellow	32–212	63
Copper, pure	at 32	226
	at 212	222
Iron :		
Pure	at 76	37
Wrought	32–527	35
Cast, 3·5 per cent. C.	at 212	28
Lead	at 59	20
Nickel	32–212	34
Platinum	64–212	41
Silver	at 64	243
Steel (mild)	32–212	35
Tin	at 32	35
Zinc	at 64	64

(*b*) NON-METALS.

Material.	Experimental Temperature Range (° F.).	λ
Asbestos	100–1000	0·04–0·12
Brick :		
Carborundum	at 1800	5·6
Building	at 70	0·4
Sil-O-Cel	at 1800	0·03
Brick and mortar wall	—	0·4
Portland cement, neat	at 95	0·5
Cork	122–392	0·03
Electrode carbon	212–1700	32·
Glass, flint	50–59	0·3–0·6
Infusorial earth (12·5 lbs./cu. ft.)	at 122	0·05
Magnesia (85 per cent. insulation)	68–310	0·04
Rubber	at 220	0·1

(*c*) Gases.

Material.	λ at 32° F.	λ at 212° F.
Air	0·0137	0·0174
Carbon monoxide	0·131	—
Carbon dioxide	0·00804	0·0120
Oxygen	0·0138	0·0180
Nitrogen	0·0138	0·0174
Hydrogen	0·092	0·123
Methane	0·0174	—
Steam	0·0095	0·0129

(*d*) Liquids.

Material.	λ at 86° F.	λ at 167° F.
Normal pentane	0·078	0·074
Kerosene	0·086	0·081
Petroleum ether	0·075	0·073
Methanol	0·122	0·119
Ethanol	0·104	0·100
Isopropanol	0·089	0·088
Normal butanol	0·097	0·094
Iso-amyl alcohol	0·086	0·084
Ethyl-ether	0·079	0·075
Acetone	0·103	0·097
Carbon bisulphide	0·092	0·087

higher temperature. The viscosity of gases changes much less, and increases with increasing temperature. The viscosity of water is known accurately, and also the viscosity of the common gases are known with a fair degree of accuracy. The viscosity of a few of the more important materials is given in Figs. 153 and 154. Very little is known of the viscosity of solutions.

The *thermal conductivity* of most liquids is unknown. The values for water are given in Table 49, and of some of the more important gases and liquids in Table 48. For solutions, practically no data are available.

The specific heats of a few liquids are known with fair accuracy, but little is known about the specific heats of solutions. A fair approximation may be made if the specific heat of the dissolved solid is known by calculating as though the solution were merely a mechanical mixture. The specific heat of water may be taken as 1·00 for all temperatures from 32 to 300° F.

The specific heat of gases may be found from the following equations :—

SPECIFIC HEAT OF GASES IN B.TH.U. PER LB.-MOL., TEMPERATURE IN DEGREES RANKINE.*

(Instantaneous values.)

Monatomic gases (He, A) .	$C_p = 4{\cdot}98$
Hydrogen (H_2) . .	$C_p = 6{\cdot}85 + 0{\cdot}16 \times 10^{-3} T + 0{\cdot}068 \times 10^{-6} T^2$
Diatomic gases (N_2, O_2, CO, HCl) . . .	$C_p = 6{\cdot}75 + 0{\cdot}337 \times 10^{-3} T + 0{\cdot}040 \times 10^{-6} T^2$
Chlorine	$C_p = 8{\cdot}58 + 0{\cdot}17 \times 10^{-3} T$
Water vapour . . .	$C_p = 8{\cdot}22 + 0{\cdot}083 \times 10^{-3} T + 0{\cdot}416 \times 10^{-6} T^2$
CO_2, SO_2 . . .	$C_p = 7{\cdot}70 + 2{\cdot}95 \times 10^{-3} T - 0{\cdot}26 \times 10^{-6} T^2$
Ammonia (NH_3) . .	$C_p = 6{\cdot}70 + 3{\cdot}50 \times 10^{-3} T$
Methane (CH_4) . .	$C_p = 5{\cdot}90 + 5{\cdot}34 \times 10^{-3} T$

LIQUID VISCOSITIES

TABLE

Point	Liquid	Point	Liquid
18	Acetic Acid 100%	7	Glycerol 50%
12	Acetic Acid 70%	31	Heptane
34	Acetone	36	Hexane (N)
17	Allyl Alcohol	15	Mercury
39	Ammonia	26	Methyl Alcohol 100%
8	Aniline	24	Methyl Alcohol 90%
25	Benzene	13	Methyl Alcohol 30%
11	Butyl Alcohol	32	Methyl Acetate
40	Carbon Dioxide	9	Naphthalene
33	Carbon Disulfide	14	Nitrobenzene
21	Carbon Tetrachloride	28	Octane
22	Chlorbenzene	38	Pentane
29	Chloroform	5	Phenol
37	Ether	35	Sulfur Dioxide
19	Ethyl Alcohol 100%	2	Sulfuric Acid 111%
10	Ethyl Alcohol 40%	3	Sulfuric Acid 98%
30	Ethyl Acetate	6	Sulfuric Acid 60%
23	Ethylene Chloride	27	Toluene
4	Ethylene Glycol	16	Turpentine
1	Glycerol 100%	20	Water

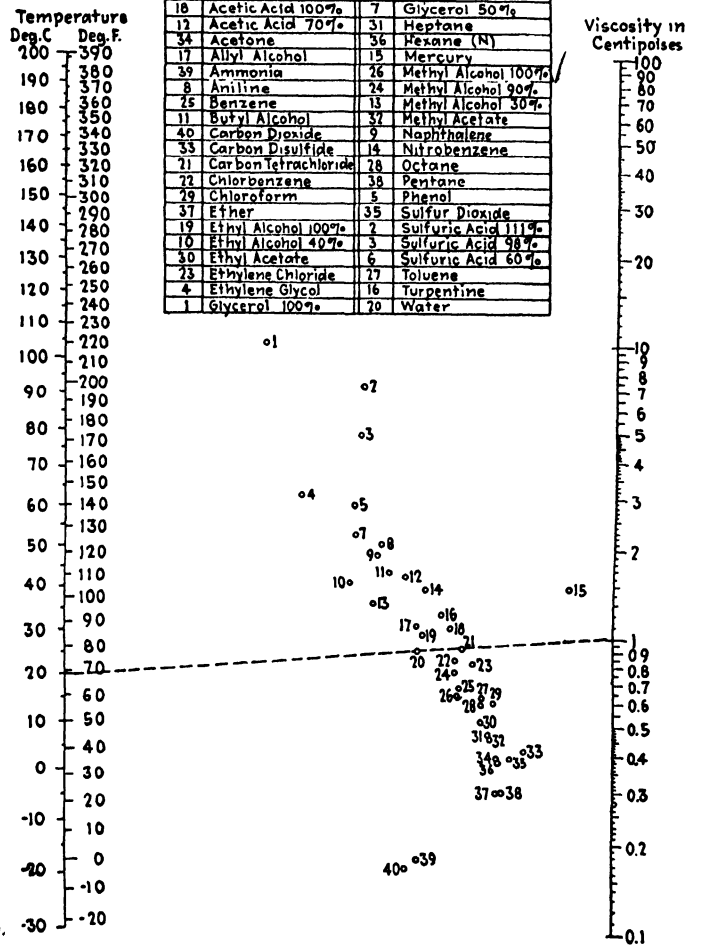


FIG. 153.

(Reproduced by permission from McAdams "Heat Transmission," McGraw Hill Book Co.)

* Eastman, *U.S. Bur. Mines Tech. Paper 445*, 1929.

TABLE 49.

Properties of Water.

Temperature (° F.).	Viscosity (Centipoises).	Conductivity (B.Th.U. per ft. per sq. ft. per hr. per ° F.).	Density (lbs. per cu. ft.).
32 . . .	1·792	0·321	62·42
35 . . .	1·692	0·322	62·43
40 . . .	1·546	0·325	62·43
45 . . .	1·419	0·328	62·42
50 . . .	1·308	0·330	62·42
55 . . .	1·210	0·333	62·40
60 . . .	1·124	0·336	62·37
65 . . .	1·047	0·338	62·34
(68·38–1·000)			
70 . . .	0·978	0·341	62·30
75 . . .	0·917	0·343	62·26
80 . . .	0·861	0·346	62·22
85 . . .	0·810	0·349	62·17
90 . . .	0·764	0·351	62·11
95 . . .	0·722	0·354	62·06
100 . . .	0·684	0·357	62·00
105 . . .	0·649	0·359	61·93
110 . . .	0·617	0·362	61·86
115 . . .	0·587	0·365	61·79
120 . . .	0·560	0·368	61·71
125 . . .	0·534	0·371	61·63
130 . . .	0·511	0·373	61·55
135 . . .	0·489	0·376	61·46
140 . . .	0·469	0·378	61·38
145 . . .	0·450	0·381	61·29
150 . . .	0·432	0·383	61·20
155 . . .	0·416	0·386	61·10
160 . . .	0·401	0·389	61·00
165 . . .	0·386	0·391	60·90
170 . . .	0·373	0·394	60·80
175 . . .	0·359	0·397	60·69
180 . . .	0·347	0·399	60·58
185 . . .	0·336	0·402	60·47
190 . . .	0·325	0·405	60·36
195 . . .	0·315	0·407	60·24
200 . . .	0·305	0·410	60·12
205 . . .	0·295	0·413	60·00
210 . . .	0·287	0·416	59·88
212 . . .	0·284	(0·417)	(59·83)
215 . . .		0·419	59·76

drop, that the heat transfer coefficient is unchanged throughout the apparatus. This is nearly correct if the temperature range through which one of the fluids is heated or cooled is not too great.

In the case of multi-pass exchangers the logarithmic mean temperature difference is no longer correct. Nagle * has worked out curves by which the logarithmic mean temperature difference may be corrected to true mean temperature difference.

Further Practical Heat Transfer Data.—The National Radiator Co. in their "Ideal Manual" give the following data for *pipes immersed in water* which flows slowly over the pipes. It is assumed that the conditions are for low or moderate water pressures, and that the steam admitted to the tubes is not higher than 50 lbs. per sq. in.

Nature of Heating Surface.	k *Water to Water.*	k *Steam in Tube, water outside Tube.*
W.I. pipe	70	140
Copper pipe	73	146

k = Coeff. of heat transfer—B.Th.U./sq. ft./hr./° F. diff. (mean).

The above formula is for clean pipes. Where scaling is likely to occur add 30–50 per cent. to *heating surface* found by calculation.

Air Heaters.—Harding & Willard ("Heating, Ventilating and Air Conditioning," 1932, Chapman & Hall, Ltd.) give the following formula for air heaters of the type wherein air blows across a bank of steam-heated plain tubes :—

$$S = (0{\cdot}1118Q + 127A) \log \left(\frac{ts - t_1}{ts - t_2}\right)$$

where S = area of heating surface /sq. ft.,
A = free air path through heater /sq. ft.,
V = velocity of air through free area of heater/ft./min. at 70° F.,
Q = flow in cu. ft./min. measured at 70° F.,
t_s = temp. of steam in pipes,
t_1 = temp. of air entering heater,
t_2 = temp. of air leaving heater.

Smoke Tubes of Boilers.—In the case of boiler tubes with flue gases passing through them, and similar cases, the heat transferred can be obtained from the following formula (Fry, *Engineering*, Aug. 27, 1920) :—

$\text{Log}\left(\log \frac{T_1}{t}\right) - \log\left(\log \frac{T_2}{t}\right) = Mx$, wherein T_1, T_2 are the mean flue-gas temperatures (° F. abs.) at two sections of the tube, x feet apart, t the mean temperature (° F. abs.) of the tube wall. M is given by

$$\log M = B - m \log \frac{W}{p}; \qquad \log (B + 1{\cdot}3) = 1{\cdot}71 - 0{\cdot}54 \log d,$$

$$\log m = \bar{1}{\cdot}36 + 0{\cdot}37 \log d.$$

* McAdams, p. 148.

where d = int. dia. tube/ins.,
p = perimeter of tube,
W = rate of flow of gas per hour in lbs.
t can be taken as the temp. of the water in the boiler with sufficient accuracy.

Condensers: Water-cooled.—Condensers attached to vacuum drying or evaporating apparatus can be designed on the basis of steam-power practice. Condensers of the surface type comprise a shell fitted with a large number of horizontal tubes between two tube plates. The cooling water should be arranged to pass through the tubes, and the vapour over the tubes. Internal guide plates are often fitted to obtain maximum turbulence and contact.

The choice of materials of construction of condensers in chemical practice depends upon any corrosion problems which often arise. In steam practice the sheet is of cast iron or mild steel, with copper alloy tube plates and tubes.

The coefficient of heat transmission (k) in condensers is usually 400–600 B.Th.U. per sq. ft. per ° F. per hr. in typical designs. In single pass condensers the flow of water through the tubes is often as high as 8 ft. per second. The presence of air in the steam materially affects the heat transmission and also the degree of vacuum obtainable, and some form of air-extracting apparatus is often essential. To prevent slime formation on the water side of the tubes chlorination may be adopted.

Tube diameters in condensers vary from $\frac{5}{8}$-in. to $\frac{7}{8}$-in. diameter. In power stations, $\frac{3}{4}$-in. diameter × 0·048-in. thick are about the standard.

Evaporators and Evaporation.

Having briefly discussed the principles of heat transfer, it is now proposed to deal with the more important types of evaporators—first from the descriptive aspect, then as heat exchangers, and finally from the point of view of particular evaporation processes.

Vertical Tube Evaporators.

The vertical tube was not the first evaporator to be built, but it was the first one to receive wide popularity, and is probably the commonest type now in use. The first one was built by Robert, Director of the Sugar Factory at Seelowitz, Austria, about 1850; and the vertical tube evaporator is often known as the Robert type. It became so common that in Europe this evaporator is known as the "standard" evaporator, and is the construction always understood unless specific reference is made to some other type.

A typical body is shown in Fig. 155. It is characterised by tube plates extending across the body, with a large opening to serve as a

downtake. Tubes are expanded between these two tube plates so that the liquor is inside the tubes and the steam is outside them. As the liquor boils, it passes up through the tubes and is returned through the downtake. Condensate is removed from any convenient place on the bottom tube plate, and non-condensable gases are usually vented from somewhere near the upper tube plate.

The first evaporators of this type were built without a downtake. These were never satisfactory and the central downtake appeared very early. There have been many changes proposed in this arrangement; such as downtakes of different cross-section, downtakes located eccentrically, a number of scattered downtakes instead of one central one, downtake pipes entirely external to the body of the evaporators, and others. The central downtake, however, remains a thoroughly standard construction. The cross-sectional area of the downtake is usually between 40 and 100 per cent. of the combined cross-section of the tubes. General practice is probably nearer the former figure than the latter one. The tubes may range from 1 in. to 4 ins. in diameter, from 30 ins. to 6 ft. long, with general practice favouring a tube about 2 ins. in diameter and about 5 ft. long. The general characteristics of this type are vertical tubes with the liquor inside, steam outside the tubes and a central downtake.

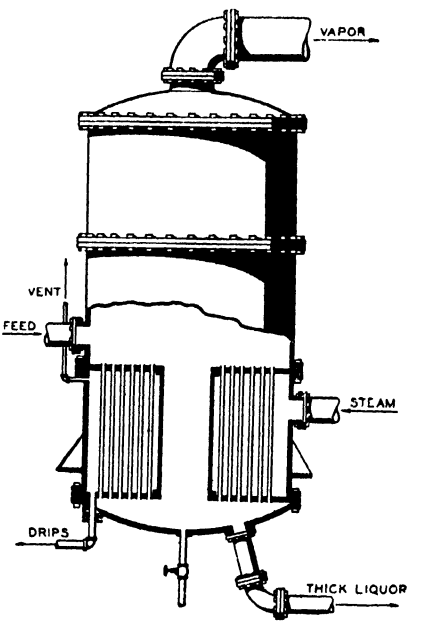


FIG. 155.—Standard evaporator.

Basket Type.

In 1877 the first basket type evaporator was made (see Fig. 156). In this type the liquid is still inside the tubes, the steam is outside the tubes, but the downtake instead of being central is annular. This construction also makes the whole heating element a single unit that may be removed bodily for repairs. Tube proportions in the basket type are about the same as in the standard vertical.

One important feature of the basket type evaporator is the ease with which a deflector may be added in order to stop spouting. The vertical tube evaporator, especially when operated with low liquor levels, boils with great violence, and tends to cause entrainment losses. Such a baffle as shown in Fig. 156 largely prevents these losses, and is much

more easily added in the basket type than a similar structure could be added to the standard type. Other than this, the differences between the standard and the basket type are largely matters of detail.

Long Tube Evaporator.

The long-tube vertical type evaporator is essentially a vertical tube evaporator with very long tubes. There is no exact dividing line, but the standard vertical-tube type normally has tubes 3 ft. to 6 ft. long, and the long-tube vertical, from 10 ft. to 20 ft. long (Fig. 157).

The controlled-level type of long-tube vertical is simply a vertical

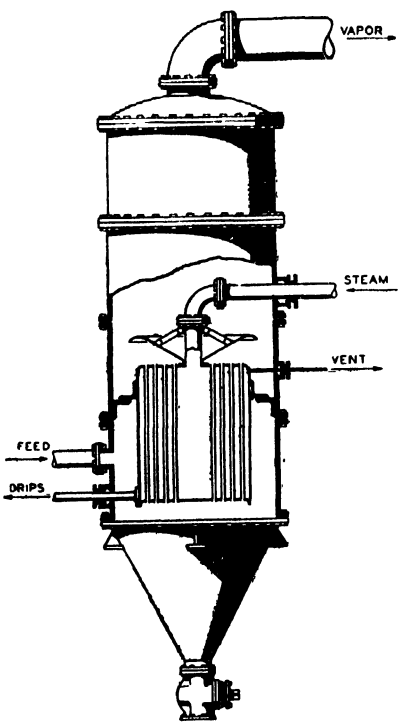


FIG. 156.—Basket type evaporator.

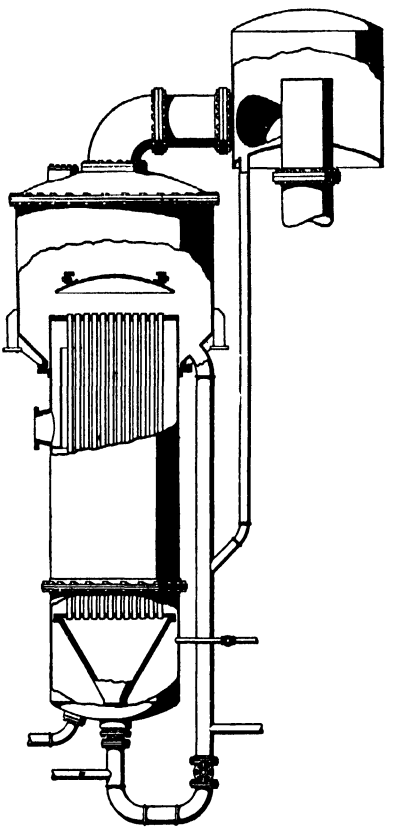


FIG. 157.—Long tube evaporator.

tube evaporator with longer tubes than usual, and so operated that the liquor level is controlled at from one-third to one-half the height of the tubes. The tubes are grouped in a heating element and this may be placed vertically or inclined at an angle to the horizontal. The tubes in the heating element discharge into a vapour head, baffled to separate the liquor and vapour ; or into a body similar, except for tubes, to the

ordinary evaporator body. A level in the tubes is maintained by float control in the down-pipe from the vapour head or attached to the body, and this controls the liquor fed to the next liquor effect.

The other type of long-tube vertical type may be more correctly spoken of as the film-type, long-tube vertical. In this type, no attempt is made to maintain any particular level in the tubes, and the liquor makes but one pass through the tubes. The liquor seeks its own level in the tubes and starts to boil at as low a point as the pressure and temperature conditions in the tube permit. The liquor is removed from the head to the next effect by a float-operated valve (to prevent by-passing steam) or by a pump. In this type, the liquor and vapour discharge from the tubes against a baffle in the vapour space and a gross separation is made between liquor and vapour. Finer entrained particles of liquid are then removed by a centrifugal type catchall situated either inside or outside of the vapour space. The pipe downtake between vapour space and the compartment below the tubes is only used during starting and the valve on it is normally closed.

Inclined Tube Evaporators.

Many attempts have been made to obtain the advantages of long tubes without the disadvantages of extreme head-room and inconvenient tube replacements. The inclined tube evaporator in various forms has been known for many years in Europe and the United States (Fig. 158). The tubes are usually 8 ft. to 10 ft. long. A single large tube, not included in the heating chamber, serves as a downtake.

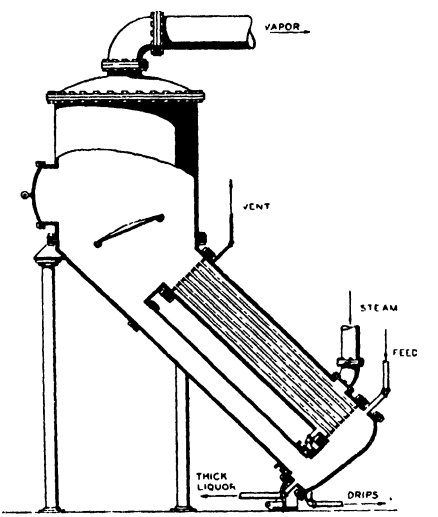


FIG. 158.—Inclined tube evaporator.

Horizontal Tube Evaporators.

The first tubular evaporator was a horizontal evaporator built by Norbert Rillieux in 1843. Rillieux's construction was not very practical and it was quickly superseded by the standard evaporator. In 1879 Hugo Jelinek and F. Wellner patented a horizontal tube evaporator that is still used in practically its original form, and from which most of the present horizontal tube evaporators have been derived. The Wellner-Jelinek was very popular in Europe during the 'eighties and 'nineties, but has passed out of favour and is now rarely found on the Continent. It has always been a popular type in the United States. Fig. 159 shows a construction characteristic of the Wellner-Jelinek type. The tubes have steam inside them and liquor

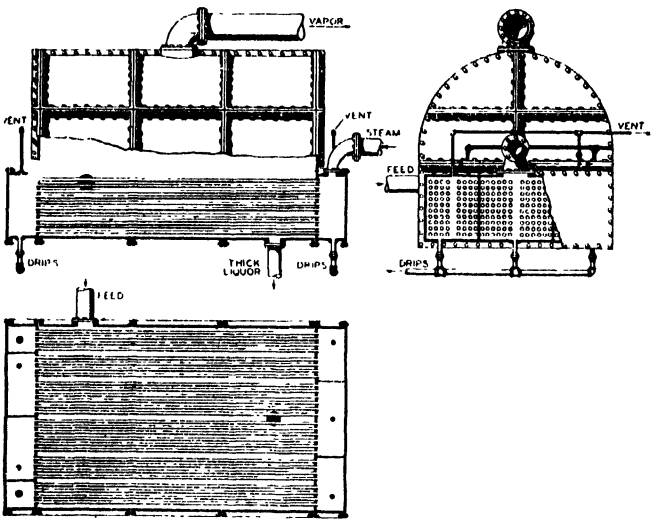


FIG. 159.—Horizontal tube evaporator.

outside. A special feature of the original Wellner-Jelinek, which has since been largely abandoned, except in the beet sugar industry, is the baffles in the steam chests that cause the steam to flow through two or three banks of tubes in series. A characteristic of the Wellner-Jelinek that still survives in many of the larger units is the half-round or trunk-shaped body, rectangular in plan.

The particular advantage of the Wellner-Jelinek, and the forms derived from it, is the ease of tube replacements. In all forms of the vertical tube evaporator, the liquor is in contact with the inside of the tubes and the tube sheets, so that the only practical method of fastening the tubes to the tube sheets is rolling or expanding. In the horizontal types this joint is in the steam space and therefore can be packed. In most cases the tubes are held in place by packing plates and conical gaskets.

The horizontal tube evaporator is often built of flat cast-iron plates. This construction has the advantage of making repairs easy and of not requiring the shipment of bulky parts. It has the disadvantage of involving a large number of joints, and this was early recognised as a disadvantage. In 1875 the horizontal tube evaporator appeared with

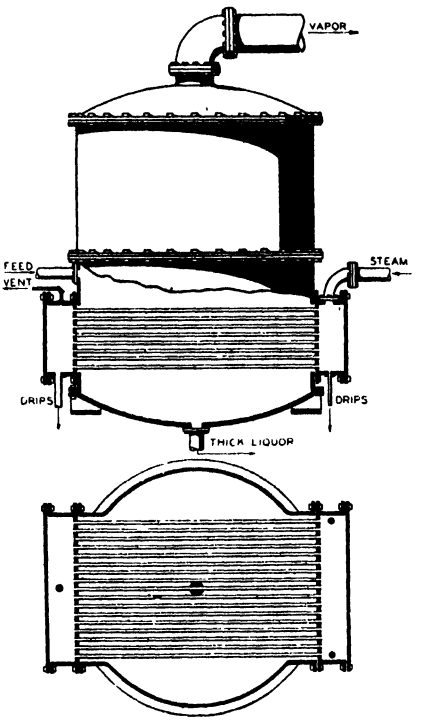


FIG. 160.—Horizontal tube vertical evaporator.

a body in the form of a vertical cylinder as shown in Fig. 160. The steam chests are usually cast as an integral part of the main ring. The ring castings are easy to assemble and easy to make tight, but are rather inconvenient to ship if the body is very large.

Forced Circulation Evaporator.

It has been mentioned above that high velocity was recognised as desirable in the early stages of evaporator development. From 1885 to 1895, many attempts were made to increase velocity by hanging filler rods in the centre of vertical evaporator tubes and operating with low levels. These devices were too troublesome and were abandoned. Propellers have been used at various times and it is not certain how far back they date. They have usually been installed in the downtakes of vertical tube evaporators where the downtake was in the centre, and were so designed that they discharged downward into the cone.

The development of the modern forced circulation evaporator has been along the lines of decreasing the diameter of the tubes and using fewer of them, thus decreasing the cross-section of the liquid path and making the size of the pump reasonable. In order to obtain sufficient heating surface, it was necessary to increase the tube length.

The construction of two such evaporators made by Escher Wyss is shown in Figs. 161 2. They were especially designed for evaporating

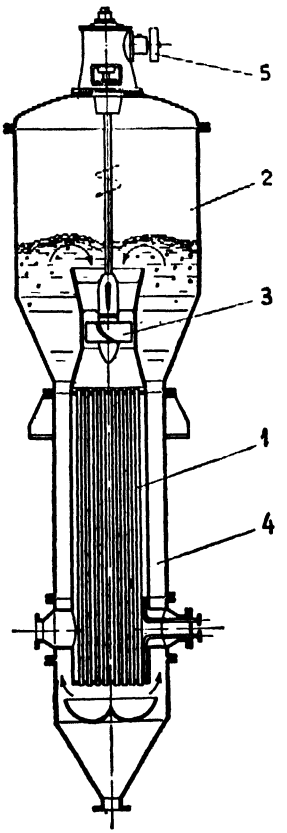


FIG. 161.—Escher Wyss circulating evaporator.

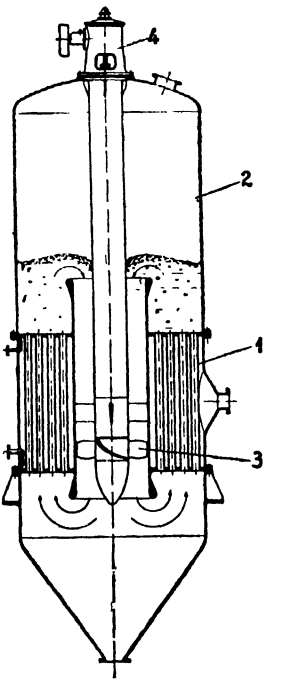


FIG. 162.—Escher Wyss circulating evaporator.

salt solutions to produce a good grain, and their construction and operation is as follows :—

In both constructions, the axis of the circulating propeller coincides with that of the evaporating apparatus, thereby securing strictly symmetrical conditions for the flow which, for low resistance, and above all, for the steady boiling process, is particularly desirable. Cross-sectional areas for the flow are amply dimensioned, and of advantageous form hydraulically, without any unfavourable contraction. The heat-

ing chambers lie well below the surface of the liquid. With this provision and sufficiently energetic circulation, any tendency to boiling in the heating tubes, with consequent formation of salt deposits on these tubes, is avoided. Owing to the provision of guide tubes and special fittings, the liquid heated in flowing through the heating system is obliged to rise to the surface of the liquid in the evaporator, and therefore any heat absorbed in the heating chamber through corresponding self-evaporation is dissipated. In this way the return of already overheated liquid is prevented. A sufficiently high velocity of flow is decided upon, in order that the crystals shall be carried along until they have attained the desired size. To permit growth of the crystals, they must be allowed to remain sufficiently long in the over-saturation zone. It is in the nature of things that, in designing the apparatus, numerous points must receive very careful consideration if the desired crystal formation shall be obtained. The conditions connected with the circulation of the flow is by no means a simple matter, but results have shown that this question can be satisfactorily solved.

The type, shown in Fig. 161, is most suitable for very pure salt solutions and for complying with further requirements such as the production of a salt of a particular coarseness. With the second type, shown in Fig. 162, it is also possible to produce salt of a good-quality crystal and its advantage lies in the still more favourable approach to the heating tubes. Impure salt solutions can also be handled in these apparatus. If the usual boiler fur should accumulate in the tubes, this can be removed, without difficulty in respect to the circulating device, by means of the usual pipe cleaners, for instance magnesium deposit by boiling out with commercial brine.

Heat Transfer Coefficients in Evaporators.

It was indicated in the discussion on heat transfer that the overall heat transfer coefficient in an evaporator is made up of a steam film coefficient and a liquor film coefficient. Equations were given for calculating the steam film coefficient, but the case of a liquor film coefficient when the liquid is boiling was not discussed. The literature on this aspect of heat transfer is fragmentary and deals with special cases.

The reason for the lack of definite information on heat transfer coefficients is twofold. The first and most important reason is that all evaporators except the forced circulation type depend on natural convection for their circulation. It is fairly obvious by analogy from the equations given on pp. 335–343 that the velocity of the liquid past the surface will be important. In a natural convection evaporator every detail of shape and size and arrangement of the parts, every change in the properties of the liquid, every change in the temperature difference or condition of the metal surface, will affect the rate of

circulation and therefore affect the capacity of the evaporator. For this reason tests in the laboratory, even on semi-plant scale apparatus, can give valuable information about trends and influences, but cannot give absolute values that can be applied in practice without question. In any case, the number of variables to be studied is so great as to make a thorough investigation of them in the laboratory a practically hopeless task.

The second reason why there is not more definite information on heat transfer coefficients for evaporators is that up to the present time film coefficients have not been determined and only overall coefficients are available. Fortunately, however, there are many practical cases where the steam film coefficient is so much higher than the liquid film coefficient that the latter is essentially equal to the overall coefficient. In such cases, reasoning based on the overall coefficient is nearly as satisfactory as if the liquid film coefficient itself were available. Nevertheless, a consideration of the factors affecting these film coefficients will be of value in attempting the overall coefficients.

Steam Film Coefficients.

On the steam side, an evaporator is no different from any other apparatus in which steam is condensed and, therefore, Nusselt's equations (see p. 344) for horizontal and for vertical tubes should also hold here. One laboratory study * on a vertical 12-ft. evaporator tube (on which there is good reason to believe the condensation was film type and not drop-wise) gave results averaging 33 per cent. higher than the Nusselt equation. This increase was probably because of turbulence in the condensate films. The Nusselt equations may be analysed qualitatively to predict the effect of various factors, but this is of no great practical importance. In practice, unless the liquor film coefficient is very high, considerable changes in the steam film coefficients have no great influence on the overall coefficient, except in two cases · changes in the coefficient due to a change from film-type to drop-wise condensation, and changes due to a change in the amount of non-condensed gases in the steam.

Too little is known of drop-wise condensation to reason about it even qualitatively. Minute differences in the condition of the surface, or the presence of minute amounts of certain impurities in the steam, will have a decided effect in changing the type of condensation from film-type to drop-wise and vice versa. A very thin film of oil or grease may promote drop-wise condensation and may be the reason why commercial evaporators are apt to have high steam film coefficients. This matter is of the greatest importance, as sufficient changes can be made in the steam film coefficient to nearly double the overall coefficient in certain cases.

* Hebbard and Badger, *Ind. Eng. Chem.*, 1934, 26, 420–4.

Effect of Non-Condensable Gases.

Steam absolutely free from non-condensable gases can only be made with the greatest difficulty and with the most elaborate laboratory technique. Steam from a modern power plant in which the boiler feed is made up almost entirely of de-ærated condensate is so nearly free from non-condensable gases that it will give practically theoretical results. In a few cases, however, one may find boiler steam that will contain as much as 0·1 or 0·2 per cent. of air or CO_2 by volume. In the case of apparatus where the steam space is under a pressure less than atmospheric, this air content will be greatly increased by air drawn in through leaks. The proper removal of non-condensable gases from steam space is an extremely important problem.

The following table shows the effect of different amounts of air on steam film coefficients for different temperature drops, when steam is condensing in film-type condensation on a vertical tube 12 ft. long.

STEAM AT 248° F.

Air Content (per cent. by vol.).	Δt, ° F.			
	20	30	40	50
0	1330	1180	1120	1090
0·25 per cent. . .	1220	1090	1030	1000
1·0 „ „ . .	1080	940	900	890
1·5 „ „ . .	980	870	840	830

These coefficients are lower than many found in practice, but this is due to the long tube and consequent thick layer of condensate. However, it shows the importance of keeping the steam space as thoroughly vented as possible.

There has been in the past a great deal of discussion as to where the air vents should be placed. As the stream of steam passes over the heating surface it tends to sweep the air along with it, and as the steam condenses the mixture that is left becomes richer and richer in air. This means that where the steam has a definite path, as in horizontal tube evaporators or in long tube vertical evaporators, the air will be swept to the far end of its path and can be removed there quite completely. Therefore, in horizontal tube evaporators the steam vents may be anywhere on the far steam chest. In long tube evaporators the steam should be introduced at one end of the tube bundle and the non-condensed gases removed from the other. In short tube vertical evaporators, however, especially where the diameter of the evaporator is large, the steam does not follow a definite path and its velocity is not high. Therefore, the air is not swept to any one point and turbulence

in the steam space tends to prevent it becoming segregated. Hence, in such evaporators a number of vents should be located at different points in both top and bottom tube sheets.

Liquid Film Coefficients.

A consideration of the equations given for the transfer of heat (pp. 335–344) will show that in all cases investigated so far, heat transfer coefficients always increase with the velocity, and decrease as its viscosity increases. Although no similar work has been done on boiling liquids, the same type of effect should be expected. Viscosity has an additional effect, however; because in most evaporators the velocity of the liquid is due to natural convection, and the greater the viscosity the less vigorous the circulation, everything else being equal. Thus viscosity has a double effect on liquid film coefficients in natural circulation evaporators.

The above discussion has been limited to film coefficients because they are those about which most definite statements may be made. The only data in the literature, however, deal only with overall coefficients and, as mentioned previously, in many cases fairly satisfactory qualitative reasoning can be applied to overall coefficients. Therefore, the rest of this discussion will deal with overall coefficients.

Effect of Liquor Level.

Fig. 163 illustrates the change in overall heat transfer coefficients with change in liquor level when boiling distilled water in an evaporator having twenty-four 2-in. iron tubes. Curves 1 and 3 had tubes 30 ins. long and curve 2 had tubes 48 ins. long. Liquor levels were measured from the bottom of the tubes. In all cases such a vacuum was carried on the evaporator that it corresponded to a boiling point of 167° F. The steam was at 212° F., giving a temperature difference of 45° F.

This temperature difference of 45° F., however, only existed at the top of the tubes. Only the surface layer of the liquid was at a pressure corresponding to a boiling point of 167° F. The layers at the bottom of the tube were under an additional pressure of 24 ins. of water, which corresponded to a boiling point of 174° F. The coefficient was, however, calculated on the basis of 45° F. temperature drop and, therefore, the true temperature drop was less than the calculated. The difference between the true and the calculated temperature drops becomes greater and greater as the hydrostatic head is greater and therefore it is to be expected that the coefficients (based on the calculated temperature drop) would be lower at high liquor levels. This is borne out by the shape of the right-hand end of the curves. However, according to this same line of reasoning the use of 48-in. tubes should give lower coefficients when the liquor is even with the top of the tubes than the use of 30-in. tubes. This, however, is not the case. Further, when

the values of the coefficients are recalculated on the basis of the true temperature drop (as nearly as it can be estimated) they still form curves with the coefficients at high levels decidedly less than the coefficients at low levels.

The answer to this apparent contradiction is found in the statement earlier in this section that in a natural circulation evaporator every change of form and proportion results in a change in the circulation, and, therefore, a change in the coefficient. For any one tube length, as the liquor levels are higher the circulation is less. As the liquor levels become lower and lower the circulation becomes more violent, the coefficients become larger, and they only begin to fall off when the level is so low that the splashing no longer carries the liquor to the top of the tubes. The 48-in. tubes, either at the same actual levels or at

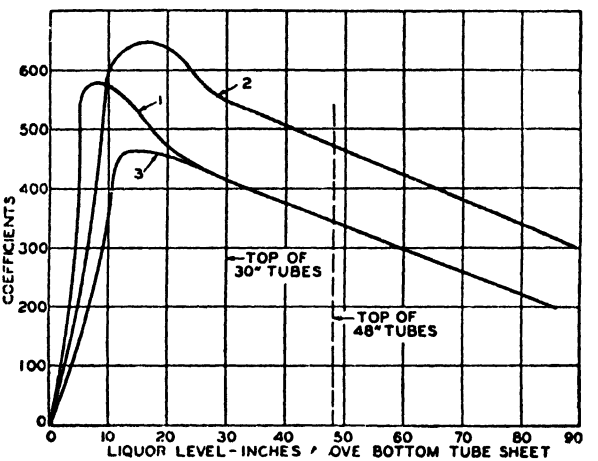


FIG. 163.—Effect of liquor level on overall heat transfer coefficient.

the same proportional levels, give higher results than the 30-in. tubes because the steam bubbles rising through a 48-in. tube have a stronger pumping action and, therefore, cause a higher velocity of circulation than in 30-in. tubes.

Systematic data are not available to predict the exact effect of continued increases in tube length. There seems to be an indication, however, that when tubes more than 5 or 6 ft. long are used with liquor levels at or above the tops of the tubes, the coefficients decrease as compared to the shorter tubes. On the other hand, when operated at low liquor levels, corresponding to the maximum points in Fig. 163, tubes up to 15 or 20 ft. long still give very high coefficients. This is the line of reasoning that led to the development of the long tube natural circulation evaporator.

Commercial operation of an evaporator under the conditions corre-

sponding to the maximum points of the curves in Fig. 163 is rather dangerous, because a slight inattention of the operator and a slight lowering of the level will not only greatly decrease the capacity of the evaporator, but will tend to bake material on the tubes. Operation with the tubes completely submerged is equally indefensible unless there is some special reason, as, for instance, in salt evaporators.

The difference between curves 1 and 3 is another striking instance of the statement that every change in the details of evaporator construction makes a corresponding change in the circulation and, therefore, in the coefficient. Curve 1 was determined with a relatively flat bottom on the evaporator so that there were only a few inches of liquid between the bottom of the evaporator and the tubes. The whole mass of liquid in the evaporator was in violent circulation even when operated at very low levels. Curve 3, on the other hand, was operated with exactly the same evaporator under exactly the same conditions, except that a 60° cone bottom was substituted for the flat bottom. The liquid in the cone had no effect on the circulation when the levels were high because it was then a small proportion of the total liquid in the machine. When the levels were low, however, the drag of this relatively stagnant liquid in the cone resulted in decreased circulation with a corresponding decrease in the coefficients as shown by the difference between curves 1 and 3.

Apparent Coefficients.

In a preceding paragraph it was pointed out that the true boiling point of the liquid in an evaporator corresponds to the vacuum in the vapour space only for surface layers. For the layers below the top, the boiling point is higher than corresponds to the pressure in the vapour space because of the hydrostatic head of the liquid on these lower layers. This effect cannot be calculated by the methods outlined above, because due to circulation the liquid is never heated as high as the boiling point calculated for the bottom layers. Therefore, the true average temperature of the boiling liquid throughout the evaporator is somewhat higher than that calculated from the pressure of the vapour space and somewhat lower than that calculated by the methods outlined above.

In addition to this, practically all liquids that are handled in commercial practice have a boiling point rather higher than the boiling point of pure water at the same pressure. For many solutions the presence of impurities means that the actual solution handled in practice will have a somewhat different boiling point than a pure solution of the principal substances involved. In any case, the measurement of the temperature of the solution in contact with the heating surface in an evaporator cannot be done with very great accu-

racy, but the pressure in the vapour space can be measured with considerable accuracy. The steam that is used in evaporators is usually saturated or wet, and, therefore, its temperature corresponds very closely to the pressure of the steam space. It can easily be shown that if the steam has reasonably small amounts of superheat, this superheat has no appreciable effect on the actual mean working temperature difference in the evaporator as a whole. As a result of these considerations a certain conventional way of calculating the temperature differences in an evaporator (and, therefore, the overall heat transfer coefficient) has become common.

The temperature of the steam is determined by measuring the pressure in the steam space and calculating the temperature by the use of steam tables. The temperature of the boiling liquid is determined by measuring the pressure in the vapour space and calculating the corresponding temperature of the liquid from the steam tables. The difference between these two is known as the *apparent temperature drop*. It should be noted that this neglects superheat in the steam, elevation of the boiling point of the liquid due to substances in solution and elevation in boiling point of the liquid due to the effect of hydrostatic head. In case the elevation in boiling point of the liquid is known, the apparent liquid temperature may be increased by the known elevation in boiling point. This gives the corrected liquid temperature, and from this there may be determined a corrected temperature difference. This corrected temperature difference ignores the superheat in the steam and the effect of hydrostatic head in the liquid, and is, therefore, still not the true mean temperature difference.

If the heat transmitted through the heating surface of an evaporator be divided by the heating surface and by the apparent temperature drop, the result is the *apparent overall coefficient*. If the corrected temperature drop instead of the apparent is known, the use of this gives a *coefficient corrected for elevation in boiling point*. Obviously, neither of these is the true mean coefficient. Practically all the heat transfer coefficients for evaporators that are available, whether determined in the laboratory or by plant tests, are either apparent coefficients or coefficients corrected for elevation in boiling point. The literature is not always specific in defining the method used in calculating coefficients. The coefficients quoted in this chapter for evaporators are all *apparent* coefficients unless otherwise specified.

In calculating a new evaporator, the apparent temperature drop is the one that the designer has available. If he is handling a solution having a known elevation in boiling point, he can determine the corrected temperature drop; but in many cases he has only the apparent temperature drop with which to work. Consequently the coefficients that are most useful to the designer are apparent coefficients.

Effects of Boiling Point and Temperature Drop.

To illustrate further the complicated factors that affect the overall heat transfer coefficient in evaporators, see Fig. 164, which shows coefficients determined in the same evaporator that was used for the determination of the coefficients of Fig. 163. In all these experiments the liquor was distilled water, and the liquor level was even with the tops of the tubes. For each curve in Fig. 164 the apparent boiling point was kept constant, and the temperature drop was varied by increasing the steam pressure.

At a constant temperature drop it will be seen that the coefficient increases rapidly with the boiling point. This is because the higher temperatures of boiling give a less viscous liquid and therefore a thinner stagnant film. With a constant boiling point, however, the coeffi-

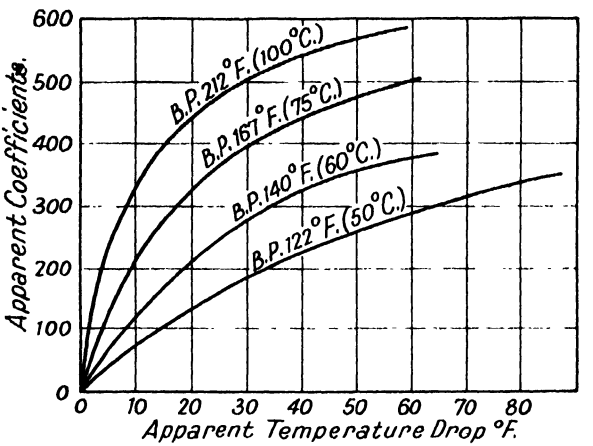


FIG. 164.

cient increases as the temperature drop increases. This is because increased temperature drop means increased amounts of evaporation, increased volumes of steam and therefore a stronger pumping action in the tubes.

This set of curves can be used to draw several qualitative conclusions. In any case, the rate of heat transfer increases with temperature drop. Therefore, multiple-effect evaporators will usually have lower coefficients than single-effect evaporators, when the total temperature drop is the same in each case. The more effects there are, the smaller will be the temperature drop per effect, and therefore the smaller the average coefficient. It is possible to employ so many effects that the temperature drop in any one becomes too small for effective circulation. The liquid then lies practically stagnant. The boiling takes place only in the upper layers and is not sufficiently vigorous to agitate the whole of the liquid. Under such circumstances

the rate of heat transfer is negligibly small. This line of reasoning applies to submerged tube evaporators and should not be applied to the forced circulation or film types.

Since the rate of heat transfer for a given temperature drop increases with boiling point, it is obvious that evaporators operating above atmospheric pressure will have much higher coefficients than evaporators operating under a vacuum. Since evaporators are often operated with exhaust steam, operation at pressures above atmospheric is not always practical. In recent years, however, the beet sugar industry in Central Europe has turned to evaporation above atmospheric pressure. By increasing the back pressure on the engines to 25 to 40 lbs. gauge, triple effects may be operated above atmospheric pressure. Although the resulting temperature drops are small, the boiling points are high, the coefficients are good, and the result is highly successful. The particular advantage of this arrangement in beet sugar manufacture is that the vapours from the third effect are then hot enough to use as process steam, and consequently the condenser and vacuum pump disappear.

This line of reasoning is fairly obvious, but the reverse line of reasoning is not so obvious. If the viscosity of water at different temperatures is examined, it will be seen that below 125° F. it is changing much more rapidly than in the upper temperature ranges. For most solutions, the change of viscosity with temperature is approximately parallel to that of water. Increasing the vacuum on the last effect by a relatively small amount decreases the boiling point rather rapidly, and therefore increases the total temperature drop. Many operators have been led by this line of reasoning to work with the highest possible vacuum. Attempts have actually been made to imitate power plant practice and operate with a vacuum of 29 ins. or better.

This rapid decrease in boiling point as the vacuum is increased results in an increase in viscosity with a consequent decrease in coefficients. A point will ultimately be reached where this decrease in coefficient offsets the increase in temperature drop, and an increase in the vacuum beyond this point actually decreases capacity rather than increases it. A single-effect evaporator usually operates with a large temperature drop, hence this effect is not reached until very high vacua are obtained. With multiple-effect evaporators and small temperature drops, the balance is often reached somewhere between 26 ins. and 28 ins. The exact balance depends on the type of evaporator and the rate of change of viscosity of the particular liquid being handled. It cannot be definitely predicted, but it is safe to say that there are relatively few cases where a vacuum of more than 28 ins. is desirable, and there are cases where a vacuum of more than 22 ins. will decrease capacity rather than increase it.

A cross-section of Fig. 164 along a line of constant temperature drop shows the effect of changing viscosity. The decrease of coefficient with temperature at a constant temperature drop can only be due to a change in the properties of water with its change in boiling point. As a matter of fact, if the apparent coefficients are multiplied by the viscosity of the solution, they fall much more nearly together than in Fig. 164. A more convincing illustration of the effect of viscosity is shown in Fig. 165. This represents the change in rate of evaporation (expressed as lbs. of steam condensed per sq. ft. per min.), in concentrating a very viscous malt syrup. It will be noted that

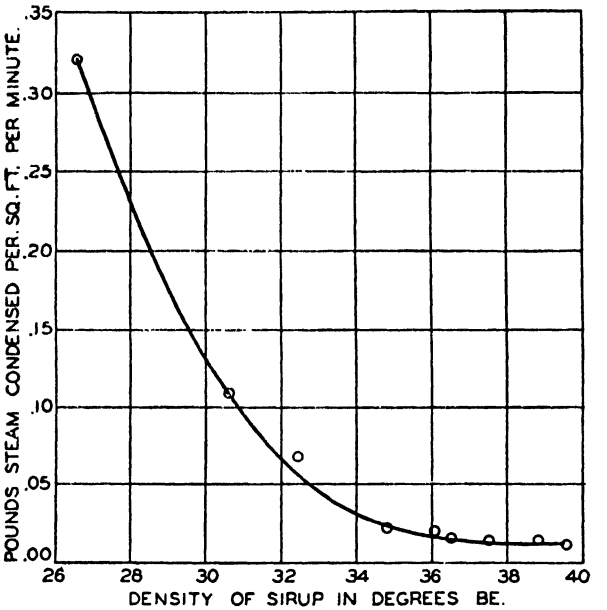


FIG. 165.—Effect of viscosity on evaporation.

the rate of evaporation falls off very rapidly as the density (and consequently viscosity) of the solution increases.

Such curves as those of Fig. 165 lead to certain qualitative conclusions regarding the operation of single-effect evaporators which concentrate a liquid under such conditions that the final product is viscous. If such machines are operated continuously, then the evaporator body is always full of liquid at approximately the final density, and therefore is at all times operating at the lowest rate of heat transfer. If this operation be carried out in batches, the evaporator starts with a charge of thin liquor and a high rate of evaporation. This rate decreases, as the final density is reached. The average rate of evaporation over the whole batch is considerably greater than the final rate, and therefore in such cases the apparatus has a greater

capacity when operated in batches than when operated continuously. The only factor that might reverse this line of reasoning is the time necessary to pump out the evaporator and start a new batch. If this time is too great in comparison to the time necessary to concentrate a batch, the advantages of batch operation may be lost. Ordinarily, however, the lost time is much shorter than the evaporating time, and therefore batch operation is the more practical.

There are many large-scale operations in which the finished material is viscous, but where batch operation is not practical. Such a case is the concentration of waste liquors from the manufacture of paper pulp. To avoid the undesirable effects of high viscosity, the evaporator should be operated in such a way that the finished liquid is as hot as possible. Such results may be obtained by feeding the thin liquor to the second effect, and returning the liquor from the last effect to the first, bringing it up to the final density in the first effect or by backward feed through all effects. Still a third method is to concentrate in multiple effect nearly to the density desired and then finish in a single effect with the largest possible temperature drop. With a moderate vacuum on the single effect and a large temperature drop, coefficients may be obtained much higher than in one effect of a multiple-effect evaporator. The effect of finishing at high temperatures is illustrated in the pressure evaporators used for beet juices in Europe. An ordinary quadruple-effect evaporator working between 5 lbs. steam and 26 ins. vacuum will require a temperature drop of 40 to 50° F. across the last effect, where the syrup is most viscous. Triple-effect evaporators whose last effect operates at about atmospheric pressure require a temperature drop of only 12 to 15° F. on the last effect, because the higher boiling point results in a less viscous syrup and therefore better rates of heat transfer.

Forced Circulation Evaporator Coefficients.

While the reasoning of the previous chapters explains the lack of studies on film coefficients in natural circulation evaporators, the case of the forced circulation evaporator is quite different. Here the velocity is not dependent on a set of factors that are a function of the conditions under which the evaporator is operated, but are under the control of the designer or experimenter. Consequently, with the most important factors under definite experimental control, studies on the forced circulation evaporator have been quite successful. Before discussing the formulæ as such, it is necessary to discuss the distribution of liquid temperature along the tubes.

When the liquid issues from the top of the tubes into the vapour space it flashes down to the temperature corresponding to the pressure in the vapour space. For simplicity this discussion will be confined to a liquid having no elevation in boiling point, but the case of liquids

having an elevation in boiling point will be quite obvious from these statements. The liquid, then, at the temperature corresponding to the pressure in the vapour space, goes down through the downtake, through the circulating pump, and arrives at the bottom of the tubes without an appreciable loss by radiation. Therefore the temperature of the liquid entering the tubes at the bottom is practically the same as that of the liquid leaving the tubes at the top.

As soon as the liquid starts up the tube it receives heat. It cannot boil, however, because it is under a pressure greater than the pressure in the vapour space. This is partly due to the hydrostatic head of the liquid in the tubes and partly due to the pressure drop resulting from friction. Therefore, as heat is imparted to the liquid it does not result in boiling, but in an increase in the liquid temperature. As the liquid goes up the tubes it is heated progressively hotter and hotter, but the pressure on it, due to both hydrostatic head and friction, is decreasing. Somewhere near the top of the tube the rise in temperature catches up with the loss in pressure, and at this point the liquid

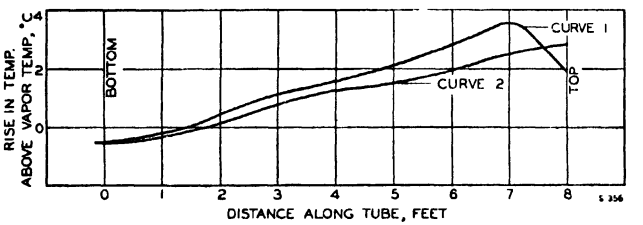


FIG. 166.

flashes. From here to the top of the tube all the heat in-put, together with the heat that has been stored in the liquid as sensible heat, is given up as flash, and the liquid rapidly drops to the temperature of the vapour space.

The result of all this is that the true average temperature of the liquid is greater than that corresponding to the pressure in the vapour space by a considerable amount. Fig. 166 shows a number of such curves, all with a boiling point in the vapour space of 176° F. This shows how the point at which flash begins is a function of temperature drop and velocity; as is also the maximum temperature reached. The curves reproduced in Fig. 166 are all at velocities somewhat lower than those ordinarily used in actual operation of a forced circulation evaporator.

It will be seen that over at least a part of the tube the liquid must be non-boiling. At higher velocities the fraction of the tube occupied by boiling liquid is relatively small. Consequently it would seem possible that the film coefficients in this evaporator could be calculated by the methods given for the calculation of film coefficients for non-

boiling liquid. Actually, over a wide range of velocities, viscosities and temperature drops the Dittus and Boelter equation (equation 9, p. 335) has been found to reproduce the liquid film coefficients quite accurately, except the determined values average about 10 per cent. lower than those calculated by the Dittus and Boelter equation. Whether this difference is due to experimental error, or whether it is a function of the part of the tube occupied by boiling liquid, is not known at present.

It must be emphasised, however, that this use of the Dittus and Boelter equation is only possible when, by the use of such curves as those in Fig. 166, the true mean temperature of the liquid can be calculated. As yet it has not been possible to calculate these curves from any data so far obtained, nor has it been possible to so correlate the true mean temperature of the liquid with its apparent temperature that the former could be predicted from the latter. Consequently, the application of the Dittus and Boelter equation to the calculation of heat transfer coefficients in a forced circulation evaporator is, at present, a matter of theoretical interest only.

Scale.

Since scale has a very marked effect upon heat transfer rates, this subject will be discussed in some detail.

In order that scale may form, it is necessary that a substance be present whose solubility curve is inverted; that is, a substance whose solubility decreases as the temperature increases. If we turn to the film theory of heat transfer, the explanation is obvious. The dissolved substance is less soluble in the liquid in the stagnant film immediately adjacent to the heating surface than in the bulk of the liquid. Consequently, it first precipitates immediately next the heating surface. If there are pits or other irregularities in the metal, even microscopic pits, the film in these pits is the hottest and the solubility there is the lowest, the solid crystallizes in them first, and thus locks the deposit to the metal. If evaporation is sufficiently rapid the bulk of the liquid may become saturated and crystals may appear there, but there will always be more rapid growth in the film because there the solubility is least and the rate of precipitation the greatest.

All substances that form scale have such curves. Sodium sulphate, sodium carbonate monohydrate, calcium sulphate and several of the calcium salts of organic acids are in this class. The last group is important in beet and cane sugar manufacture. Obviously, if there are slightly soluble materials present whose solubility curve is not inverted, they will not cause scale of themselves, but if scale is being formed they will be entangled in the stagnant film and will appear in the scale.

It has been shown that if this explanation of the mechanism of scale formation is correct, the change in the rate of heat transfer with time is represented by the equation :—

$$\frac{1}{U^2} = a + bT, \quad . \quad . \quad . \quad . \quad (18)$$

where U is the heat transfer coefficient at any time, T hours after scale has begun to form, and a and b are constants. Fig. 167 shows some data from the evaporation of sodium sulphate. Curve 1 shows the coefficients as actually determined. It is obvious that to determine such a curve, a number of readings are necessary, and the extrapolation of such a curve to predict the coefficient at some later time is quite difficult. On the other hand, equation 18 is the equation of a straight

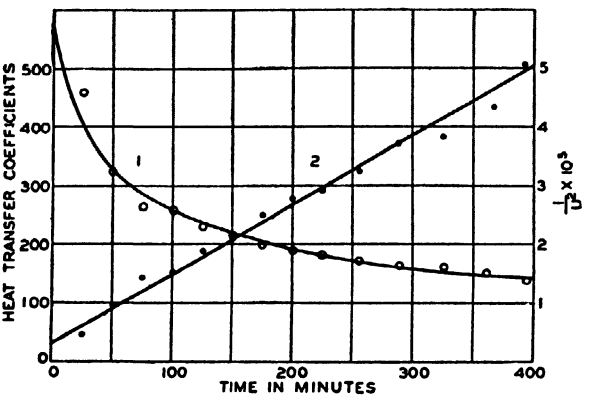


FIG. 167.—Scale formation.

line, and this is confirmed by curve 2. Consequently, only two readings are necessary to determine this line, and it may be accurately extended to future times.

It is not necessary to actually determine the coefficient itself. If the evaporator is operated under fairly constant conditions as regards rate of feed and temperature drop, any quantity that is proportional to the coefficient, such as rate of feed or rate of steam consumption, can be plotted instead of U. From such a curve it is possible to derive formulæ to determine the time between cleanings that will result in maximum capacity. Obviously, if the evaporator is cleaned too often, the average coefficient will be high, but the lost time will be too great and the total capacity will be low. On the other hand, if it is cleaned too seldom, the lost time will be small, but the average coefficient will be low, and again the total capacity will be low. There is some optimum cycle for each case of scale formation that will give the maximum total capacity.*

* McCabe, *Chem. Met. Eng.*, 1927, **33**, 86–7.

From the above discussion of the mechanism of scale formation, it is obvious that the way to diminish scale formation is to remove the stagnant film so far as is practicable. Since the stagnant film may only be removed by increasing the turbulence of the mass of the liquid, and since Reynolds' criterion measures this turbulence, Reynolds' criterion gives a qualitative clue to the methods to be used in preventing scale. If either D, u or ρ are increased, or if Z is decreased, the value of Reynolds' criterion is increased, the amount of turbulence is increased, the stagnant film becomes thinner, and there is less chance of scale formation. Increasing D, the tube diameter is not practical. If scale is to form at all, this diameter must be chosen

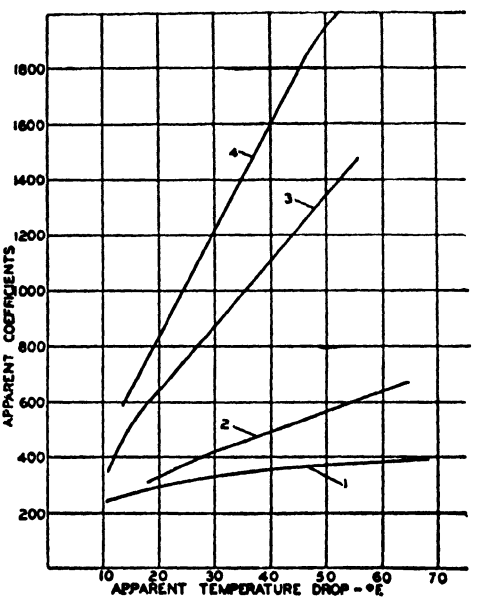


FIG. 168.—Effect of surface conditions on coefficients of heat transfer.

large enough to permit the use of a tube cleaner. ρ cannot be increased because it is fixed by the properties of the liquid being evaporated. Z can be decreased by increasing the boiling points, but the most effective means is by increasing u, the velocity of the liquid. This is confirmed by results from practice, where every factor that increases the velocity of the liquid decreases the rate of scale formation. Thus, within limits, long tubes scale less rapidly than short tubes, because of the higher velocity they produce. The introduction of propellers or other means for artificially circulating the liquid decreases the rate of scale formation. This idea is carried to its logical conclusion in forced circulation evaporators. It is, of course, well known that the presence of scale decreases the rate of heat transfer ; for example,

a very thin layer of rust on an iron tube may cut the rate of heat transfer to one-fifth or even one-tenth of that obtained with a clean iron tube. The reason for the widespread use of copper tubes as heating surfaces is not that copper has a greater thermal conductivity than iron, but that under most plant conditions copper stays cleaner than iron, and therefore gives higher coefficients.

Fig. 168 illustrates the effect of tube cleanliness on coefficients. Later experiments showed that by cleaning the tubes with dilute hydrochloric acid and keeping the water acid, coefficients as high as 4000 were obtained in the same evaporator under the same circumstances. Such conditions of perfect cleanliness are, of course, impossible in commercial operation, but it is surprising, however, how much difference there is between a clean tube and a nearly clean tube.

Comparison of Evaporator Types.

If the evaporators illustrated in pp. 351-356 are compared on the basis of these discussions, the following conclusions may be reached :— The vertical tube evaporator of either Fig. 155 or Fig. 156 gives good liquor velocities, and therefore minimises the effect of viscosity and of scale formation. On the steam side, removal of non-condensed gas is not positive, and the condensate must drain the whole length of the tube before it escapes. Therefore, conditions on the steam side are relatively poor, but those on the liquid side are favourable. In spite of this reasoning, in most cases the steam film coefficient is still much higher than the liquid film coefficient, and hence this disadvantage is not serious. The vertical tube evaporator is practically the only one that may be used when scale forms ; because the removal of scale from the inside of a tube is fairly simple, while its removal from the outside of a tube is relatively difficult.

The evaporators of Fig. 157 and Fig. 158 result from attempts to increase liquor velocity (and hence heat transfer coefficients) by employing the strong pumping action of long tubes when operated at low levels. (The inclined tube evaporator is much less common than the long tube vertical evaporator.) In this evaporator the long cylindrical steam chest gives good steam velocities and positive displacement of air, but the condensate film is probably thicker at the bottom of the tubes than in the short tube evaporators. High velocities of the liquid film give very high coefficients. This evaporator is indicated for all concentrating problems where neither salt nor scale will be formed.

In the horizontal tube evaporators of Fig. 159 and Fig. 160, conditions on the steam side are good, air venting is good ; and if the tube bank is shallow and the liquid not viscous, circulation is quite vigorous. This type cannot be used where scale may form, as scale

cannot be removed from the outside of tubes by any ordinary tube cleaner. Tube removal is fairly simple, and first cost per unit of heating surface is low. The cross-section of the vapour space is large, the surface for disengaging vapour from the liquid is large, and hence entrainment is lower than in the standard vertical.

The forced circulation evaporators of Figs. 161–2 give very high heat transfer coefficients, but their disadvantage is the cost of power for circulation. This type is particularly suited for cases where soluble scale forms or salt crystallises during evaporation, because the positive circulation decreases the rate at which deposits of either salt or soluble scale form on the tubes. Another advantage is the small heating surface required and consequent lower first cost where expensive metals are indicated.

In the past, the universal choice was the vertical tube evaporator of Fig. 155 or Fig. 156 when salt or scale might form, and the horizontal tube evaporator of Fig. 159 or Fig. 160 for clear, non-scaling and non-salting liquids. Even under the most favourable conditions neither of these evaporators can give such high coefficients of heat transfer as the long-tube types. At present the tendency is decidedly in favour of the long tube natural circulation vertical tube evaporator of Figs. 157, 182 for clear liquids, and the forced circulation or vertical tube evaporator of Figs. 161–2 or Fig. 183 when scale or salt may form.

It should be understood in considering the question of vacuum evaporation, that there are two distinct problems. In the one case, it is desired to operate under vacuum, in order to reduce the boiling point of the liquor, because it is sensitive to heat. In the other case, the vacuum is used to utilise exhaust or low pressure steam or, alternatively, if the plant is working in multiple effect.

Evaporator Steam Economy.

Principles of Multiple-Effect Evaporation.

Consider the evaporator of Fig. 169 which represents a standard horizontal tube evaporator boiling pure water under atmospheric pressure. The temperature of the vapour will be 212° F. Assume that steam is supplied at 20 lbs. per sq. in. corresponding to 259° F. There is therefore a temperature drop of 47° F. in this evaporator.

The total heat content of 1 lb. of vapour leaving the evaporator is almost the same as that of 1 lb. of steam at 20 lbs. gauge entering it; and the question arises, why may not this vapour be used for heating another evaporator? Obviously, the only difficulty is that since the temperature of this steam is 212° F. it could not be used to boil water at atmospheric pressure. If it is desired to use this steam as the heating medium for another evaporator, it is only necessary

that the water in the second evaporator boil under a partial vacuum, so that its boiling temperature shall be lower than the temperature of the vapour from the first evaporator.* Such an arrangement is shown in Fig. 170.

If a vacuum be put on body II so that water will boil at a temperature of 165° F., there will be in this body also an available temperature drop of 47° F. Assuming equal heat transfer coefficients and equal

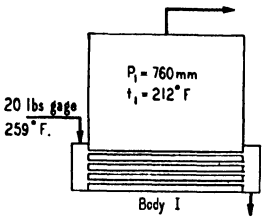


FIG. 169.

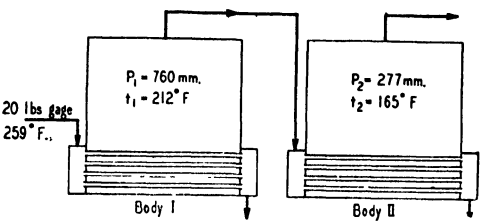


FIG. 170.

heating surfaces, this body will have the same capacity as body I. This temperature of 165° F. corresponds to a pressure of 277 mm. absolute, or a vacuum of approximately 19 ins. on a 30-in. barometer. Still a third body may be added as shown in Fig. 171. If it is still desirable to have a working temperature drop of 47° F., this body must have a pressure of 83·5 mm. absolute (26·75 ins. vacuum referred to a 30-in. barometer) and a boiling point of 118° F. For simplicity

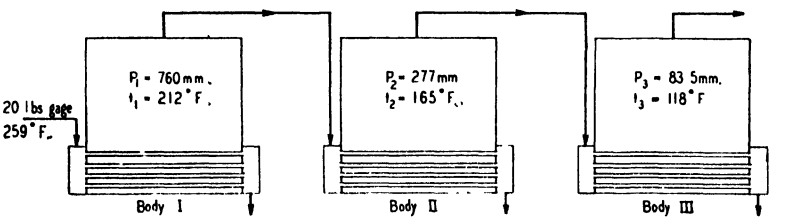


FIG. 171.

of explanation, it has been assumed that each body was to have a temperature drop of 47° F. It will be shown later that in multiple-effect operation the bodies all have different temperature drops.

Economy of Multiple-Effect Evaporation.

Since the latent heat necessary to evaporate a pound of water at 212° F. is very nearly the same as the latent heat liberated in condensing

* It is customary to use the term " steam " for the material which heats an evaporator, and the term " vapour " for the material evolved from the boiling solution. This distinction is merely one of convenience, for the " vapour " from one evaporator may be the " steam " in the next one.

a pound of steam at 20 lbs. gauge, the evaporator of Fig. 169 will evaporate approximately 1 lb. of water for every pound of steam condensed. This assumes that the liquid fed to the evaporator is at the boiling point and that losses by radiation are negligible. According to the same line of reasoning, it will appear that the evaporators of Fig. 170 will evaporate approximately 2 lbs. of water per pound of steam supplied, while the evaporators of Fig. 171 will evaporate nearly 3 lbs. of water for every pound of steam supplied. Thus it will be seen that the *principal object accomplished by multiple-effect operation is an increase in evaporation economy*, if economy is defined as the number of pounds of water evaporated per pound of steam.

Capacity of Multiple-Effect Evaporation.

In Fig. 169 the single-effect evaporator is represented as operating at a temperature of 212° F. If it is feasible to produce a boiling point of 118° F. as was done in body III of Fig. 171, there is no reason why this same vacuum might not be applied to Figs. 169 and 170. If a condenser and vacuum pump capable of producing a boiling point of 118° F. were applied to all three cases, and if it be assumed that the resulting temperature drop is distributed equally among the different effects, conditions will be as follows: —

	Single (° F.).	Double (° F.).	Triple (° F.).
Steam to first effect	259	259	259
Vapour from first effect	118	188·5	212
Temperature drop, first effect	141	70·5	47
Steam to second effect	—	188·5	212
Vapour from second effect	—	118	165
Temperature drop, second effect	—	70·5	47
Steam to third effect	—	—	165
Vapour from third effect	—	—	118
Temperature drop, third effect	—	—	47

It will be noted that the single effect of Fig. 169 then has a working temperature drop of 141° F., each body of the double effect has a working temperature drop of 70·5° F., while each body of the triple effect has a working temperature drop of 47° F. Assume that each body has the same number of square feet of heating surface, and assume further that the heat transfer coefficient is the same in all cases. The quantity of heat transferred in any body is given by equation 6 (p. 333):

$$Q = UA\Delta T.$$

Where Q is heat transferred in B.Th.U. per hr., U is the overall heat transfer coefficient, A is the heating surface in sq. ft., and ΔT is the temperature drop in ° F. Since U and A are the same for all the cases, it follows that the heat transmitted in one body of the double effect is half that in the single effect, while the heat transmitted per body in the triple effect is one-third of that in the single effect. Therefore, 1 sq. ft. of heating surface will evaporate half as much in a double as in a single, one-third as much in a triple as in a single, and so on. If it be required to evaporate a certain number of pounds of water per hour, a definite heating surface will have to be provided in the evaporator of Fig. 169. If the same total evaporation is to be performed by the evaporator of Fig. 170, it follows that each effect of Fig. 170 will have to have the same heating surface as the evaporator in Fig. 169, because each square foot of its surface is operating at one-half of the capacity of a square foot in a single effect. In like manner it can be shown that each body of the triple effect of Fig. 171 must be as large as the single effect of Fig. 169 if the total number of pounds of water to be evaporated is to be the same.

If the *capacity* of an evaporator be defined as the pounds of water evaporated per square foot per hour, then it follows that the capacity of the double effect is one-half, and that of the triple effect is one-third of the capacity of the single. In order to secure the same total evaporation, it has been necessary to use twice the heating surface in the double, and three times the heating surface in the triple, that is necessary to obtain the same output in a single effect. Thus passing from single effect to multiple effect has increased the steam economy, by evaporating more pounds of water per pound of steam ; but has increased the cost of the equipment by requiring more heating surface to accomplish the same amount of evaporation.

The above discussion has been based on single, double and triple effects, but the same principles apply to quadruple effects and mere effects. The largest number of effects that have ever been successfully operated is eight.

Temperature Distribution in Multiple-Effect Evaporators.

For the sake of simplifying the initial presentation it has been assumed in the previous discussion that in all of the evaporators considered the coefficients of heat transfer were the same. It has also been assumed that in multiple-effect evaporators the total temperature drop is equally distributed among the bodies. In actual operation neither of these assumptions is true, although this does not invalidate the theoretical deductions made above.

In discussing the effect of various factors on rates of heat transfer, it was shown that for a given temperature drop and concentration the

coefficient is smaller as the boiling point is lowered. If this consideration be applied to a multiple-effect evaporator, it follows that the coefficient in the different effects cannot be the same. Hence in the double effect of Fig. 170 the effect having a boiling point of 118° F. cannot have so high a coefficient as the effect having a boiling point of 188·5° F.

Suppose that the heating surfaces of the two bodies are equal, and that the temperatures were distributed as indicated in Fig. 170. Then the total heat evolved in the form of steam from the first body (neglecting radiation and heat necessary to heat feed) is 70·5 U_1A B.Th.U. per hr. The total heat transmitted through the heating surface of the second effect is 70·5 U_2A B.Th.U. per hr. Since U_2 could not be as large as U_1 if this temperature distribution existed, the second effect could not condense as much steam as is liberated in the first effect. If the steam were not condensed in the second effect as fast as it was liberated in the first effect, the result would obviously be to increase the pressure in the vapour space of the first effect. This would increase the boiling point and the temperature of the vapours in the first effect, with a result that ΔT_1 would decrease, and ΔT_2 would increase, until the two products, ΔT_1U_1A and ΔT_2U_2A, were equal.

It will be noted that in this discussion it has been assumed that the temperature of the steam to the first effect has been held constant at 259°, while the boiling point in the second effect has been held constant 118°. As long as these two are held constant, the evaporator will automatically adjust its own temperature distribution between effects so that the quantity of heat transmitted in the first effect is approximately equal to the quantity of heat transmitted in the second effect. It also appears that the temperature drops in the two effects will be inversely proportional to the heat transfer coefficients. In actual practice this last statement is slightly modified by differences in radiation losses, in heat necessary to heat the feed, and in heat lost in condensate, but it is approximately true even under practical conditions.

The same line of reasoning holds true for any number of effects. In the triple effect of Fig. 171, for instance, if the steam to the first effect be held constant and the vacuum on the last effect be held constant, the evaporator will automatically take up such a distribution of temperature that (approximately)

$$\Delta T_1U_1A = \Delta T_2U_2A = \Delta T_3U_3A.$$

This holds true for any number of effects. Further, if anything happens during regular operation to change the heat transfer coefficient in any effect (such as the formation of scale), the evaporator will automatically redistribute its temperature drop so that the above equation is still true. In actual practice the distribution of temperature in the

double and triple effects of Figs. 170 and 171 would be approximately as follows :—

	Double (° F.).	Triple (° F.).
Steam to first effect	259	259
Vapour from first effect	209	224
Temperature drop in first effect	50	35
Steam to second effect	209	224
Vapour from second effect	118	184
Temperature drop in second effect . . .	91	40
Steam to third effect	—	184
Vapour from third effect	—	118
Temperature drop in third effect . . .	—	66

Figs. 172, 173, 174 show the evaporators of Figs. 169, 170, 171, with approximately correct temperature drops.

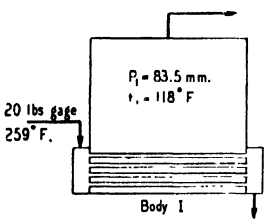


FIG. 172.

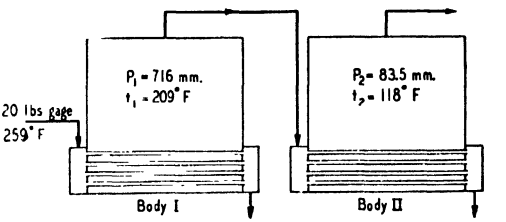


FIG. 173.

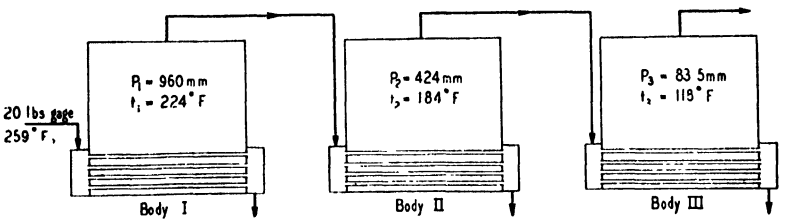


FIG. 174.

Effects of Boiling-Point Elevation and Hydrostatic Head.

Under the discussion of heat transfer in evaporators it was pointed out that their capacity was influenced by the effect on ΔT of hydrostatic head and boiling-point elevation. These factors enter into the performance of each effect of a multiple-effect evaporator just as they did in a single effect. However, their influence is even more important in the case of multiple-effect evaporation than in the simpler case.

Consider an evaporator that is concentrating a solution with a high elevation of boiling point. The vapour coming from this solution is

at the solution temperature and is therefore superheated by the amount of boiling-point elevation. This superheat represents a very small fraction of the total available heat in the steam, because the specific heat of superheated steam is only about 0·5 B.Th.U. per lb. Part of this superheat is dissipated by radiation before the steam reaches the next effect. Even if the steam enters the steam chest of the next effect with any superheat, the small amount of superheat present is quickly transmitted. Throughout most of the steam space the steam is saturated and therefore at a temperature corresponding to the pressure of the previous effect rather than its temperature. Therefore the temperature drop across any effect is that calculated on the basis of saturated steam at the pressure of the steam chest. This

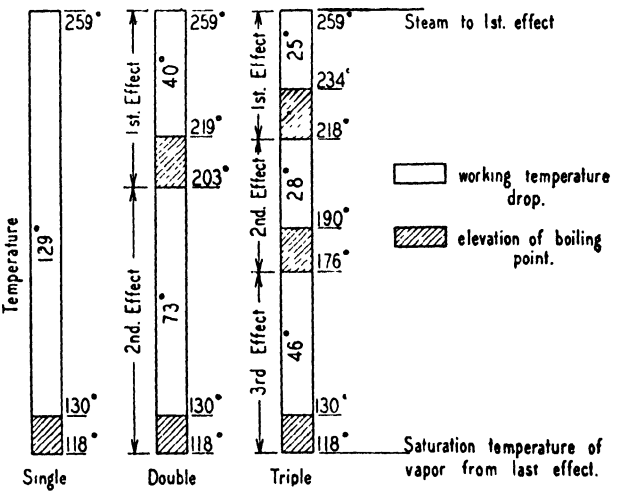


FIG. 175.

means that the boiling-point elevation in any effect is lost from the total available temperature drop. This loss occurs, not in one effect only, but in every effect of a multiple-effect evaporator, and the resultant loss in capacity is often important.

The effect of these losses in temperature drop on the capacity of a multiple-effect evaporator is shown in Fig. 175. The three diagrams of this figure represent the temperature drops over a single, double and triple effect, respectively. The terminal conditions are the same for all three cases—that is, the steam pressure to the first effect and the saturation temperature of the vapour to the condenser are identical in all cases. Each body contains a liquid with boiling-point elevation. The total height of each column represents the total temperature spread from steam temperature to saturation temperature of the vapour from the last effect.

Consider the single effect. Of the total temperature drop, that

part that is shaded represents the loss in temperature drop due to the boiling-point elevation. The actual driving force for the transfer of heat (working temperature drop) is represented by the unshaded portion. The diagram for the double effect must show two such shaded portions because there is a boiling-point elevation in each of the two effects. If these boiling-point elevations are approximately the same, it is apparent that the total temperature drop left as a working temperature drop, and represented by the unshaded portions, is less than is the case in the single effect. In the triple effect, the shaded segments appear three times, since there is a loss of temperature drop due to boiling-point elevation in each of the three effects, and the total net working temperature drop is correspondingly less.

The economy of a multiple effect is not affected by boiling-point elevations if minor influences of the temperature of the feed are neglected. It still must be true that a pound of steam condensing in the first effect will generate a pound of vapour, which will condense in the second effect, generating another pound there, and so on. The economy of a multiple-effect evaporator depends on heat balance considerations and not on the rate of heat transfer. On the other hand, if the solution has an elevation of boiling point, the capacity of a double effect is less than half of the capacity of two single effects, each of which is operating over the same terminal temperature differences, and the capacity of a triple is less than one-third that of three singles with the same terminal temperatures.

Methods of Feeding.

In the previous discussion it has been taken for granted that 1 lb. of steam will evaporate 1 lb. of water in a single effect, 2 lbs. in a double, 3 lbs. in a triple, etc. In actual practice the results are considerably modified by factors which it seemed desirable to omit from the preliminary discussion. The most important of these factors is the temperature of the feed and the point at which the feed is introduced.

Forward Feed.

The simplest method of feeding a multiple-effect evaporator is to introduce the feed to the first effect, allow the liquid to pass from effect to effect, and withdraw thick liquor from the last effect. This has the advantage of simplicity because unless there is a large number of effects and very high pressure steam used in the first effect, no feed pump will be needed, nor will any pumps be needed between the effects. Consequently this is the method most often used. One consequence of forward feed is that as the liquid leaves the first effect and is drawn into the second, it is superheated with respect to the pressure existing in the second effect and therefore some flash vapour is formed. If there are a number of effects, this flash is available for producing

evaporation in all succeeding effects, and in any case represents evaporation for which heating surface does not have to be provided. It may or may not be an advantage, as will be shown later.

The principal disadvantage of forward feed appears when the feed is cold. If the feed enters the first effect considerably below the boiling point, in the first effect some steam will be condensed to heat it to the boiling point, and this steam, of course, is not available for evaporation in later effects. Because in a multiple-effect evaporator the total steam fed to the first effect is a small fraction of the total evaporation, the steam used for heating may be a large proportion of the total steam consumed by the evaporator. A further disadvantage of forward feed is that, due to flash, the weight of vapour increases from effect to effect and therefore a relatively large amount of cooling water is needed in the condenser.

Backward Feed.

In this method the feed liquor is introduced in the last effect and then fed towards the first from which the thick liquor is removed. This has the advantage that much of the heating is done by steam that has already evaporated one or more times its weight of water. Further, whereas in forward feed all of the feed liquor must be heated to the temperature of the first effect, in backward feed only part of the liquor must be heated to the temperature of the first effect. The weight of vapour liberated decreases from the first to the last effect and therefore less cooling water is used in the condenser.

One disadvantage of backward feed is that the liquor must be transferred from effect to effect by pumps, which require power.

Mixed Feed.

The liquid may be fed to all effects in parallel, but this is rarely done except where the feed is a saturated solution as in the case of salt evaporators.

Evaporator Calculations.

The results of the different methods of feed are best brought out by certain calculations. It must be noted that all evaporator calculations involve, first, the making of certain assumptions and, second, the solution of equations based on these assumptions by the method of trial and error. Two problems will illustrate the method and at the same time point out the relative advantages of forward and backward feed.

It is desired to concentrate a solution from 10 per cent. solids to 50 per cent. solids in a triple-effect evaporator. Steam is available at 15 lbs. per sq. in. gauge (249° F.) and a vacuum of 26 ins. referred to a 30-in. barometer is maintained in the vapour space of the last effect. This pressure corresponds to 125° F. The feed to the evaporator is 55,000 lbs. per hr. and its temperature is 70° F. The condensate leaves

each effect at the temperature of the steam. The solution has a negligible elevation in boiling point, and its specific heat may be taken as 1·00 at all concentrations. Coefficients may be assumed as 550 in the first effect, 350 in the second, and 200 in the third, for forward feed ; and 450, 350 and 265 for backward feed. All bodies are to have the same heating surface.

Calculate the heating surface, the steam consumption, the distribution of temperatures, the pounds water evaporated per pound of steam, and the heat going to the condenser,

(*a*) with forward feed ;

(*b*) with backward feed.

Solution.

The evaporation is to be the same in both cases, and may be calculated from an overall material balance, assuming that the solids go through the evaporator without losses.

	Lbs. Total.	Lbs. Solids.	Lbs. H_2O.
In feed liquor	55,000	5,500	49,500
In thick liquor	11,000	5,500	5,500
Evaporation	44,000	—	44,000

If the heating surface is to be the same in all effects, there are seven unknown quantities in this problem :—(1) steam to the first effect ; (2), (3), (4) evaporation in each effect ; (5) temperature of boiling liquid in first effect ; (6) temperature of boiling liquid in second effect ; and (7) the heating surface in each effect. There are seven equations which might be written : A heat balance for each effect, a rate equation for each effect, and the known sum of the three individual evaporations. However, if these seven equations were written, their algebraic solutions would be extremely complicated, and this problem is most easily solved by a combination of the algebraic method with the method of trial and error.

The procedure will be as follows :—

(1) Assume values for the temperature of the first and second effects.

(2) By means of heat balance equations across each effect, determine the evaporation in each effect.

(3) By means of the rate equations, calculate the heating surface needed for each effect.

(4) If the heating surfaces so determined are not essentially equal for the three effects, redistribute the temperature drops and repeat items (2) and (3) till the heating surfaces are equal.

The second or third trial can usually be made to give the desired results, so that the method is not unreasonably long.

Case A—Forward Feed.

As a guide in the first attempt to distribute the total temperature drop across the effects, certain general principles are of value. As discussed on p. 373, the temperature drop across a given effect must be larger as the heat transfer coefficient is smaller. Also, if any effect has an extra load, more temperature drop must occur across that effect. In this problem, the total temperature drop is (249 — 125), or 124° F. The last effect must have the largest drop, and because of the large amount of heating to be done in the first effect, this effect may have a larger drop than the second effect. From these considerations, the first assumption will be

$$\Delta T_1 = 38°,\ \Delta T_2 = 33°,\ \Delta T_3 = 53°.$$

The conditions will then be as follows :—

Steam to first effect	249° F.	latent heat = 946·0
Boiling point in first effect	211° F.	B.Th.U./lb.
ΔT_1	38° F.	
Vapour from first effect	211° F.	latent heat = 971·0
Boiling point in second effect	178° F.	
ΔT_2	33° F.	
Vapour from second effect	178° F.	latent heat = 991·0
Boiling point in third effect	125° F.	latent heat = 1021·6
ΔT_3	53° F.	

Heat balance equations may now be written across each effect as follows :—

Let

X = lbs. evaporated in first effect.
Y = lbs. evaporated in second effect.
Z = lbs. evaporated in third effect.
W = lbs. steam furnished to first effect.

The datum temperature for each effect will be the boiling point in that effect. In feeding from the first to the second effect, and from the second to the third, there will be some vapour formed by flashing.

Across the first effect :—

(Heat in steam above 211°) — (heat to heat feed to 211°)
= (heat in vapour at 211°) (heat in condensate above 211°).

It will be noted that the difference of the first and last terms is the latent heat of the steam entering at 249°. Hence it follows that

$$946.0W - (55000)(211 - 70) = 971{\cdot}0X.$$

This simplification (using the latent heat instead of writing a rigorous heat balance) always results when the condensate leaves at steam

temperature, or so near steam temperature that the sensible heat recovered from it may be neglected.

Similarly for the second effect

$$971{\cdot}0X + (55000 - X)(211 - 178) = 991{\cdot}0Y,$$

for the third effect

$$991{\cdot}0Y + (55000 - X - Y)(178 - 125) = 1021.6Z,$$

and for all three effects

$$44000 = X + Y + Z.$$

Solving these four equations gives

$$\begin{aligned} X &= 13{,}595 \text{ lbs.} \\ Y &= 14{,}710 \text{ ,,} \\ Z &= 15{,}695 \text{ ,,} \\ \text{Total} \quad & 44{,}000 \text{ lbs.} \end{aligned}$$

$$W = 22{,}150 \text{ lbs.}$$

Turning to rate equations for each effect.
In the first effect

$$A_1 = \frac{971X\,(55000)\,(211 - 70)}{38 \times 550} = 1003 \text{ sq. ft.}$$

$$A_2 = \frac{971X}{33 \times 350} = 1141 \text{ sq. ft.}$$

$$A_3 = \frac{991Y}{53 \times 200} = 1375 \text{ sq. ft.}$$

The problem stated that the heating surface was to be the same in all effects, but the above solution shows that to maintain the temperature distribution that has been assumed will require widely different surfaces.

Hence the temperature distribution must be readjusted.

By the method of trial and error these calculations are repeated until it is found that temperature drops of 32°, 32° and 60° satisfy the conditions of the problem. Under these circumstances the results are as follows :—

Weight of steam to first effect . . .	22,540 lbs.
Heating surface	1200 sq. ft. per effect
Evaporation per lb. of steam . . .	1·95 lbs.
Total heat going to condenser . . .	16,040,000 B.Th.U.

It will be noticed that the evaporation is far from the theoretical evaporation of 3 lbs. of water per lb. of steam. This is because in the present problem the temperature of the feed has been taken unusually low.

Backward Feed.

After several trials, temperature drops of 35°, 42° and 47° are found to satisfy the conditions of the problem. The equations then are :—

$$X + Y + Z = 44{,}000$$
$$994{\cdot}6Y = 1021{\cdot}6Z + (55000)\,(125 - 70)$$
$$969{\cdot}1X = 994{\cdot}6Y + (55000 - Z)\,(172 - 125)$$
$$946{\cdot}0W = 969{\cdot}1X + (55000 - Y)\,(214 - 172)$$

Solving these equations gives the following results :—

Weight of steam to first effect . . .	19,160 lbs.
Heating surface	1165 sq. ft. per effect
Evaporation per lb. of steam . . .	2·30 lbs.
Heat to condenser	11,875,000 B.Th.U.

If the results of these two cases are compared, it will be seen that backward feed effects a saving of 15 per cent. of the steam used in case A. This is the usual result of using backward feed when the temperature of the feed is low. The heating surface needed for backward feed is slightly less than in forward feed, but this is largely

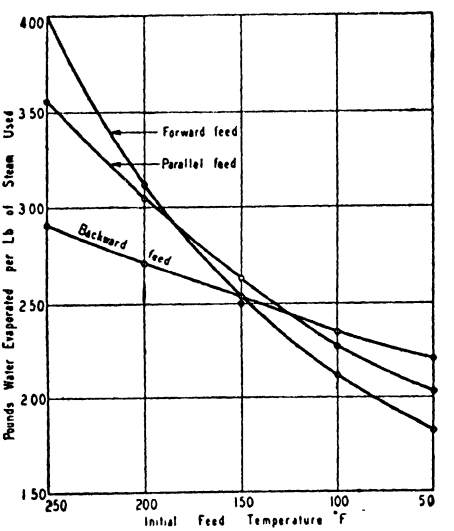


FIG. 176.

due to the particular values assumed for the coefficients and is not a general result for all cases of backward feed. The use of backward feed has not only decreased the steam consumption by 15 per cent., but has decreased the heat going to the condenser (and therefore the amount of cooling water needed) by 26 per cent.

It is difficult to summarise quantitatively the effects of forward versus backward feed, because the quantitative results are affected by every change in conditions. Webre * has made a number of calculations for a triple effect with different values for the feed temperatures, but all other factors held the same. The results of these calculations are shown in Fig. 176. It must be remembered, however, that the calculations summarised in Fig. 176 are based on a particular initial temperature, a particular final temperature, a particular set of coefficients and a particular ratio of thick liquor to thin liquor. Altering any of these conditions would alter the numerical values of Fig. 176, and would alter the point for which backward feed and forward feed would give the same results. Qualitatively, however, Fig. 176 shows plainly the advantages of forward feed when feed is hot, and of backward feed when feed is cold.

Extra Steam.

Norbert Rillieux, who built the first multiple-effect evaporator, contributed an idea regarding the position of the avaporator, in the steam flow sheet of a process that has been fully appreciated in the beet sugar industry, but which has never been properly appreciated elsewhere. If heating operations (or, in general, any operation that uses what is known as " process steam ") are carried out in the same plant in which a multiple-effect evaporator is also used, then the possibility of taking vapour from the evaporator to replace the process steam should be carefully considered. The extent of the savings so produced may be best illustrated by a problem.

Consider the triple evaporator discussed above, operating with forward feed, and assume that 4,000 lbs. of vapour are withdrawn from the second effect for use elsewhere in the plant. By the method of trial and error used in solving the previous problems it is found that the temperature drops will be 35°, 36° and 53°. Heat balance equations are written and solved as before, from which the following results are obtained :

Weight of steam used in first effect, 23,720 lbs.
Heating surface, 1150 sq. ft. per effect
Evaporation per lb. of steam, 1·86
Heat passing to the condenser 13,245,000 B.Th.U.

If this case is compared with Case A, it will be seen that there has been an increase of 1,180 lbs. in the steam used by the evaporator. However, in Case A, approximately 4,000 lbs. of steam must have been taken from the mains as live or exhaust steam, to do the work done by the 4,000 lbs. withdrawn from the evaporator in this case. Hence, the total steam consumption for the evaporator, and this other operation combined, was 26,540 lbs. in Case A, but only 23,720

* *Chem. Met. Eng.*, 1922, 27, 1073–8.

lbs. in this case—a saving of 2,820 lbs. of steam per hr., or 10·6 per cent. of the total steam used in Case A. In addition, there has been a saving in condenser cooling water of 17·5 per cent. These savings have been accomplished without any changes in the evaporator except adding a connection in the vapour line between the second and third effects.

Evaporation in Evaporators using the Vapour Recompression Method.

Fig. 177 shows the principle of evaporators using the vapour recompression system. The evaporator proper is of the usual standard pattern but with an auxiliary steam coil beneath the lower tube plate. Evaporation of the liquid is begun by heating by means of the auxiliary steam coil. When the liquid begins to boil freely the vapour compressor (6) is started up and withdraws the vapour from

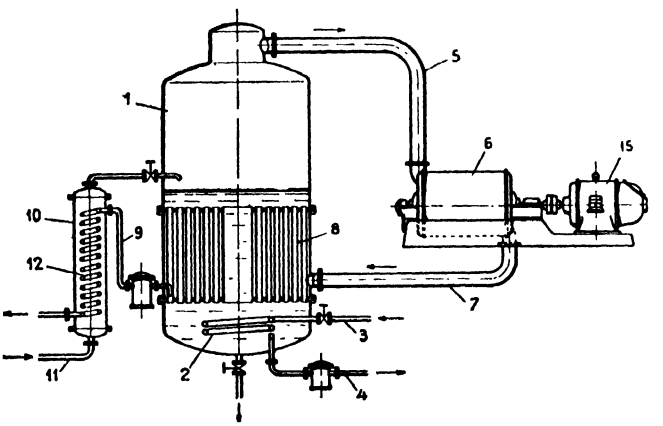


FIG. 177.—Evaporator by Escher–Wyss, with vapour recompression.

the steam space as shown. The compressed vapour is discharged into the steam chest and is thereby used as a supplementary source of heat.

The compression of the vapour may be carried out either by means of a turbine or motor-driven turbo-blower, or by a steam nozzle. Galperin (*Trans. Chem. Eng. Cong.*, London, 1936, **2**, 364) deals in detail with the performance of turbo-compressors, and Figs. 178–9 give particulars of the power requirements for various compression ratios, and also the degree of superheat attained during compression. The efficiency of compression is taken as 0·60.

The chief field for vapour compression by turbo-compressors driven electrically would appear to be where electric or hydraulic power is cheap and the cost of fuel relatively high.

Another method of compressing the vapour is by injector compression. Such an apparatus is simple and effective and the profitable limit of its use depends upon the degree of compression required.

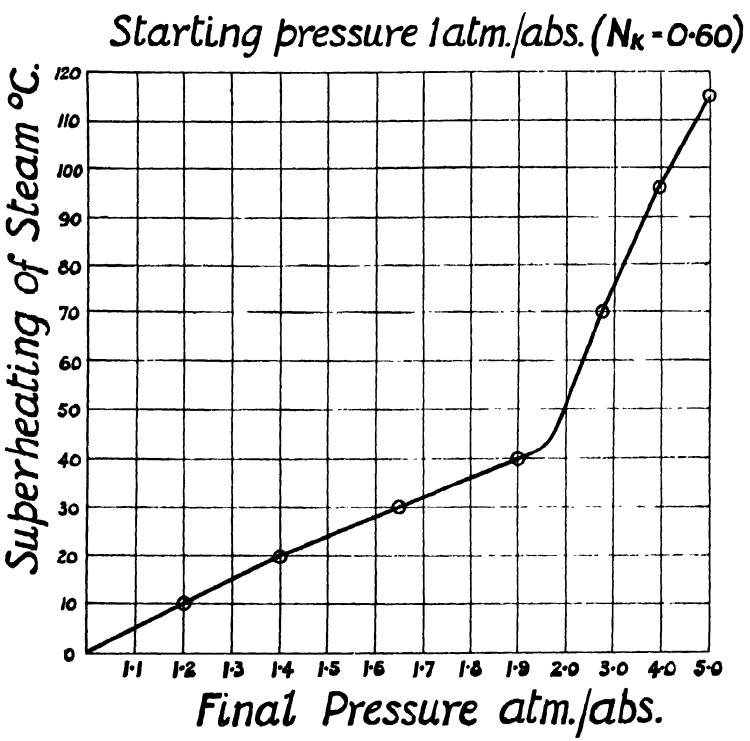


FIG. 178.

An example of a large plant using vapour compression by turbo-compressor is seen in Fig. 180. The plant is installed at the Bavarian Salt Works at Reichenhall and handles 13,200 lbs. of evaporation per hr. (= 3500 lbs. of common salt) The current for the motor-driven compressor is supplied from the hydro-electric plant of the salt works. An evaporator by Prache and Bouillon, using the nozzle injector method of vapour compression, is seen in Fig. 181. High-pressure steam admitted at (1) draws into the injector some of the vapour from the evaporator, so that when the mixture is discharged into steam heating chamber (3), its temperature is such that there is sufficient heat drop for evaporation to take place within the evaporator. The condensation from the heating steam is led away by the pipes (9). Vapour for preheating the incoming liquor is led

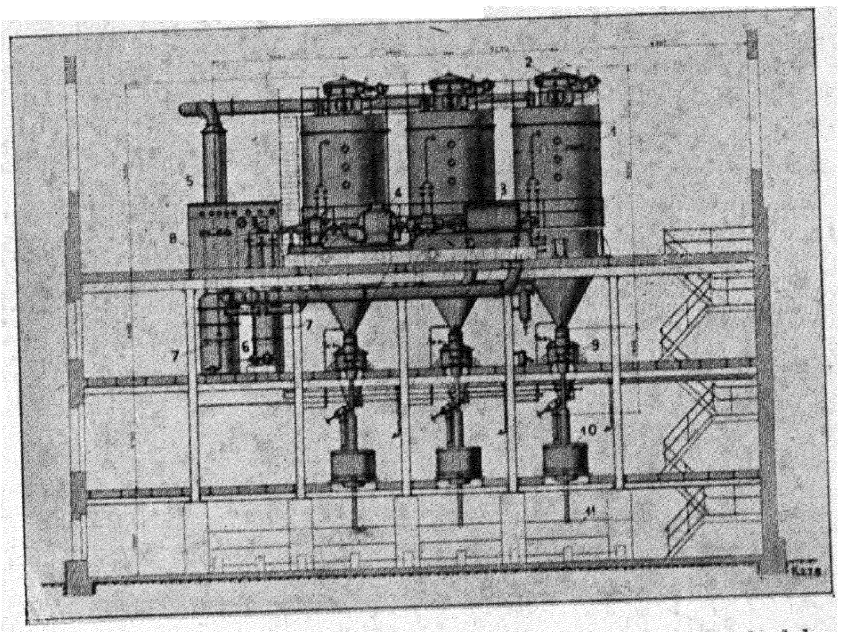


FIG. 180.—Large evaporator using vapour recompression method by Escher–Wyss.

[*To face page* 388.

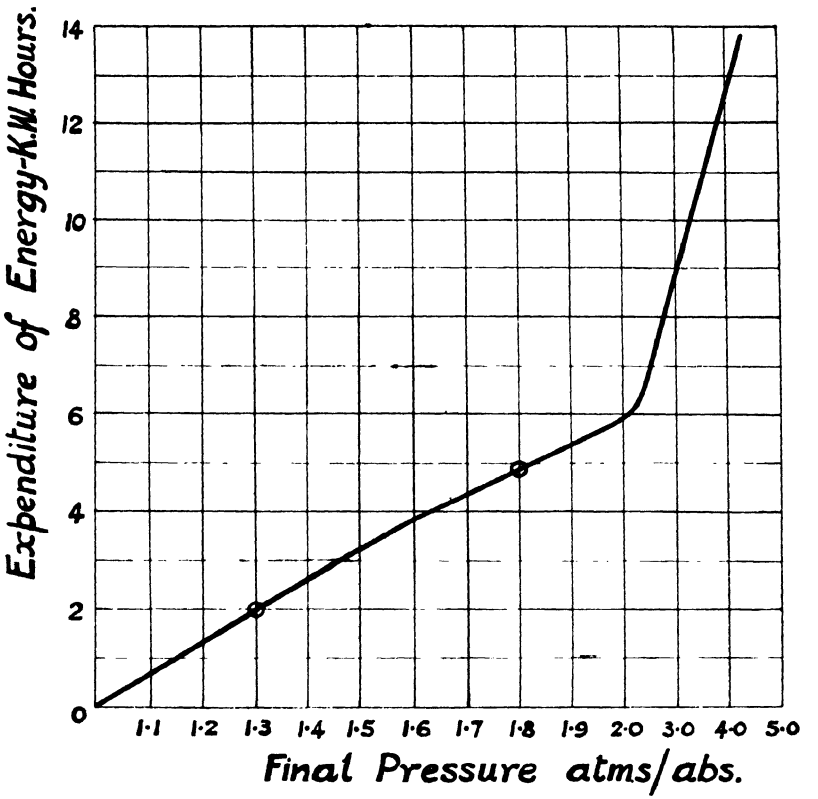


FIG. 179.—Expenditure of energy to compress 100 kgm. steam in kw. hours. Starting pressure P_1 = 1 atm. (N_k = 0·60).

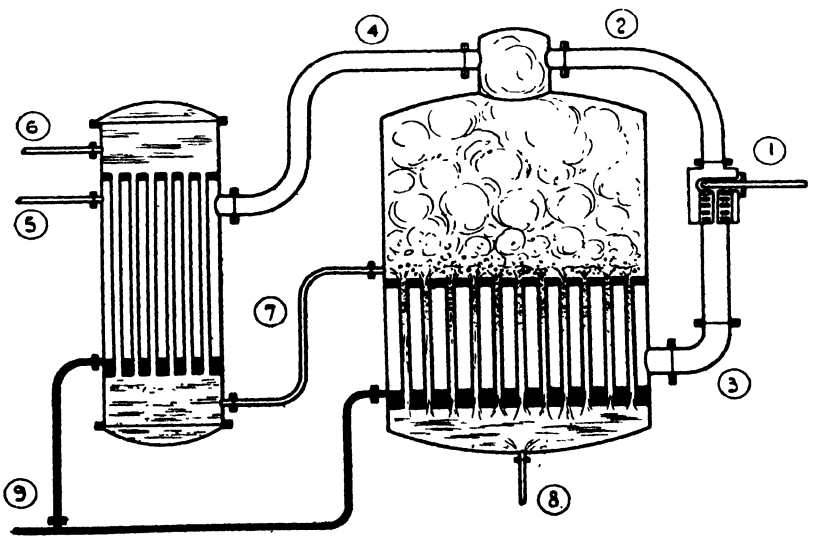


FIG. 181.—Evaporator and vapour compression by Prache & Bouillon.

to the preheater by pipe (4) and any excess taken to atmosphere by pipe (5).

An actual example of the above method of evaporation in the production of distilled water is as follows :—1 lb. of live steam at 160 lbs. gauge draws in and compresses 2 lbs. of vapour to the desired pressure ; 3 lbs. of compressed vapour is directed to the heating chamber and by simple heat exchange evaporates 3 lbs. of water. Of the vapour, 2 lbs. goes to the vapour-compressor and 1 lb. to the preheater. A plant of this type produces 4 lbs. of distilled water per lb. high-pressure steam.

Description of Typical Commercial Evaporators.

Kestner Film Evaporators—Long Tube Type.

Of the several advantages of the film evaporator, which is constructed in single or multiple effect, one of the most important is the high velocity and the very short time of contact. Such evaporators are of the continuous type and the short time of contact is of particular advantage in dealing with materials that are sensitive to heat. It has been found in a large number of cases that it is not so much the temperature of the liquor that is of importance, as the actual time of contact with the heated surface.

Fig. 182 shows a Kestner vertical climbing film evaporator ; the construction is clear from the illustration.

There are several types of film evaporator, such as the climbing film and the falling film, the latter being used where a higher percentage of evaporation is required than would be obtained by the climbing film. The principle of the falling film is similar to the climbing film, the essential difference being that the liquor and vapour pass up the calandria in one pass and then down the calandria in a second pass, the separator being placed at the bottom of the calandria at the end of the second pass.

The falling film is generally used when evaporation is more than some 50 per cent. and it is easy to remove for one passage through the evaporator, up to some 80 per cent. of water.

In certain cases, as for the concentration of tannin extract, a serpentine is used, in which there are still further passes. This will produce, in one passage, a very concentrated liquor which, although fluid when hot, solidifies on cooling.

A further development, to avoid deterioration of sensitive materials, is the Kestner high vacuum multi-circulation film evaporator. This is essentially a climbing film plant, but is arranged so that the vapour is separated from the liquor in two or more stages before the final evaporation is completed. This is used where the lowest possible evaporation temperatures are required, in addition to the short time of contact.

It is obvious that there is a certain friction drop in the passage of the liquor and vapour through the evaporator, which results in an elevation of boiling point, depending on the length of travel through the plant. By separating the vapour in stages before the concentration is finally completed, this friction drop is naturally reduced to a minimum. Plants of this type are used successfully for milks, fruit juices, etc., either of the double or triple circulation type—that is to say, having two or three intermediate separations.

When dealing with liquids from which a salt would separate, during evaporation it is essential that this salt should be deposited away from the evaporator tubes. The Kestner salting type evaporator (Fig. 183) has been developed for this purpose. With this plant it is seen that the heat is supplied to the liquor in the calandria, but the actual evaporation and deposit of salt takes place in the separator itself. One of the advantages of this plant is that one or more calandrias can be arranged around one separator. In many cases this salting type plant is arranged with forced circulation. (See also the Escher–Wyss evaporators for cases where salts crystallises out during evaporation, Figs. 161–162.)

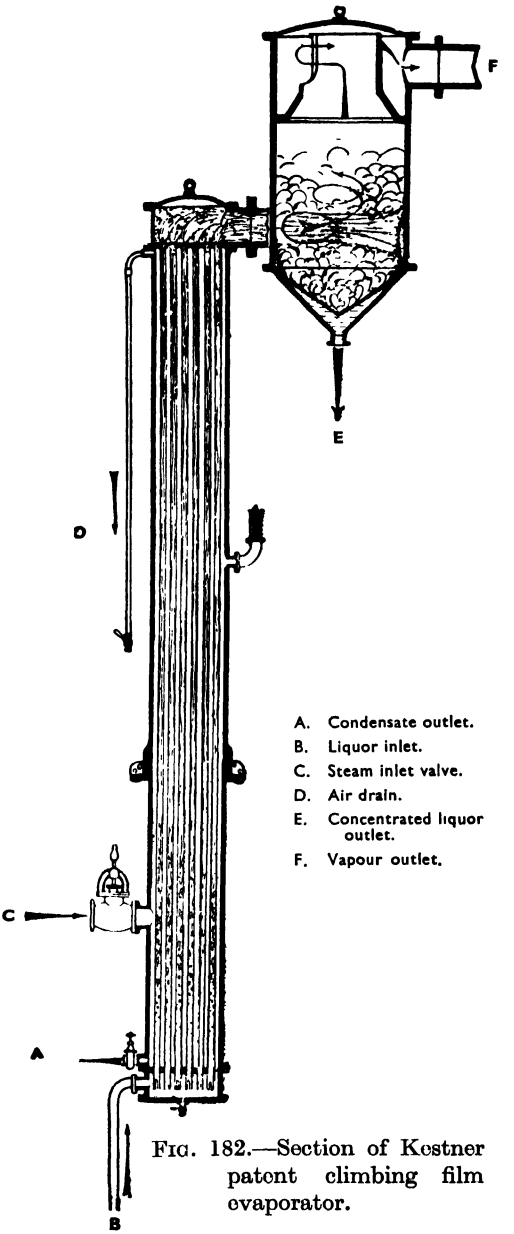


FIG. 182.—Section of Kestner patent climbing film evaporator.

Messrs. Kestner have developed a special acid evaporator of the climbing film type for dealing with corrosive liquors such as the concentration of waste sulphuric acid in the artificial silk and parchment paper industries. This

special type of evaporator comprises one or more calandrias each with a single evaporator tube around a single separator. The tubes are constructed of lead or silicon iron alloy.

On account of the high boiling point, the plant is worked under vacuum and the concentrated liquor passes from the separator to a seal pot in the circulating tank on ground level, by barometric discharge. There is a circulating tank on each unit, into which the weak liquor is fed. It is, therefore, possible to feed different strengths

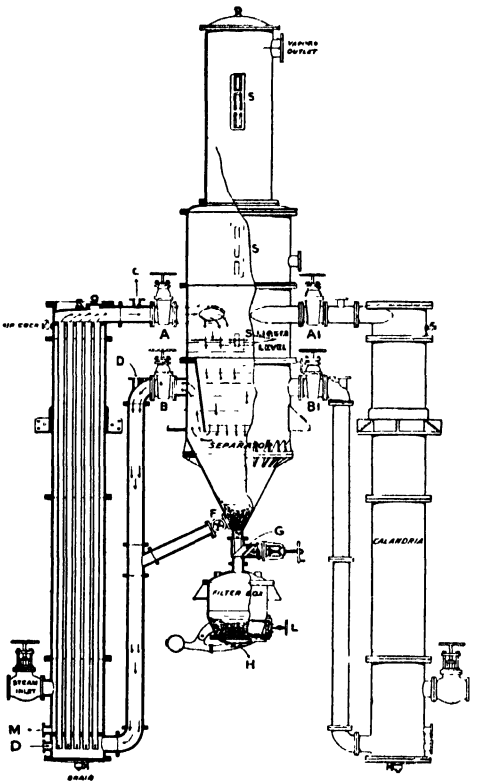


FIG. 183.—Section of Kestner patent salting type evaporator.

of liquor to the different units, although the vapour evaporated, on leaving each separator, is connected by a common main to the save-all and condensing plant, which is common to all units. The save-all is used to deal with possible entrainment, caused by sudden fluctuation in operating conditions, and the vapours leaving this pass to a barometric condenser, the non-condensable gases being dealt with by a steam-operated air ejector, which has the advantage of avoiding all moving parts which would present difficulties, due to corrosion if, for example, a vacuum pump were employed.

These evaporators are widely used and can concentrate up to some

75 per cent. H_2SO_4, utilising ordinary saturated steam at pressures up to 140 lbs. gauge.

An interesting form of multiple-effect evaporator is the Multiplex Patent Film Evaporator as made by Blair, Campbell & McLean, the method of operation of which is as follows (Fig. 184).

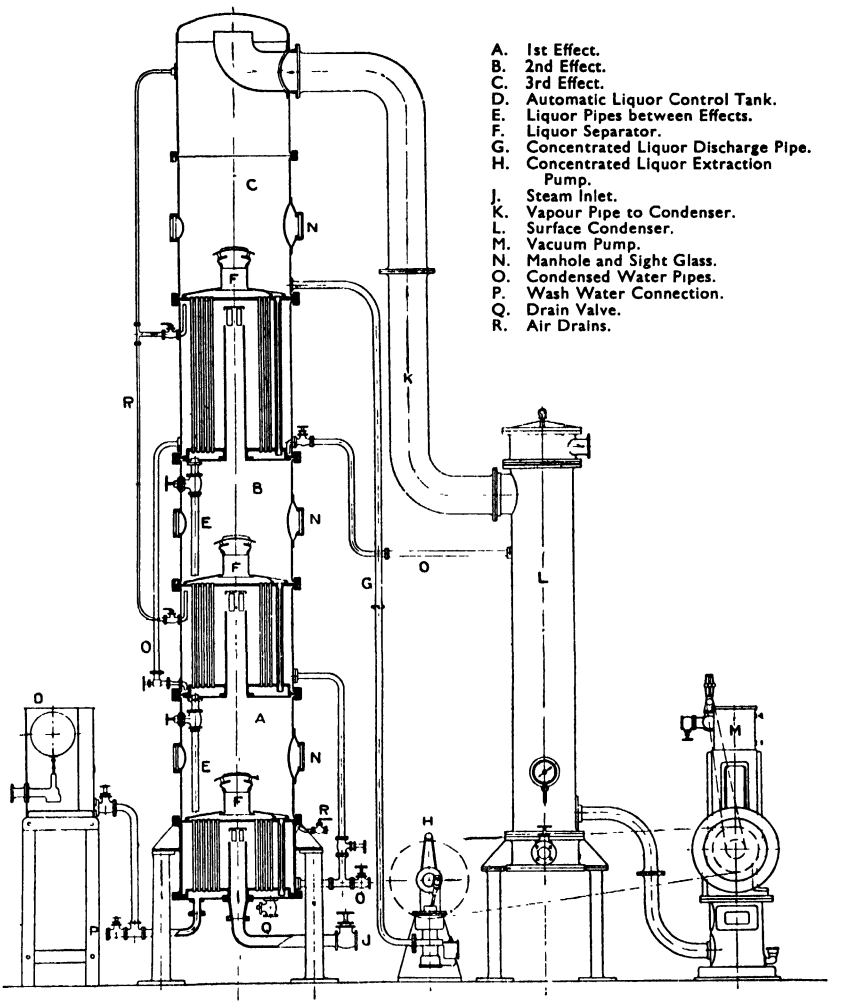


FIG. 184.—Triple effect evaporator by Blair, Campbell & McLean.

The weak liquor to be concentrated is fed into the liquor chamber of the first effect, the quantity being regulated by means of a special valve with indicating device, and a steady and constant feed is maintained by means of an automatic controlled float valve in the auxiliary feed tank supplied with the apparatus. This is an advantage over

feeding by a pump, as it reduces working expenses and obviates the trouble sometimes caused owing to irregular feeding due to the pulsations of the feed pump.

The liquor, if fed in a temperature closely approaching its boiling point, rises to a uniform height in the evaporating tubes, and imme-

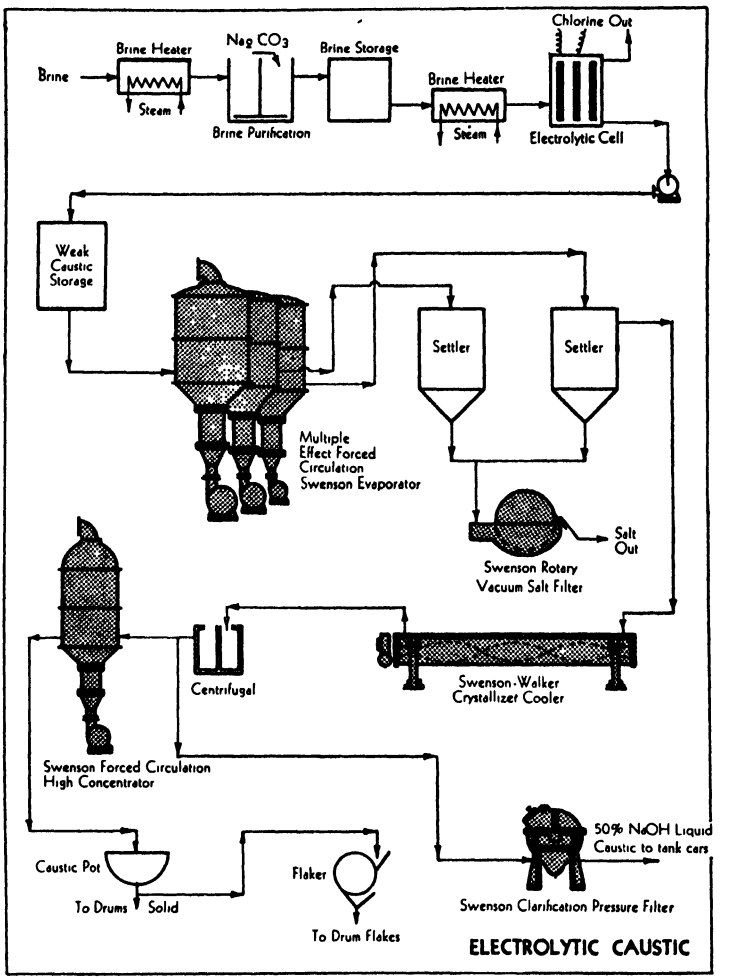


FIG. 186.

diately begins to evaporate, giving off vapour. In cases where the liquor is cold a preheater of Blair's improved rapid-circulation design is often installed, this being heated by exhaust steam, by the condensed water from the first effect, or by means of the vapour given off during the evaporation of the liquor in the evaporator.

As soon as ebullition takes place at the lowest portion of the heating tubes, the vapour forms bubbles to begin with, but as its volume

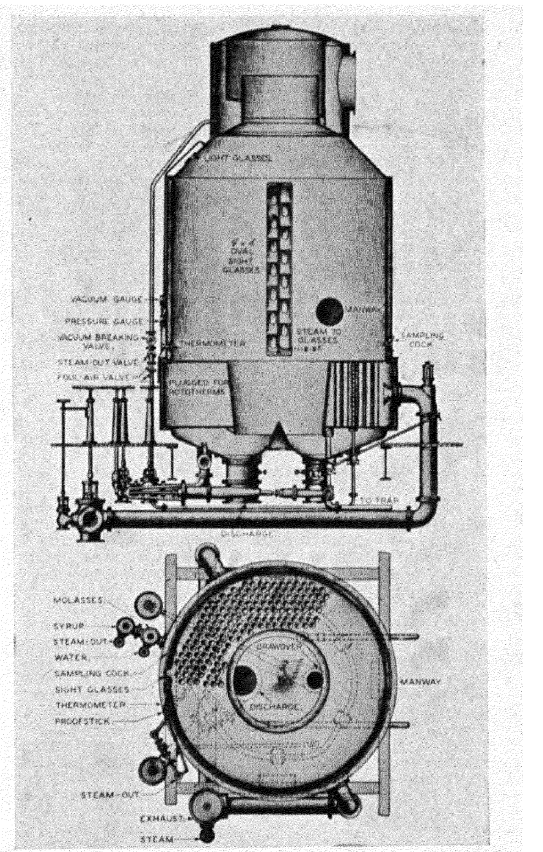


FIG. 185.—Evaporator by Mirrless Watson.

[*See page* 396.

[*To face page* 394.

steadily increases with a corresponding high increase in velocity the liquor attaches itself to the tube walls in the form of a uniform film, the vapour forming a centre core, and both liquor and vapour leave the tubes at the top at a very high velocity. On account of this high velocity of the liquor through the apparatus the maximum heat transmission is obtained.

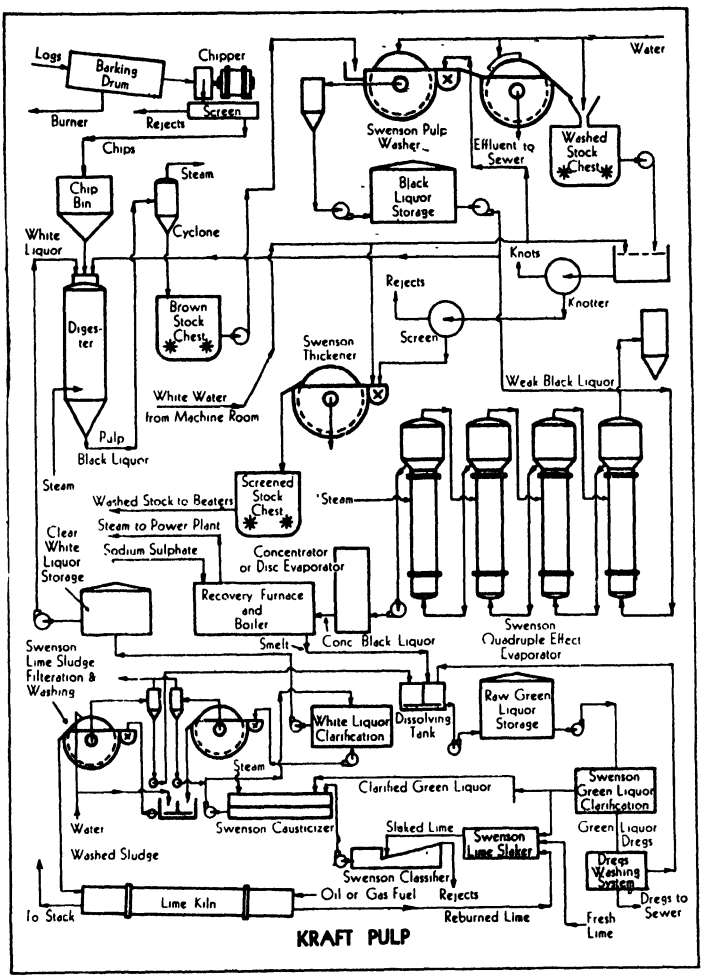


FIG. 187.

The liquor and vapour on leaving the evaporating tubes are projected with great velocity against the baffle plate, and through the tubular connection into the separator, where the liquor is separated from the vapour by means of the specially devised foam separator which ensures good separation and freedom from entrainment. The liquor is carried downwards on to the baffle plate, and is then

drawn up owing to the reduced pressure in the second effect, through the internal liquor pipe into the liquor chamber of the second effect. The vapour passes into the heating chamber of the next effect through the central intake, thus ensuring equal distribution in the vessel, so that all the heating surface is heated uniformly. This process is repeated in the following effects.

The concentrated liquor at the required density is removed from the last effect by means of a pump, but where conditions are suitable this can be dispensed with, the liquor being discharged continuously under a barometric head. The condensed steam from the first chamber can be used for boiler feeding or passed on into the second effect, where, on account of the lower pressure in the chamber, it vaporises, and the heat contained does further useful work. The condensed steam from the second effect is taken into the heating chamber of the third effect, where it also gives up some of its heat.

The vapours from the last effect are taken through the condenser, and the condensed steam from the heating chamber is either withdrawn through the condenser or by means of a separate pump.

As a guide to the performance of these Multiplex evaporators, the evaporation per lb. of steam applied is 1·66, 2·75 and 3·38 lbs. for double, triple and quadruple effect respectively.

Fig. 185 shows a vacuum evaporator pan by Mirrless Watson for the sugar industry. The calandria is constructed of boiler plate, and the tube plate and circulating well are of copper bearing steel (or copper and brass, if desired). These pans are made up to 15 ft. diameter, at which maximum size of heating surface is 3050 sq. ft. When boiling low-grade sugars these pans are fitted with circulating devices.

Figs. 186–7 show the use of multiple-effect evaporators in two important chemical processes. (These flow-sheets are included by courtesy of the Swenson Evaporator Company.)

Accessories for Evaporators.

Such accessories include condensers and vacuum pumps. Condensers are of the low level jet, high level barometric, or surface condenser types. Fig. 188 shows a double effect salting evaporator by Blair, Campbell & McLean, with *jet condenser* and wet air pump. The condenser merely consists of a device (G) to spray efficiently a sufficient amount of cooling water to condense the desired amount of vapour. Note in Fig. 188 that the feed to the evaporator is heated by the vapours from the second effect before these enter the condenser.

A barometric condenser consists of a condensing head where the vapours are condensed by sprays of cooling water. The condensed vapour and cooling water flows away by a fall pipe, which must be of such a length that the head of water is greater than the barometric pressure, so that the water flows away naturally from the bottom of

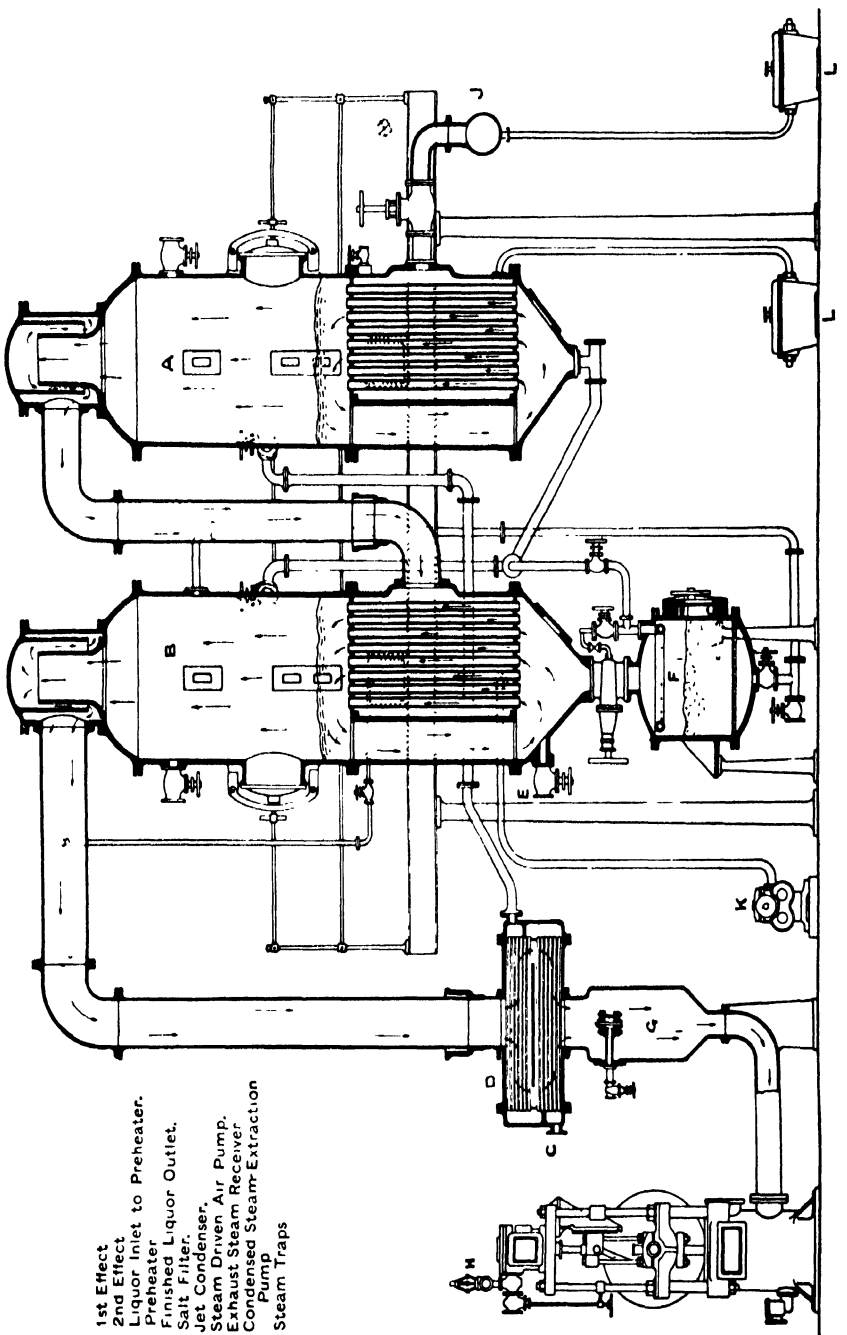


FIG. 188.—Line drawing showing double effect evaporator for salting liquors.

the fall pipe. The air is removed from the head of the condenser by a dry air pump. Figs. 189–90 illustrate a barometric condenser with fall pipe, and a barometric condenser head by Blair, Campbell & McLean. Surface condensers follow the well-known steam-power practice.

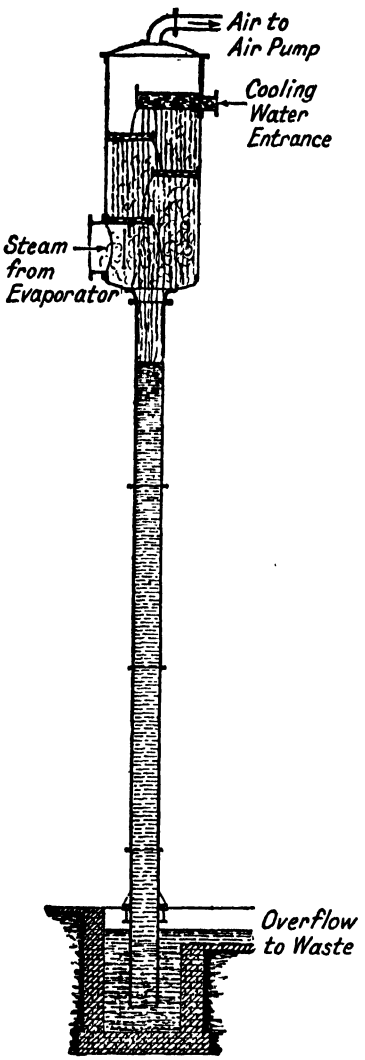


FIG. 189.—Barometric condenser.

As to choice of condenser type, the low-level jet type is used for medium size plants where a really high vacuum is not essential. The high-level barometric type is used for fairly high vacua and where salt or impure condensing water must be used. The surface condenser is used for cases where it is desired to recover all the evaporated water, and where economy of operation is essential, since it is usually cheaper to instal and run than the ordinary jet condenser. It is, for example, used with the Blair, Campbell & McLean evaporator shown in Fig. 184.

Vacuum Pumps for use with the above condensers are usually of the wet or dry reciprocating type, depending upon the design of the condensing system. For jet condensers a wet vacuum pump is used, usually of the vertical multiple valve bucket type (see, for example, Fig. 188). If d is the diameter of the pump barrel in inches, s the stroke in inches, n the number of revs. per min., and W the weight of steam condensed per hour, the air pump capacity for jet condensers is found by :—

$$0{\cdot}785d^2sn = 55\text{W—single acting}$$
$$= 27{\cdot}5\text{W—double acting.}$$

This gives about 2 cu. ft. of air pump displacement (single acting), or 1 cu. ft. (double acting), per pound of steam condensed in the same period of time.

For surface condensers as ordinarily arranged the air pump capacity is found by

$$0{\cdot}785d^2sn = 17\text{–}21\text{W},$$

which gives 0·6–0·75 cu. ft. of air pump displacement for each pound

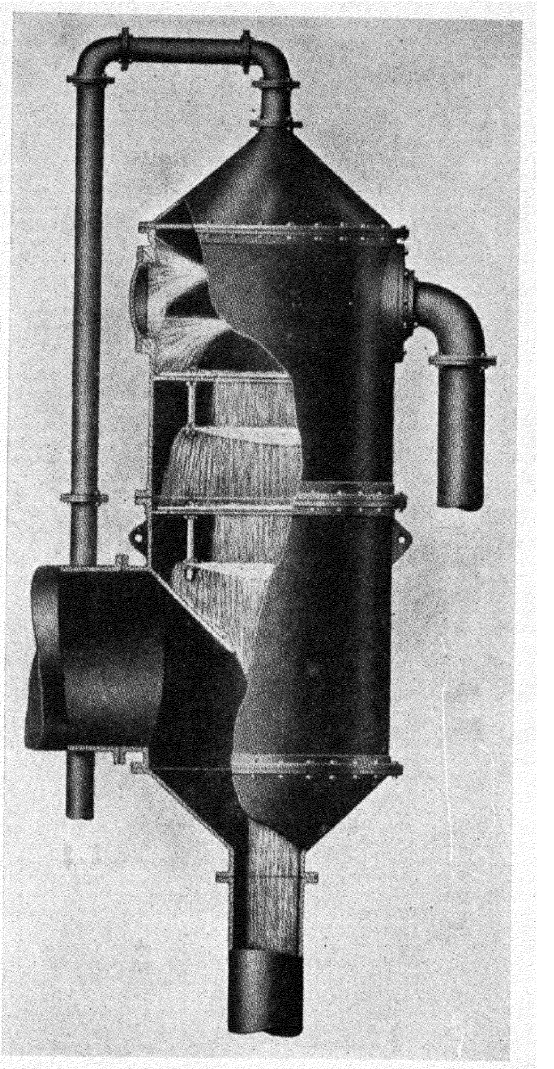


FIG. 190.—High-level barometric condenser head.

[*To face page* 398.

of steam condensed in unit time. Naturally an air pump for a surface condenser is smaller than for a jet condenser of equivalent condensed steam capacity, because the former only withdraws the condensed steam, whereas the latter must also deal with the cooling water.

For barometric condensers dry air pumps are used to extract the air from the head of the condenser (Fig. 189). The water escapes by the barometric leg. Such dry air pumps usually follow established air compressor practice.

Ejectors, either water- or steam-operated, are sometimes used with evaporators, but the great majority of evaporating plants are fitted with either surface or jet condensers.

Heating by Circulation of Hot Fluids.

Many processes demand means whereby reactions may be carried out at high temperatures. Towards temperatures of 600° F., if steam were employed as the heating agent, it would necessitate high pressure (say 1500 lbs. per sq. in.) unless the steam were superheated. If superheated steam is used, this would give only a low heat transfer rate, since the operation temperature would not permit of the use of the latent heat of the steam at the saturation pressure. If direct firing is used, temperature control is difficult, and often fire dangers are present.

The need for a high temperature heat transfer fluid has been met by two materials :—

(1) *Heating by Circulation of Heated Oil.*—This method is suitable up to about 575° F., and a typical plant comprises an oil heater, a circulating pump, and the apparatus to which the heated oil is led. The oil heater may be fired by solid fuel, gas, or oil, and in the two latter cases thermostatic control is readily fitted. The pressure in the oil heater pipe line is not higher than 20 lbs. per sq. in., so that ordinary pipe practice is sufficient. Plants made, for example, by Messrs. Kestner Evaporator & Engineering Co., Ltd., can be obtained in capacities up to about 3,500,000 B.Th.U. per hour.

(2) *Diphenyl and Diphenyl Oxide.*

The hydrocarbon diphenyl (C_6H_5–C_6H_5) has a melting point of 70° C. and a boiling point of 255° C. In the pure state it is a white crystalline solid and has a somewhat sweetish but not unpleasant odour. The commercial product is usually yellowish in colour, with a pronounced odour not unlike naphthalene. Diphenyl is manufactured by heating the vapour of benzene to about 800° C.

Diphenyl oxide (C_6H_5–O–C_6H_5) has a melting point of 27° C., and a boiling point of 259° C. It has a very pungent odour which in low concentrations resembles that of rose geranium.

Diphenyl is manufactured in the U.S.A. by the Monsanto Chemical Company and the Dow Chemical Company, and diphenyl oxide by the Dow Chemical Company.

" Dowtherm " is a eutectic mixture of diphenyl and diphenyl oxide, and consists of 73·5 per cent. diphenyl oxide and 26·5 per cent. diphenyl. This mixture is being increasingly used for heat transfer problems involving the temperature range 450–750° F., and its properties are given in table 50, p. 401. (W. L. Badger, *Industrial Chemist*, 1937, **13**, 343.)

Thermal Stability of Dowtherm.—This material is remarkably stable at high temperatures. Decomposition may take place in two ways. Above about 750° F. two molecules of diphenyl may react to yield one molecule of *p*-diphenyl benzene and one of benzene. The *p*-diphenyl benzene dissolves in Dowtherm, but the benzene, being a non-condensing vapour in practical Dowtherm heating installations, escapes via vent-pipes. There is a similar reaction in the case of diphenyl oxide.

As an illustration of the stability of Dowtherm under practical conditions, the Dow Chemical Company has operated a Dowtherm boiler plant and accessories at a rating of 4,000,000 B.Th.U. per hour and 650° F., for a period of five years, and at the end of that time the decomposition was so unimportant that the material was suitable for further service without purification.

If, however, the Dowtherm is seriously overheated, complete decomposition into carbon and hydrogen may take place. When this begins, the carbon forms as a skin on the heating surfaces of the boiler and this increases the thermal resistance, so that the decomposition is greatly accelerated. In this manner a Dowtherm boiler may be filled completely full of carbon in a few hours, though this decomposition can be avoided by correctly designed equipment working within prescribed temperature limits.

Toxicity.—Evidence shows that neither diphenyl nor diphenyl oxide is in any way toxic to human beings in any possible concentration. The odour is exceedingly pungent and penetrating even in slight concentrations, so that only low concentrations can be tolerated.

Advantages of Dowtherm as a Heat Transfer Medium.—In general the advantages of Dowtherm over other methods in the same temperature range (400–750° F.) are high rates of heat transfer, uniformity of temperature, and precision in temperature control.

Heat Transfer Coefficients. (W. L. Badger, *Ind. Eng. Chem.*, 1937, **29**, 910–12.)

The condensing of Dowtherm vapours in coils and jackets gives rise to heat transfer rates of 200–300 B.Th.U. per sq. ft. per hour per ° F.

Installation of Dowtherm Equipment.

It is to be noted that a Dowtherm system comprises usually a boiler in which the Dowtherm is heated, a pipe system to convey the Dowtherm vapour to the equipment to be heated, and a return pipe to convey the condensed Dowtherm back to the boiler.

Both diphenyl and diphenyl oxide are entirely without action on any of the common metals, hence no special difficulties arise in this respect. It is to be noted, however, that, partly because of its low viscosity, but more particularly because of its high wetting power, it is able to penetrate through leaks in gaskets and joints far more readily than ordinary liquids or gases. Hence jointing must be carried out with extreme care.

TABLE 50.

PROPERTIES OF SATURATED DOWTHERM VAPOURS

73·5 per cent Diphenyl Oxide ; 26·5 per cent. Diphenyl.

Temperature.		Pressure.		Heat Content (B.Th.U./lb.).			Spec. Heat.	Density (lb./cu. ft.).	
°F.	°C.	Lbs./sq. in Abs.	Vacuum in Hg.	Liquid.	Latent.	Total.	Liquid.	Liquid.	Vapour.
53·6	12·0	—		0·0	164	164	0·37	—	—
70·0	21·1	—	—	6·2	162	168	0·38	—	—
90·0	32·2	—	—	14·0	160	174	0·39	—	—
100·0	37·8	—	—	18·0	158	176	0·40	—	—
120·0	48·9	—	—	26·0	157	183	0·40	—	—
140·0	60·0	—	—	34·2	155	189	0·41	—	—
160·0	71·1	—	—	42·6	154	197	0·42	—	—
180·0	82·2	—	—	51·2	152·0	203	0·43	63·1	—
200·0	93·3	—	—	60·0	150	210	0·44	62·5	0·0012
220·0	104·5	—	—	69·0	148	217	0·45	61·9	0·0020
240·0	115·0	0·18	29·63	78·2	146	224	0·46	61·4	0·0034
260·0	127·0	0·30	29·39	87·7	144	232	0·48	60·8	0·0056
280·0	137·0	0·48	29·023	97·5	143	240	0·49	60·1	0·0080
300·0	149·0	0·74	28·45	108·0	142	250	0·50	59·6	0·012
350·0	177·0	1·91	26·11	133·0	138	271	0·54	58·1	0·030
400·0	204·0	4·10	21·66	162·0	134	296	0·57	56·7	0·068
450·0	232·0	7·54	14·66	192·0	129	321	0·60	55·4	0·14
			lbs. in. gauge						
500·0	258·0	14·7	0·0	222·0	123	345	0·63	54·1	0·28
550·0	288·0	27·0	12·3	253·0	117	370	0·65	52·3	0·48
600·0	315·0	44·3	29·6	288·0	110	398	0·66	50·4	0·88
650·0	343·0	68·4	53·7	323·0	104	427	0·67	48·6	1·29
700·0	371·0	104·0	89·3	358·0	97	455	0·68	46·9	1·7
750·0	399·0	150·0	135·0	393·0	89	482	0·68	44·4	2·3

CHAPTER XI.

DRYING.

WHEREAS " evaporation " may be defined as the removal of a relatively large quantity of water from solutions, the word *drying* usually refers to the removal of comparatively small amounts of water from solid or nearly solid materials, or the removal of water vapour from gases. The principal methods whereby drying is effected in the chemical industry are as follows :—

(*a*) *Vaporisation of the Water by the Application of Heat.*—This is the most common method, and typical examples are rotary dryers (wherein the drying is effected by passing hot air or flue gases over the product in counter current), compartment batch dryers, and the like.

(*b*) *Pressing out of the Water by Mechanical Pressure.*—Examples of this are found in the textile industries, where materials are squeezed by hydraulic or steam presses to remove water, or in the drying of peat by application of pressure.

(*c*) *Deposition of the Moisture as Ice or Water.*—This method is used for the drying of gases. The principle is to reduce the temperature of the gas below the dew point to deposit a proportion of the water vapour. An example of this on a very large scale is the Gayley dry blast system for the removal of water vapour from air for blast furnaces used in the smelting of iron-ores. Water may also often be separated from liquids by converting it into ice, and in this form separating it from the portion having a lower freezing point.

Naturally the amount of moisture remaining in air or gas dried by cooling depends upon the temperature to which it is cooled. In the case of a liquid the amount of water it is possible to remove also depends upon the temperature to which the liquid is cooled, but the limit is reached when a eutectic mixture remains.

(*d*) *Adsorption.*—Water is readily removed from gases by substances like activated carbon, silica gel, and activated alumina. Since these materials are used industrially for adsorption of other substances than water vapour, the whole subject of adsorption is dealt with in one chapter, and the drying of gases is dealt with therein as a special application of the principles of adsorption (see Chapter XII).

(*e*) *Absorption.*—The capillary action of certain materials is used for the removal of water in special cases, such as the removal of most of the water from the paste of clay and water in the pottery industry by placing the paste in moulds of plaster of Paris.

(*f*) *Decomposition of the Water.*—Small amounts of water may be removed in the small scale by decomposition thereof, e.g. the drying of ether by contact with metallic sodium.

(*g*) *Chemical Precipitation.*—Examples of the use of this principle are drying by passing gases over lime, phosphorus pentoxide, and calcium chloride, and in the drying of liquids in which these substances are insoluble.

In the case of the drying of such solids, the great majority of drying operations in the chemical industry are carried out by the application of heat, i.e. by vaporisation of the water, and the remainder of this chapter will be devoted to a discussion of the principles and practice of drying of solids by this method.

Many dryers operate by means of a current of heated air passing across the material to be dried. Consequently the theory of this method of drying involves consideration of the velocity, temperature, and humidity of the air, and the properties of the material being dried.

The transfer of moisture from the interior of a solid into a drying medium surrounding it involves two stages. Firstly, the moisture must diffuse through the solid, and having reached the interface between the solid and the moving stream of heated air or other drying medium the moisture must then be absorbed and carried away by this medium. Consequently there are three distinct ways in which drying is effected, and these are based upon the following reasoning :—

(1) In the first method of drying, evaporation takes place at the interface, and the main resistance to drying is the resistance to evaporation. In this case the resistance to internal diffusion is small in comparison to the resistance to evaporation.

(2) In the second type of drying, evaporation takes place at the interface and the resistance to internal diffusion is large compared with the resistance to the removal of vapour, i.e. evaporation, from the interface.

(3) In the third case the evaporation takes place before the liquid reaches the interface. The liquid diffuses to a certain point in the solid, evaporates and diffuses from that point in the vapour phase. It is then transferred to the drying medium from the interface still as vapour.

Before discussing the above cases, several equilibrium relationships must be considered. A given wet material if brought into contact with air of a definite temperature and humidity will reach a given moisture

content which will be unchanged by further exposure to the same air. This is known as the *equilibrium moisture content* of the material under the prevailing conditions. Again, if the material is drier than the equilibrium value, it will absorb water from the air until the equilibrium value is reached. Naturally the time required for the attainment of exact equilibrium conditions may be long, but nevertheless the final result is the same provided sufficient time is allowed.

The equilibrium moisture content varies widely for different materials. A non-porous insoluble solid such as quartz would have quite a small equilibrium moisture content, whereas in the case of fibrous materials such as wool and wood, these have equilibrium moisture contents which vary widely as the temperature and humidity of the surrounding air changes.

It will be readily understood that the equilibrium moisture content represents the limit to which the material may be dried so long as air of the corresponding temperature and humidity is employed. The moisture in excess of the equilibrium moisture content is known as the *free moisture* content, and this proportion of the total moisture in the material is the part amenable to removal with given conditions of air humidity and temperature.

Rate of Drying under Constant Drying Conditions.

Constant drying conditions mean that the air velocity, temperature and humidity and direction of air flow are constant during the period under review. If a material is very wet, and is dried under constant drying conditions, it will lose moisture at a constant rate until a definite point is reached, when the material has reached a *critical moisture content.* From this point the rate of loss of moisture becomes increasingly slow until the equilibrium moisture content is reached. The critical moisture content varies with the material and the conditions under which it is dried.

A typical drying curve is seen in Fig. 191 (T. K. Sherwood, "The Drying of Solids," *Ind. Eng. Chem.*, 1929, **21**, 976). The curve refers to the drying of an experimental slab of whiting by a stream of heated air under closely controlled conditions. From the curve it will be observed that the material lost moisture at a constant rate until the content was 8·3 per cent., i.e. at the critical moisture content. After this the rate decreased until 4 per cent. moisture was reached, when a further decrease in the rate of drying occurred. These three rates of drying will now be discussed in greater detail.

Drying during the Constant Rate Period.

During this period, evaporation takes place at the interface and the material is so wet that a continuous surface of water is exposed to the drying medium. Moisture diffuses through the material so rapidly

that the process is in effect the evaporation from the surface of the water.

Drying during the Falling Rate Periods.

In Fig. 191 two decreases are noted in the rate of drying, and the explanation is as follows :—

At the moment the critical moisture content is reached, although evaporation from the interface is still the controlling factor in the drying rate, the surface of the material begins to show a network of

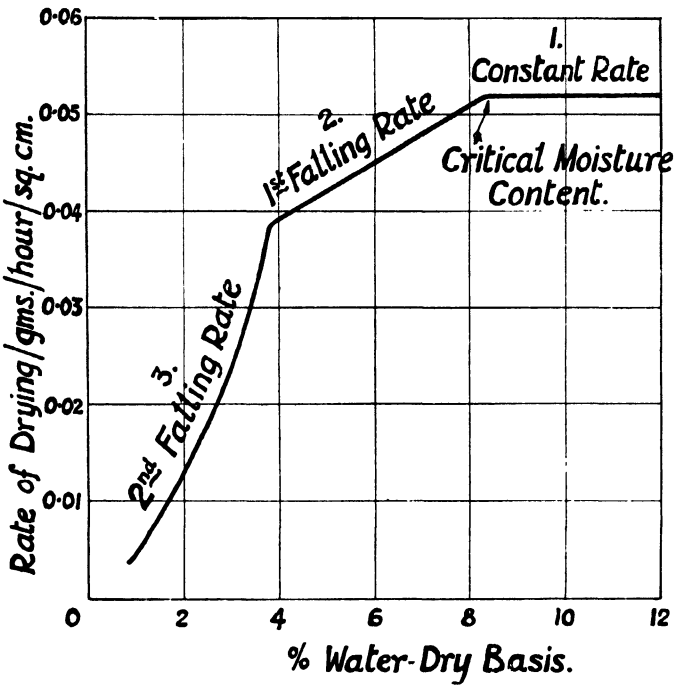


FIG. 191.—Rate of drying curve.

solid of low moisture content. Hence the effective surface of evaporation is reduced, and as the graph is drawn on a basis of rate of drying per unit area of exposed surface, the rate apparently drops.

The *second* decrease in the rate of drying is due to the control of the rate by the rate of diffusion of moisture through the material, and during this period the moisture content of the surface approaches the equilibrium moisture content.

Bearing in mind these principles governing the rate of drying, it is now possible to ascertain the *qualitative* effect of the variables of the drying process, viz. the temperature and humidity of the air, the velocity and direction of the air, and the temperature of the material.

The Humidity of the Air.

The air film flowing over the surface of the material offers a definite resistance to the flow of vapour through it, and the driving force is the difference between the humidity at the interface and that of the air stream. Thus in the drying stage when evaporation from the interface is the controlling factor, if the humidity of the air is increased, the rate of drying must decrease. This must apply during both the stages in

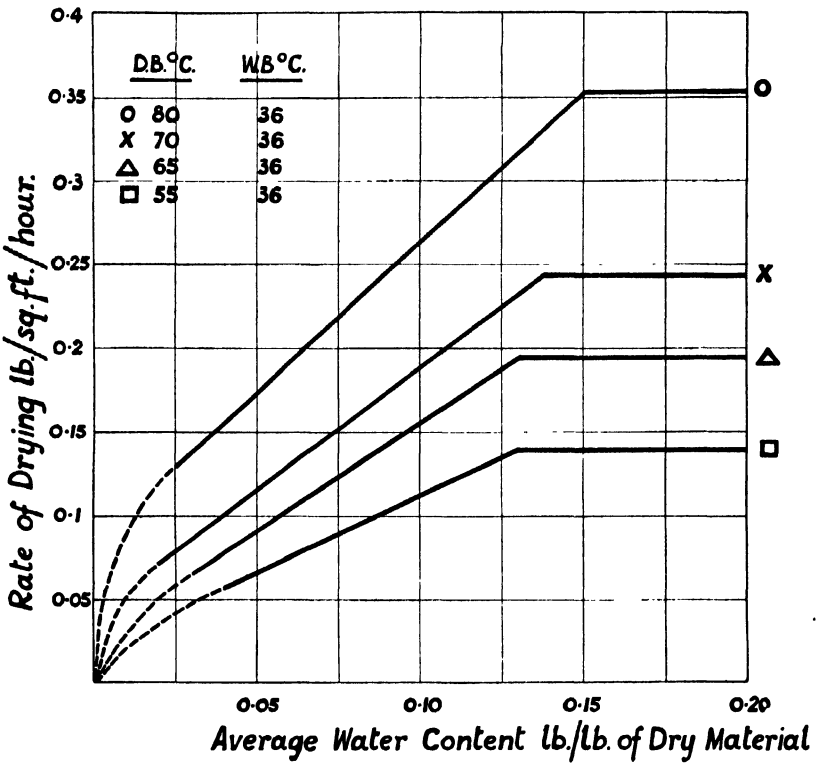


FIG. 192.

which evaporation from the interface to the controlling factor is the rate of drying. This is shown graphically in Fig. 192, which shows the rate-of-drying curves of the drying of asbestos (McCready & McCabe, *Trans. Amer. Inst. Chem. Eng.*, 1933, **29**, 131). The relative humidity of the drying air was changed, while all other variables including the wet bulb temperature of the air were kept constant. When, however, the diffusion rate through the material becomes important, the humidity of the air will not have the same effect and the rate of drying will be more independent of the air humidity.

Effect of Velocity of Air across the Material.

A little consideration will show that the velocity of air across the material will increase the drying rate through the first two phases, but will have much less influence upon the drying rate when diffusion becomes the controlling factor.

The Direction of the Air Stream.

If the direction of the air flow is parallel to the drying surface consideration will show that the rate of drying will be less than if the air flows perpendicularly to the material, but when diffusion of moisture through the material becomes of importance the air direction is not very material.

Temperature of the Material.

During the stage of drying when evaporation from the interface is important, an increase of temperature of the material will naturally increase the rate of drying. Also the rate of diffusion of the moisture through the material will also increase because of reduced viscosity.

Skin Effects.

Many materials suffer a decrease in volume as their moisture content is reduced, and this may have undesirable effects. Firstly, in the case of colloidal materials, the surface layer may shrink and produce a hard skin which is impenetrable to the moisture in the remaining bulk of the material. Secondly, some materials may become warped and stressed in the drying process, and to avoid these effects it is necessary to control both the humidity and temperature of the air stream to give optimum drying conditions.

Summary.—To sum up the foregoing discussion of the fundamentals of drying for practical purposes of design, it is to be noted that the rate of drying is in general proportional to the surface exposed, the difference in temperature between the drying medium and the material being dried, the relative humidity of the drying medium, and the velocity of the drying medium over the material being dried. In addition, the rate of drying depends upon the *turbulence* of the drying medium in the region of the material, and this aspect is of prime importance in practical commercial dryers.

Any practical solution of a particular drying problem will be a compromise between the necessity to give effect to the foregoing requirements and considerations of expenditure of energy, and naturally the best solution will be the one giving the least cost of drying, taking every factor into consideration, i.e. initial cost of

apparatus and accessories, power, energy and labour requirements, cost of maintenance and repairs, and quality of product.

Note.—Since dewatering is much more economically carried out in hydro-extractors (or centrifugals), filter presses, screens, etc., advantage should always be taken of such mechanical appliances before the material is subject to thermal drying.

Obtaining Maximum Surface exposed to Drying Medium.

The surface exposed to the drying medium may be increased in various ways, such as spreading the material on trays, by agitation, by drying the material in the form of a finely divided spray as in spray drying, or in film form as in drum drying. The creation of the maxi-

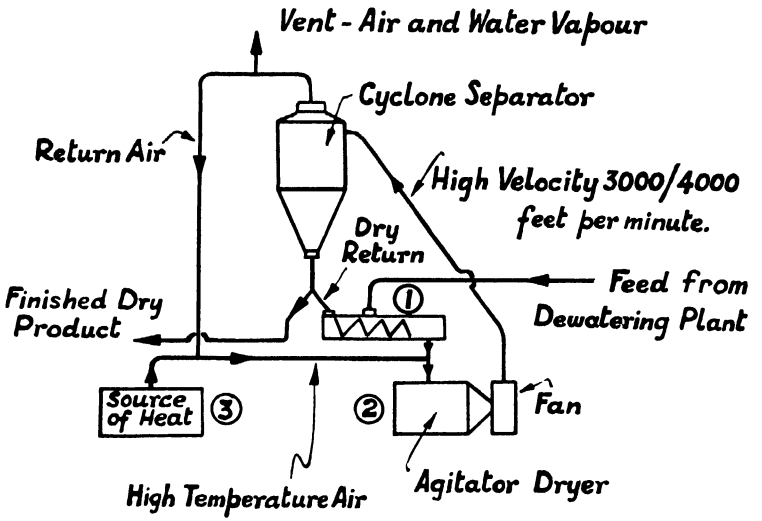


FIG. 193.—Diagrammatic sketch of flash dryer installation.

mum amount of drying surface has two important beneficial effects, in that it increases the area from which moisture may be liberated and also reduces the distance through which the moisture must travel by diffusion. Agitation of the material within the stream of drying air naturally reduces the inert vapour film on the surface of the material and brings a greater quantity of drying air into contact with the material in a given time.

The following description is of a type of drying equipment in which all the principles of efficient drying have been incorporated. It is known as a "flash dryer," and the particular example quoted is apparatus made by the Raymond Company. (See Fig. 193.) (Richard F. O'Mara, *Chem. Met. Eng.*, 1936, **43**, 186.)

Wet material is first dewatered mechanically and then mixed with some of the previously dried material to spread the moisture over as

great an area as possible (i.e. increasing the drying surface). This mixing is carried out in (1), and the material then passes to the agitating chamber (2), where it is dried under conditions of high turbulence by the heated air from the heater (3). The material, suspended in the hot air stream, is sent to the cyclone separator, from which point some air is recirculated and a little of the material sent back through the mixer (1) for mixing with the fresh incoming material. Normally the material is only in the plant for a few seconds, and the following table gives particulars of typical materials handled by such apparatus (Table 51). By the addition of suitable classifying devices such as screens or mechanical air separation, such dryers are capable of producing material of a desired particle size, so that the appliance serves as a dryer and light grinder.

TABLE 51.

Material.	Dewatered by	Per cent. Moisture entering Dryer.	Per cent. Moisture leaving Dryer.
Chlorine powder	Filter	—	—
Chrome green	Leaf filter	25	0·1
Clay (acid treated)	Filter	60	8
Cooked blood	Press	80	5
Copper sulphate	Hydro ext.	—	monohydrate
Gypsum	—	20–22	4–5
Milk albumin	—	50–60	5–6
Orange pulp	Press	82	4–10
Sodium sulphite	Hydro ext.	50–52	0–0·1
Starch	Filter	42	7
Synthetic casein	Filter	80	7
Tannins	Filter	60	3
Waste yeast	Leaf filter	60	5

Notes on Considerations Affecting the Choice of Suitable Industrial Drying Equipment, using the Evaporation Method.

Apart from considerations of thermal and mechanical efficiency, the number of factors governing the practical design of dryers is probably greater than in any other type of process plant. In making the final choice of drying equipment, the following aspects must be often regarded as far more important than even mechanical or thermal efficiency.

(1) *Permissible Working Temperature.*—Some materials are not heat sensitive and can be dried at high temperature without ill effects, whereas others are so sensitive that quick drying under high vacuum is essential.

(2) *Contamination.*—According to the degree of purity desired, the treatment falls into one of three general classes : direct fire or flue-gas contact, filtered hot air as the drying agent, and a treatment under vacuum in closed apparatus.

(3) *Handling.*—Most products permit of ready handling without involving serious loss by powdering and dusting. There are, however, numerous exceptions to this, when great care must be exercised to avoid change of crystalline structure or cause loss of product by excessive dusting. In a few cases there is the problem of avoiding explosive dust formation, and the danger of ignition by discharge of static electricity.

(4) *Materials of Construction.*—The choice of suitable materials depends upon the nature of the material to be handled, and the working conditions. Naturally, special requirements in the way of drying conditions often necessitate the use of special materials of construction.

Classification of Dryers Operating by the Application of Heat.

A rough classification based on the method of removing the moisture after evaporation would divide the majority of commercial dryers into two groups, i.e. (1) dryers in which the moisture is carried away by the drying medium such as air or flue gases, or (2) dryers wherein the moisture is removed by condensation in a separate condenser.

A more complete classification would be as follows, based upon the kind of material to be dried.

(*a*) *Granular or Loose Materials* are dried usually in a form of rotary drier which may be designed for either atmospheric or vacuum, with direct or indirect heating.

(*b*) *Pastes or Sludges* are dried by agitator batch, or continuous flash dryers, the former working either at atmospheric or reduced pressure, the latter at atmospheric pressure.

(*c*) *Materials in solution or fine suspension* are dried by atmospheric or vacuum drum dryers, or spray dryers.

(*d*) *Material on trays or on conveyors* dried either in cabinet dryers of the atmospheric or vacuum type or continuous conveyor or tray dryers.

Typical designs of each of the above classifications are as follows :—

Rotary Driers for Granular or Loose Material.

In the simplest form rotary dryers consist of a slightly sloping cylinder open at both ends and supported on rollers so that it may revolve freely. The material is fed into the upper end, and hot air or products of combustion of coal or other fuel are sent in at the lower end.

A typical air-heated rotary drier is seen in Fig. 194. Air is heated by means of the steam battery shown, passes up the enclosed rotary

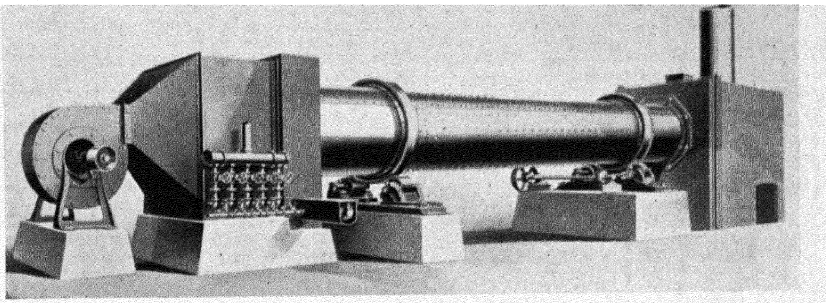


FIG. 194.—Rotary dryer by the C. O. Bartlett & Snow Co., Ltd.

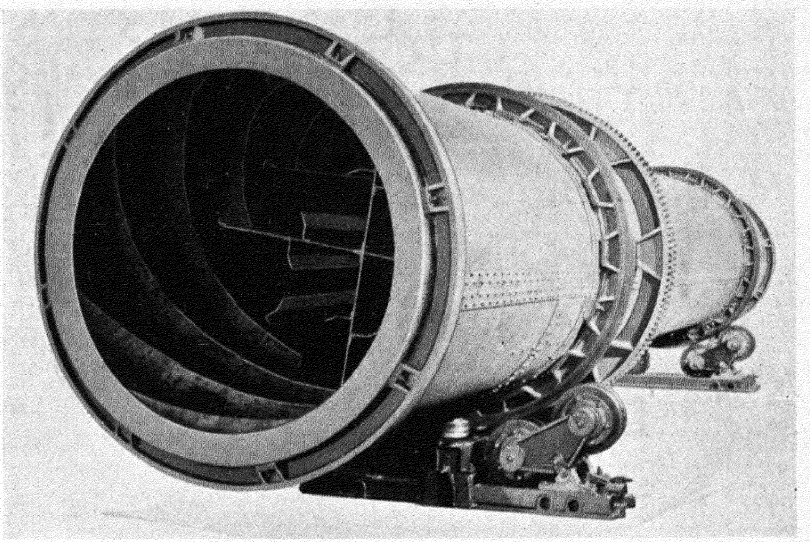


FIG. 195.—Interior view of a typical rotary dryer.

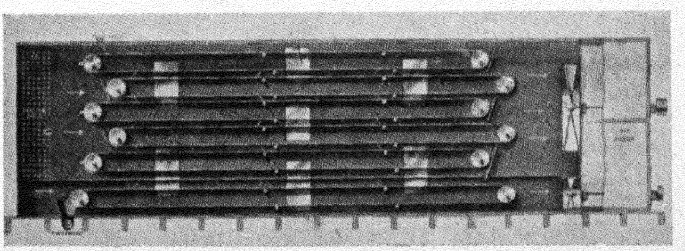


FIG. 198.—Continuous band drying machine for spices, pepper and similar materials by L. A. Mitchell, Ltd., Manchester.

[*See page* 416.

[*To face page* 410.

dryer and is exhausted through the chimney in the brickwork setting. The material to be dried is passed down the inclined cylinder and is removed by the worm-gear seen adjacent to the steam-heating battery. Care is taken to seal the ends of the cylinder, and in the feed and discharge arrangements to prevent any leakage losses. An interior view of a typical cylinder is seen in Fig. 198, and it clearly shows the louvres fitted to ensure good agitation of the material within the air stream.

Such dryers may be heated by flue gases with either direct or indirect heating arrangements. An example of the former method, where contact of flue gases with the material is unimportant, is seen in Fig. 196. The dryer is heated by an external furnace with connecting flues built round the cylinder. The products of combustion pass externally around the dryer, being drawn from the furnace by a

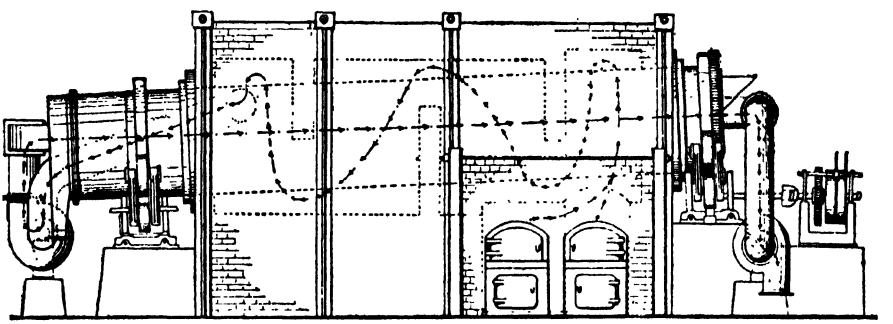


FIG. 196.—Rotary dryer by Manlove Alliott & Co., Ltd.

fan, then travel through the interior in the opposite direction to that in which the material travels, and are finally discharged by a second fan to the atmosphere.

I am indebted to the C. O. Bartlett & Snow Company for the following interesting preliminary survey of the drying of ammonium chloride for a client who gave the following particulars for estimating purposes :—

Material	Ammonium chloride crystals
Moisture	6 per cent. initial and 0·15 per cent. final
Capacity	6500 lbs. of product per hr.
Maximum material temperature	200° F.
Source of heat	Steam available at 80 to 100 lbs. per sq. in. gauge
Material particle size	$\frac{1}{8}$ in. to 3 ins. in diameter, with 5 per cent. being through 30 mesh
Material of construction	Material contacting surfaces to be of rubber or 18–8 stainless steel.

In arriving at a final choice of type and size of dryer for this particular problem, there are several factors to be anticipated and given

consideration. Those factors exerting a major influence on the final results are :—

1. Capacity.
2. Temperature restrictions.
3. Velocity restrictions on the warm air.
4. Sufficient time of passage through the dryer.
5. Advantages of using stainless steel construction over rubber or vice versa.

(1) The capacity of 6500 lbs. per hr. of dry product when drying from 6 per cent. moisture does not result in an excessively high hourly heat requirement. However, the restrictions that are necessarily placed upon the operating conditions result in a larger dryer than would ordinarily be required.

(2) A maximum permissible crystal temperature of 200° F. definitely restricts the temperature of the drying air, and to satisfy a given net heat requirement when using comparatively low-temperature air it will obviously be necessary to pass a greater weight of air through the dryer than would be required if higher air temperatures were used. In considering the use of rubber lining, the temperature restrictions become more exacting and the necessity for passing a greater weight of low-temperature air through the dryer is increased.

(3) Since it will be necessary to pass the relatively large weight of comparatively low temperature air through the dryer at a velocity that will not tend to create an excessive dust loss or nuisance, it follows that the cross-section of the dryer cylinder must be such that it will result in a low linear velocity of air and still afford adequate heat transfer to satisfy the heat requirements. It is therefore necessary to determine the proper velocity that would obtain for the required diameter and length of dryer under the temperature drop of the air that would be necessary to produce adequate heating. If all the crystals were of a size of $\frac{1}{8}$ in. to 3 ins., the permissible velocity would be quite high. However, 5 per cent. is through 30 mesh and there will be some productions of fines, due to the dryer action. Therefore, it is not good practice to base velocity considerations on a $\frac{1}{8}$-in. minimum size. The permissible air velocity is a function of specific gravity, particle size and shape. For crystals of ammonium chloride the maximum velocity of air to avoid carrying out 60-mesh material is 228 ft. per min. For the purpose of determining the recommended dryer sizes, the *average* velocity of air through the dryer has been arranged to be a little under 220 ft. per min. It would be good practice, however, to use a cyclone dust collector in conjunction with the dryer, since the 5 per cent. through 30 mesh implies that there may be some crystals of 100 to 200 mesh or smaller.

(4) The length of time required to reduce the moisture of the crystals is dependent upon

(i) the initial and final moisture content;
(ii) the thermal head available in the dryer;
(iii) the physical properties of the material in regard to the ease with which the moisture may be removed.

After having established the proper length of time of passage, it is necessary to operate the dryer at the speed and slope that will convey the material through the dryer at the desired rate.

(5) The choice between rubber and stainless steel as materials of construction involves consideration of the advantages that one or other of these materials has from a corrosion-resistant or contamination standpoint and the economics involved in the cost of a dryer fabricated with each of these materials.

The use of a rubber-lined construction limits the available thermal head to a greater extent than would be experienced if the only temperature restriction was that of the 200° F. maximum crystal temperature. Manufacturers of hard rubber linings have indicated that a maximum air temperature of 210° F. would be permitted on the rubber (American Hard Rubber Company). It is possible to utilise air of an inlet temperature of 250° F. if a stainless steel construction is used, without exceeding the 200° F. crystal temperature. Accordingly, it is clear that the dryer incorporating the rubber lining must be of a larger diameter than one in which a stainless steel is used.

Apart from the difference in diameters and lengths of the two dryers, the general arrangement and type would be the same for either the rubber-lined or the stainless dryer.

The type of dryer recommended is the Bartlett-Snow Style J Dryer (see Fig. 194), in which the material to be dried and warm air pass in counter direction. Air of room temperature is drawn through steam-heating coils at the discharge end of the dryer. Adequate draught and velocity of air through the dryer is obtained by means of an induced draught fan at the feed end of the dryer. The spent air and vapours which are drawn through the cylinder are sent into a cyclone dust collector.

Anticipated Performance of this Rotary Dryer.

The following data is offered as a comparison of the rubber-lined dryer and stainless lined dryer :—

Dryer :—	*Rubber lined.*	*Stainless.*
Diameter of cylinder	84 ins.	72 ins.
Cylinder length	45 ft.	36 ft. 6 ins.
Speed of rotation	2·8 r.p.m.	3 r.p.m.
Slope	¼ in. per ft.	¼ in. per ft.
Time of passage of material	45 mins.	40 mins.

Capacity, same for both dryers :—		
Feed per hour at 6% H_2O		6908 lbs.
Discharge per hour at 0·1 per cent. H_2O		6500 „
Moisture removed per hour		409 „
Temperatures :—	*Rubber lined.*	*Stainless.*
Air entering steam heater	60° F.	60° F.
Air leaving heater and entering dryer	210° F.	250° F.
Air leaving dryer	110° F.	120° F.
Log mean air temperature	154° F.	177° F.
Material temperature entering dryer	60° F.	60° F.
Material temperature leaving dryer	170° F.	170° F.
Velocities :—		
Air through heater (face velocity)	300 f.p.m.	300 f.p.m.
Air entering dryer cylinder	224 „	245 „
Air leaving dryer cylinder	190 „	200 „
Velocity of air at log mean temperature	205 „	220 „
Draught Requirements :-		
Total estimated head on fan, including necessary head for cyclone dust collector and heater resistance	1⅛ in. water	1⅛ in. water
Fan duty, including leakage	7200 c.f.m.	6000 c.f.m.
Power Requirements (Motor Horsepower) :—		
Dryer drive	7½ b.h.p.	5 b.h.p.
Fan drive	3 h.p.	3 h.p.
Steam Consumption :—		
Steam pressure (gauge)	50 lbs.	80 lbs.
Pounds steam per hr.	1300	1250

Fuel Requirements of Rotary Dryers.

Regarding fuel consumption of rotary dryers, the steam consumption of the steam-heated type varies between 2–5 lbs. of steam per lb. of water removed. Much depends upon the type of material being dried and the temperature range involved.

In the case of fire-heated rotary dryers, 6–8 lbs. of water removed per lb. of fuel has been achieved, but average figures are about 4½–5½ lbs. of water per lb. fuel.

Vertical Continuous Dryers for Granular Loose Materials.

Figs. 197–197A show an interesting form of vertical continuous dryer by Huntington, Heberlein & Co., Ltd. It is suitable for a wide variety of materials such as coal, ores, rock and stone products, brewers' grains and maize. The principle of operation is as follows (Fig. 197). The raw material is fed into the boot (1) of an elevator (2), which conveys it to the feed hopper (9) of the dryer. From this hopper the material is fed through a worm conveyor or star feeder on to a horizontal shelf (see Fig. 197A) on which work a series of rabble arms (4) which gradually push the material inwards until it is dis-

charged gently down a central cone on to the shelf below. Here the rabble blades work in the opposite direction and push the material outwards until it falls over the edge of the shelf on to the one below, and so on through the dryer, the material moving alternately inwards and outwards on successive shelves.

The material descending through the body of the dryer (4) (Fig. 197), meets in its passage a current of hot gas generated in the combined furnace and air heater (5). This hot gas is drawn through the dryer by way of the pipe (6) by means of the exhausting fan (3), and the moist gases pass through the fan into a cyclone separator (10) in which

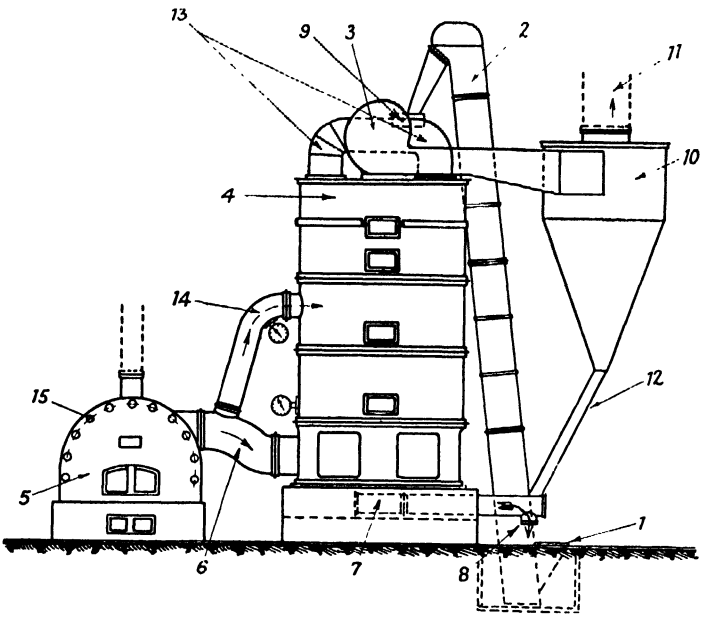


FIG. 197.—Vertical continuous dryer by Huntington, Heberlein & Co., Ltd.

any dust is separated out and the clean waste gas is discharged to the atmosphere through the stack (11). The dust collected in the cyclone is perfectly dry, as the temperature in the cyclone is kept above the dew point of the gases and accordingly the dust can be returned to the discharge worm (7), which conveys the dried material to the discharge spout (8), from which it can be bagged off or transported away by other means. The discharge chute from the cyclone to the dried material discharge worm is indicated by (12). The moisture-laden gases are drawn off from the body of the dryer by means of the twin branch pipes (13).

Sometimes it is necessary to put through the dryer very wet material, in which case it may be found that moisture driven off in the lower parts of the dryer commences to condense in the upper

sections of the machine. In such cases, the bleeder pipe (14) is made use of. A damper in this pipe is opened and fresh hot gases are admitted to the upper sections of the dryer in order to help to drive off any moisture that might tend to deposit there.

A continuous band dryer wherein all the bands conveying the material to be dried are within the airstream is seen in Fig. 198. It

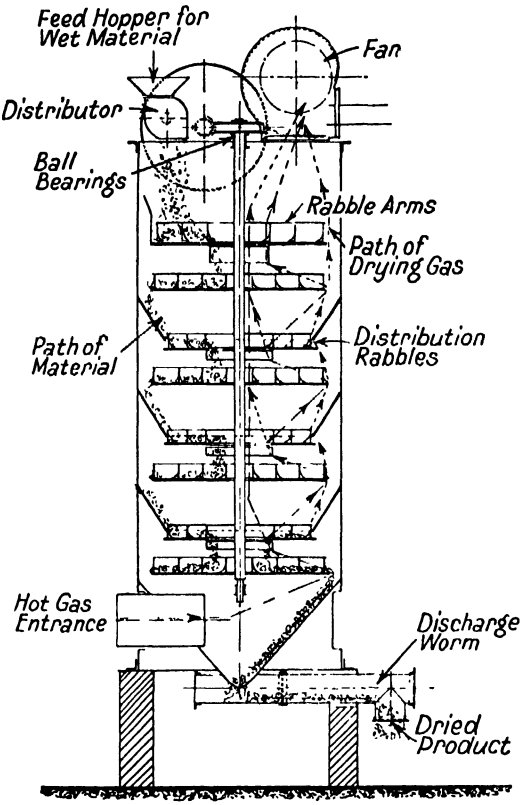


FIG. 197A.—Section through vertical continuous dryer by Huntington, Heberlein & Co., Ltd.

is specially designed for the drying of spices and the like, and is supplied with filtered and heated air.

Spray Dryers.

The principle of spray drying is the atomising or breaking up of the liquid into a fine degree of subdivision and bringing it into intimate and uniform contact with the heated air, which is almost universally adopted as the drying medium. The dried product in well-designed equipment is removed from the air stream in a practically dry condition.

It is again important to remove as much water as practicable by mechanical dewatering, and also in the case of spray drying by preliminary evaporation in efficient evaporating plant.

The early spray, drying plants used high-pressure nozzles for obtaining the spray, and frequently pressures up to 3000 lbs. per sq. in. were used. Latterly it has become the practice to secure the spray by means of centrifugal dispersion.

Spray Drying Chamber.

A chamber developed by the Kestner Evaporator & Engineering Co., Ltd., is seen in Fig. 199. The liquid is sprayed by being forced on to the surface of the conical centrifugal atomiser shown in the centre of the upper portion of the chamber, and the heated air is sent into the chamber in three streams, A B B. The method of entry of the air is so arranged that it is given a centrifugal or whirling action, so that the atomised liquid is in contact with the air for the longest possible time before it touches the sides of the chamber. The air outlet is through C and D, and the dried powder is withdrawn at E.

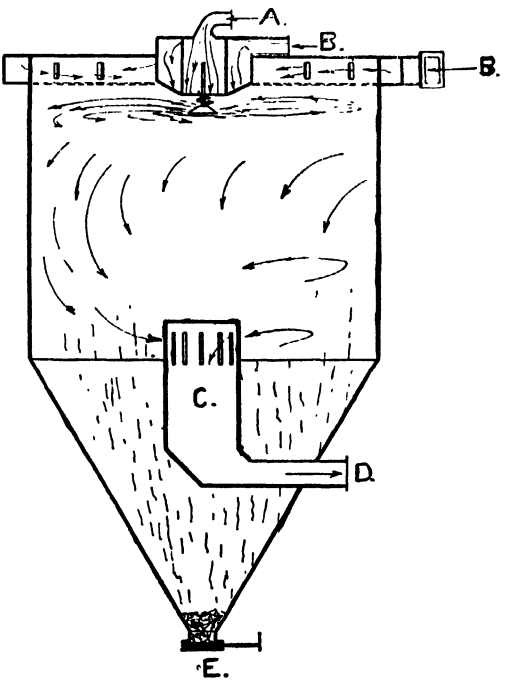


FIG. 199.—Spray drying chamber by the Kestner Evaporator & Engineering Co., Ltd.

There is naturally a tendency for some of the dried powder to be entrained by the air leaving the chamber, but this is recovered by passing the air through a separator or by washing the air with the incoming liquid. In some cases products of combustion can be used as the heating medium, but more frequently air, heated by steam batteries, is used. Some of the more important products dried by means of spray drying are :— milk and milk products, malt, yeast and vegetable extracts, precipitated chalk, magnesium sulphate and carbonate, sodium fluoride, sulphite, phosphate, acetate, silicate.

A complete spray drying plant is seen in Fig. 200. In this case the air is heated by means of the Merrill patent oil system, which comprises

a heat absorber, a circulating pump and the vessels to which heat is supplied.

The pump circulates the heating medium, which is a special grade oil, through the absorber, where the heat generated in the furnace, which may be either oil, gas, or coal fired, is absorbed, and thence through suitably designed pipe lines to a heater shown in Fig. 200.

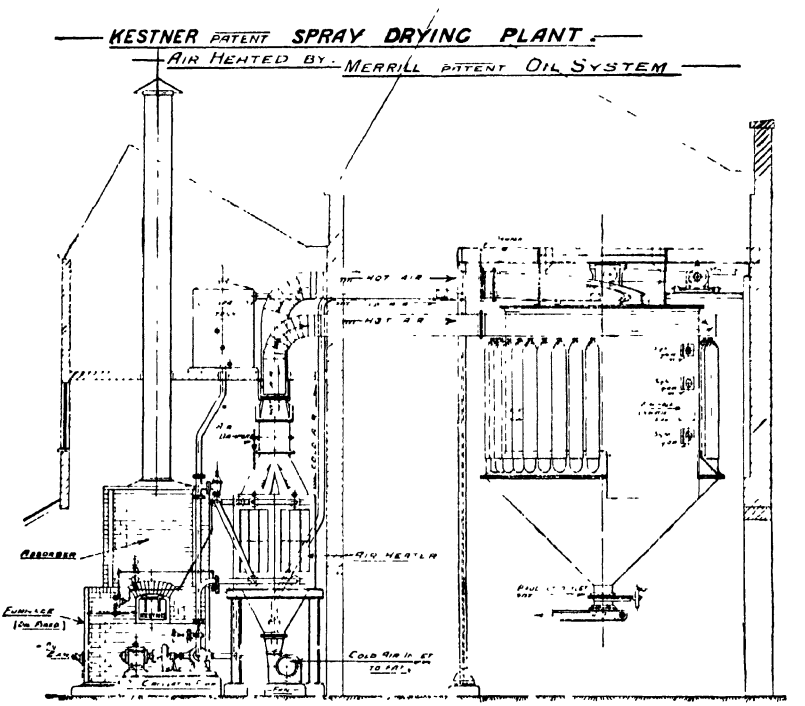


FIG. 200.—Complete spray drying plant.

Special Note.—In the case of dryers using a stream of heated air, in many cases the supply of air is taken in at ordinary temperature, and is heated usually by steam coils, to a predetermined temperature. If all the air which has been sent through the dryer is rejected to atmosphere at its final temperature, a larger quantity of heat is necessary than if some of the air leaving the dryer were recirculated with make-up air, the mixture being so arranged that the humidity is not increased beyond a point when drying would be retarded. This principle is used in many commercial dryers, and in addition in large installations it is desirable to fit heat interchange units, whereby some of the heat of the rejected air may be absorbed by the entering make-up air.

Agitator Batch Dryers.

One of the simplest machines of the type is seen in Fig. 201. It

is a steam-heated dryer with steam-jacketed flat bottom and sides and provided with agitator gear which is driven through heavy bevel gearing. This class of machine is manufactured especially for manure,

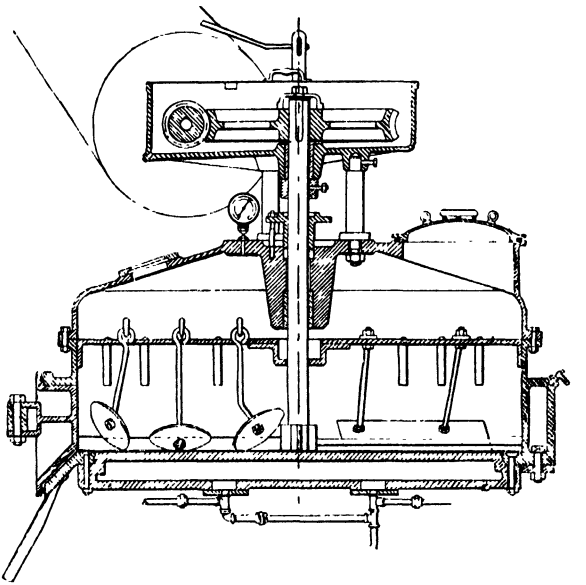


FIG. 201.—Steam-heated agitator batch dryer (Manlove Alliott).

sludges, pastes and granular substances. The special advantages of this type are simplicity of operation, and the ease with which it can

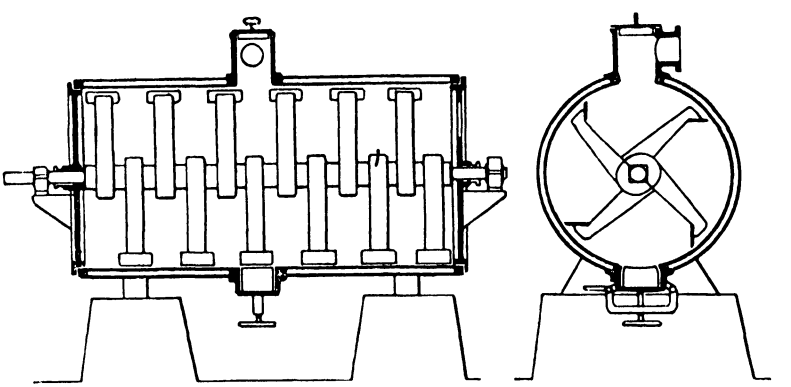


FIG. 202.—Steam-jacketed agitator batch dryer.

be charged and discharged, the latter by a hinged door provided in the flat bottom. The type shown is arranged for vacuum operation.

Such machines can also be arranged for heating by solid fuel or oil where steam is not available. E. A. Alliott (*Jour. Soc. Chem. Ind.*, July, 1919) gives interesting data about machines of this class. For

example, an 8-ft. diameter machine would handle per batch 18 cwt. of crystalline material and reduce the moisture from 4 per cent. to below 0·5 per cent. in two and a half hours, including time required for charging and discharging. For an 8′ 0″ dia. machine the speed of agitator is about 7 r.p.m. and the power about 7 h.p.

Variations of this type of machine are seen in Figs. 202 and 203. These also can be arranged for vacuum operation if required.

A large-capacity vacuum steam-heated batch dryer by W. J. Fraser & Co., Ltd., of Dagenham, is seen in Fig. 204. It is suitable for the vacuum drying of a wide variety of products, including white lead, shellac, pastes, and the like. A totally enclosed worm dryer operates a powerful stirring gear so arranged that slow speed of stirring

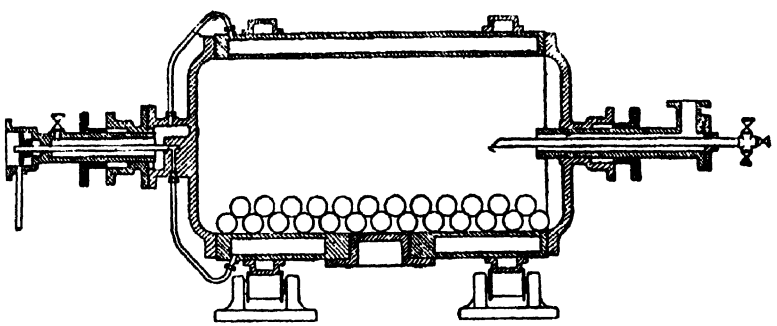


Fig. 203.—Steam-jacketed agitator revolving batch dryer.

can be obtained when the product becomes stiffer during drying. One or more large diameter doors permit of rapid charging and discharging. The plant is fitted with surface condenser and dry vacuum pump.

Drum Dryers.

The process of drum drying consists of applying liquid materials to a revolving steam-heated drum or drums, by which the moisture is removed by evaporation and the dry material is then removed by means of a knife or scraper. This principle applies to all drum dryers, both atmospheric and vacuum types. Various feeding methods are adopted, naturally depending upon the material to be handled.

Single drum dryers are chiefly used for the drying of sticky materials and slurries. The twin drum dryer is often used for dilute liquors, in which case the liquid is boiled between the drums and is thereby concentrated. This improves the coating adhering to the drum surface.

The drums are usually made of close-grain alloy cast-iron, but when corrosive conditions are present the drums can be chromium plated, or made of bronze, stainless steel, etc.

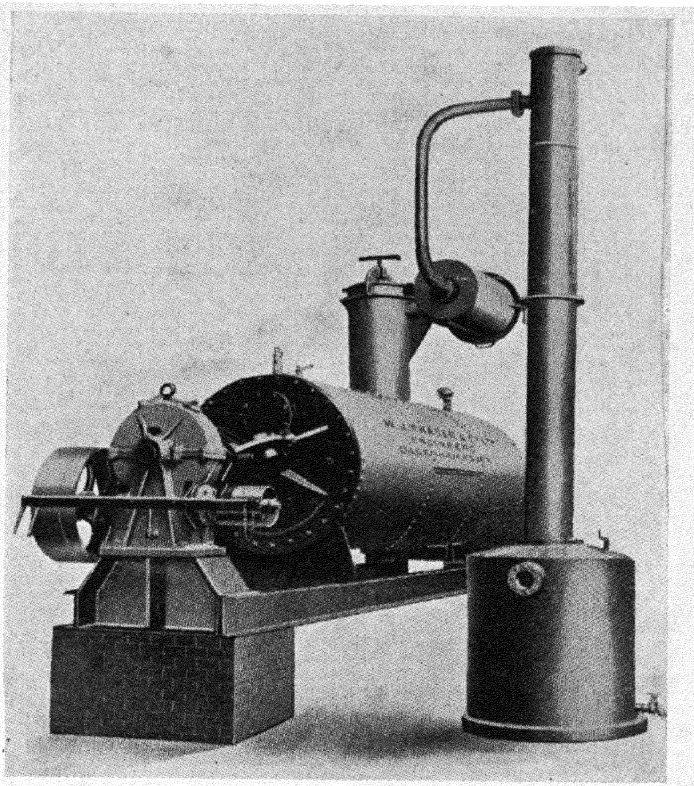


FIG. 204.—Horizontal steam-jacketed vacuum batch dryer by W. J. Fraser & Co., Ltd.

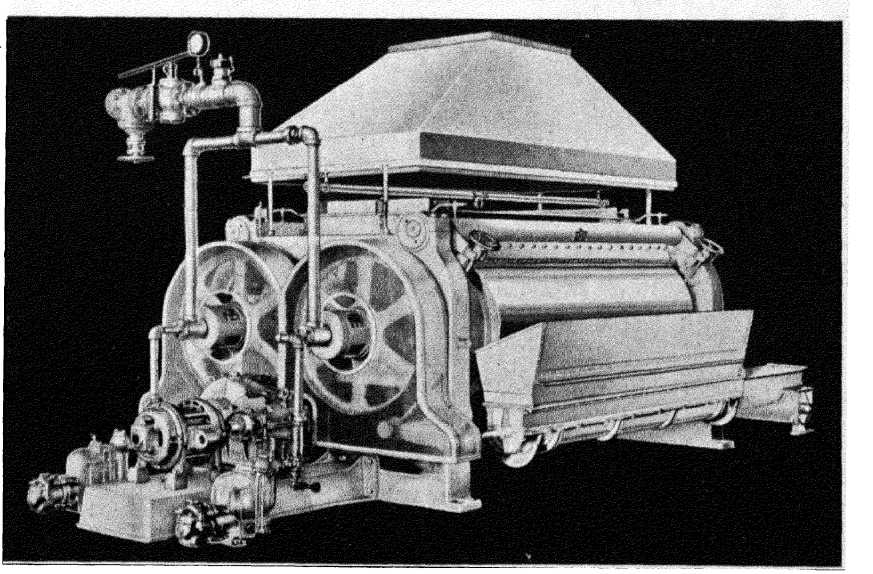


FIG. 205.—Twin-drum dryer.

[*To face page* 420.

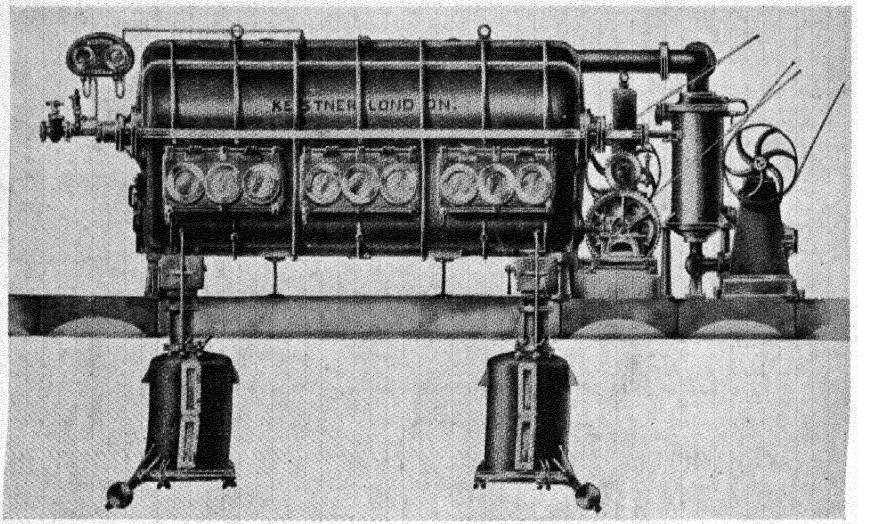


FIG. 206.—Kestner vacuum type drum dryer.

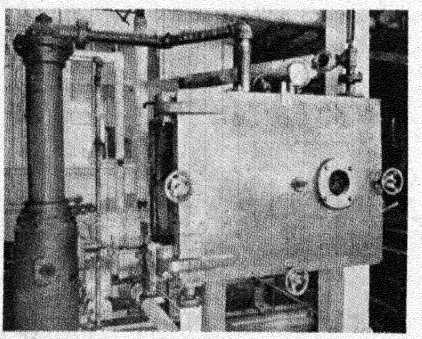


FIG. 207.—Vacuum batch dryer—shelf type—with surface condenser by the Buffalo Foundry & Machine Co., Ltd.

[*To face page* 421.

A double drum dryer by the Buffalo Foundry & Machine Company is shown in Fig. 205. The drums are 42 ins. diameter × 90 ins. long.

Where heat-sensitive liquids are to be handled, vacuum drum dryers are used. Vacuum drum dryers are frequently used in the drying of food products, both to maintain a low temperature and to prevent atmospheric contamination. One made by the Kestner Evaporator & Engineering Co., Ltd., is seen in Fig. 206.

With this type the drum is completely encased in a cast-iron shell in which a vacuum is maintained. The product to be dried is fed into the feed tray and, on being removed from the drum, falls down into a trough containing a screw conveyor, which discharges it into either of two vacuum receivers which are filled alternately. Immediately one receiver is filled the valve to the other is opened and the gears reversed. Then the first receiver is shut off by its valve and opened to atmosphere, and the bottom door operated so that the product can fall into the required receptacle, or on to a conveyor, to pass to other parts of the works. This method is very simple, and makes the continuous operation of the dryer possible.

The vapour leaving the dryer casing is carried either to a surface or a jet condenser, depending upon the requirements of the installation.

Vacuum Shelf or Compartment Dryers.

Dryers of this type usually comprise a cast iron or steel square chamber with quick release door. Trays are fitted within the chamber to hold the material, and each tray is usually fitted with a steam jacket for heating purpose. The vacuum is obtained by a dry vacuum pump working in conjunction with a surface condenser. Fig. 207 shows a typical vacuum shelf dryer by the Buffalo Foundry & Machine Co., Ltd.

CHAPTER XII

ADSORPTION

DURING recent years, both liquid phase and vapour phase adsorption processes have been increasingly employed in many branches of chemical technology, particularly in the recovery of solvents, and the drying of air and gases.

The physical phenomena known as " sorption " or " adsorption " are highly complex in character, and as yet no single explanation covers all the facts. The majority of the industrially important applications, however, can be satisfactorily explained by what is generally regarded as the theory of capillary condensation. The following notes are taken from a theoretical paper by Griffiths (*Journ. Inst. Fuel*, June 1935), and although the subject is dealt with from the point of view of activated carbon, yet most of the matter applies equally well to other industrially important adsorption materials including silica gel and activated alumina.

Adsorptive or Activated Carbon.

This material may be regarded as one having an unusually high surface development with countless numbers of very fine capillaries with a vast area in proportion to the bulk. It is estimated that one cubic centimetre of active carbon may contain pores having a total wall or surface area of 600 square metres. The process of manufacture of activated carbon is directed to the production of a pore structure best adapted to particular requirements. The technique of manufacture has now been so much improved that the makers are not only able to secure a large capillary development but to arrange some measure of control over the distribution of capillary sizes.

Capillary Condensation Theory.—Consider the system shown in the diagram (Fig. 208). If it is assumed that the meniscus at A is a hemisphere the pressure on the convex side must be less than the pressure on the concave side by $\frac{2s}{r}$ where r = radius of tube and s = surface tension. Also the difference in the vapour pressures (dp) above the surfaces B and A is

$$dp = \frac{h}{V} \text{ where V = spec. vol. of vapour}$$

$$= \frac{2vs}{Vr} \text{ where } v = \text{spec. vol. of liquid}$$

Note that V will vary over the height h.

$$\int \frac{dp}{p} = \frac{2vs}{\mathrm{RT}r}$$

$$\log_e \frac{p}{p_s} = \frac{-2vs}{\mathrm{RT}r}$$

where p = vapour pressure at curved surface in tube
p_s = vapour pressure at plane surface
s = surface tension
v = mol. vol. of condensed liquid
R = gas constant ($8{\cdot}315 \times 10^7$ ergs.)
T = abs. temp.
r = radius of capillarity.

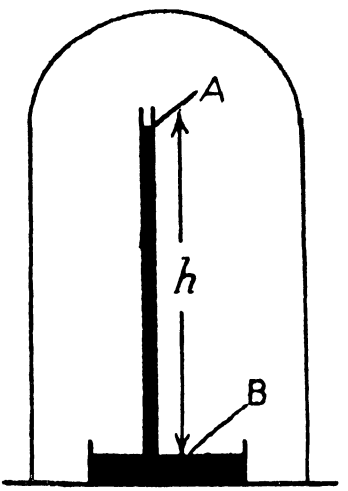


FIG. 208.

From this it is possible to calculate the maximum effective pore size which would be operative in say adsorbing benzene from a gas with a concentration of 32 gm. per m.^{3}, corresponding to one-tenth saturation at 20° C.

Substituting in above equation,

$$\log_e \frac{p}{p_s} = 2{\cdot}303 \log_{10} \frac{1}{10} = \frac{2 \times 29 \times 89{\cdot}7 \times 293}{r \times 8{\cdot}317 \times 10^7}$$

whence $2r = 1{\cdot}86\ \mu\mu$.

Consideration of the data obtained from discussion of Fig. 208 will clarify the reasons for the difference in vapour pressure produced by a capillary, and it is to be noted that the vapour pressure at the surface of the liquid in the capillary is less than that at the plane surface by a pressure equivalent to the height of the vapour column.

If this were not so, distillation would take place continuously and this would be equivalent to perpetual motion.

On the basis of the above considerations, the theoretical diameter of capillary required to produce certain effects can be calculated. In the calculation on page 423, to illustrate Fig. 208, an estimate was made of the maximum size of capillary which would come into action when activated carbon say is in equilibrium with air containing benzene vapour at a partial pressure corresponding to one-tenth saturation. If the concentration of benzene was less than this, only smaller capillaries would come into action, and by applying the same method of calculation over a range of concentrations a relationship can be obtained giving particulars of the maximum size of capillary which would be

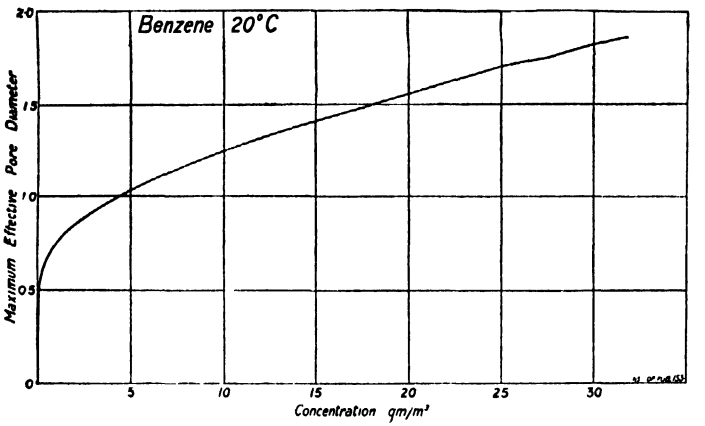


FIG. 209.—Curve showing relationship between capillary sizes and concentration.

effective at various concentrations of benzene. This is shown graphically in Fig. 209. In practice it is found that activated carbon behaves closely in accordance with the above reasoning.

Mechanism of Adsorption.—Some of the more important of adsorptive materials may be expressed graphically by the Freundlich exponential isotherm. It is usual to plot this on ordinary squared paper, but for many purposes it is better to plot on logarithmic paper. Fig. 210 shows both methods of plotting.

From these isotherms (Fig. 210) it is possible to derive the volume of capillaries of each size in the adsorptive structures. The results of such an analysis for two samples of activated carbon, one of silica gel and one of activated bleaching earth, are given in Fig. 211.

The foregoing theoretical treatment permits of the visualisation of adsorptive carbon. From the adsorption isotherms certain maximum pore sizes have been calculated which will come into operation when the

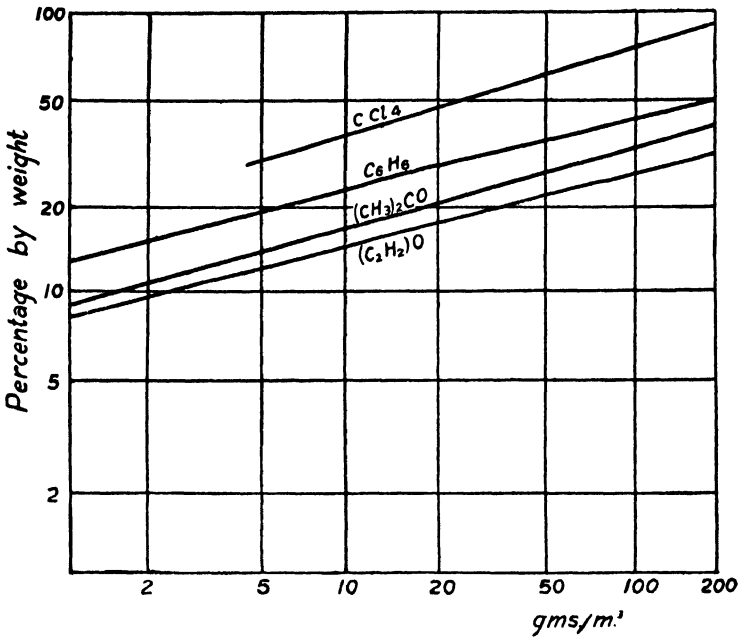


FIG. 210.

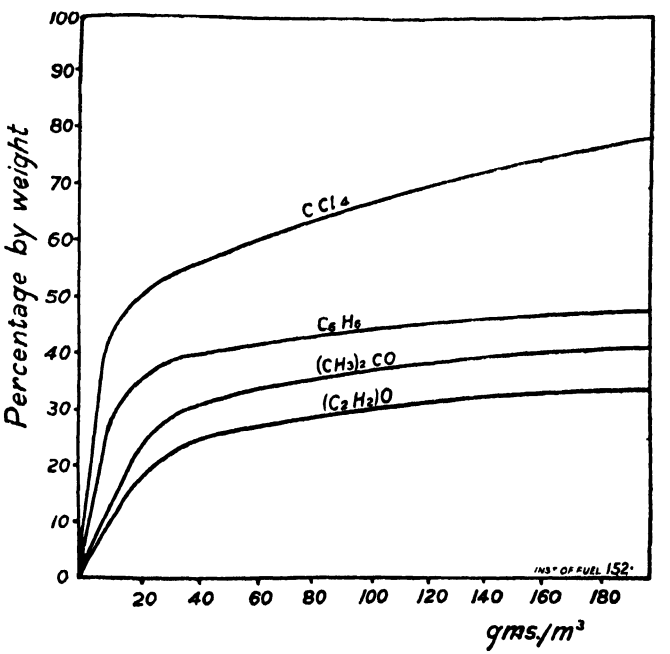


FIG. 210A.

FIGS. 210 and 210A.—Curves of adsorption isotherms plotted on squared paper and logarithmically.

carbon is in equilibrium with vapour of specified concentrations, i.e. at certain partial pressures.

In the case of an adsorptive material in equilibrium with air containing vapour at low concentration, only the smallest capillaries will come into action, whereas at higher concentrations the adsorbed vapour will fill also the larger capillaries.

All the commercial adsorptive materials have a specific and selective action, and this property is often made use of in practice.

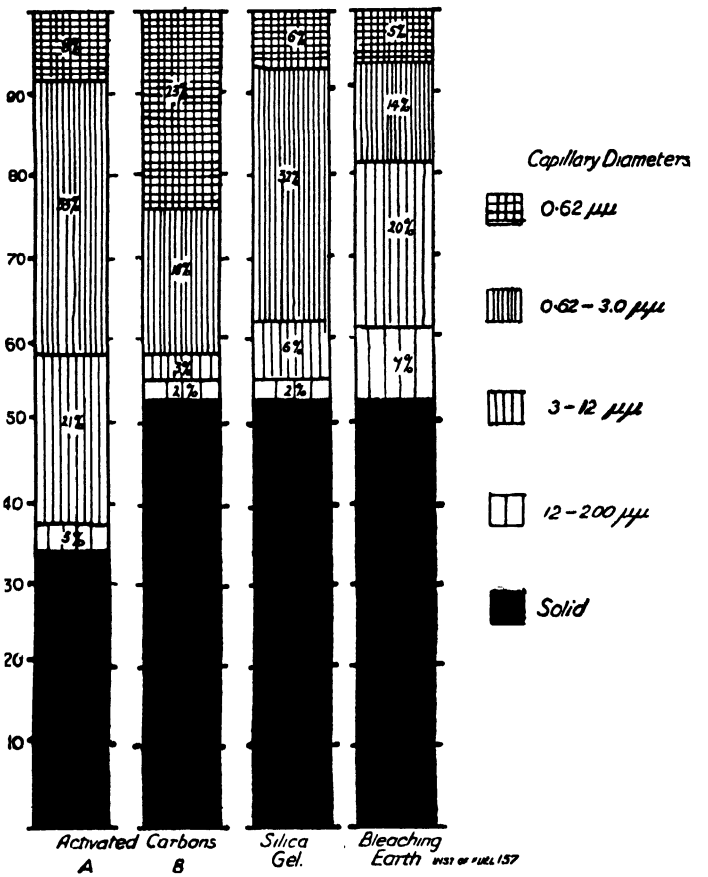


FIG. 211.—Structure analyses of adsorptive materials.

Operation of Industrial Vapour Phase Adsorption Plants using Activated Carbon.

Fig. 212 shows diagrammatically a typical carbon adsorption plant for the recovery of solvents from large volumes of air or gas. The essential portion of the plant comprises two adsorbers containing beds of the appropriate grade of activated carbon through which the air or gases are passed alternately. With one adsorber in use for

recovery, after a certain time when the carbon has adsorbed as much solvent as is economically practicable, the other bed is brought into use, and the first bed is regenerated by passing steam through it as indicated in the figure. The mixture of steam and solvent is condensed as shown and non-miscible solvents are separated by the usual gravity method. The carbon bed is dried before being again put into service by passing through it a stream of heated air. The use of the adsorbing units of appropriate size permits of continuous operation. Plants of this type are now in general use in the rubber and allied industries.

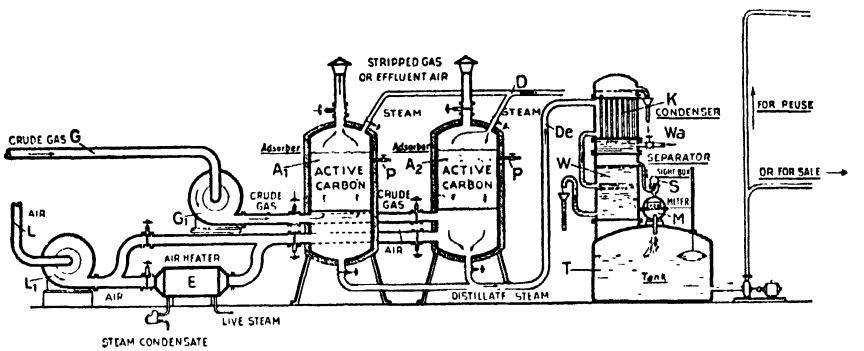


FIG. 212.—Carbon adsorption plant for solvent recovery.

As an example of the size of vapour phase activated carbon plants now available, the British Carbo Union have erected a plant at the Beckton Works of the Gas Light & Coke Co. with a daily capacity of 80 tons of benzol and a gas throughput of 77,000,000 cu. ft.

The *Liquid phase* applications of activated carbon in decolorisation and similar processes are well known, and form recognised branches of technique in industries such as sugar refining, edible oils and fats, mineral oils and chemicals generally.

The theoretical considerations of the liquid phase are more complex than in the case of the vapour phase, but similar reasoning can be applied, bearing in mind osmotic pressure considerations.

Practical equipment for decolorisation, clarification, etc., is either of the batch type where a batch of material is mixed with a small amount of activated carbon and subsequently filtered. In some cases it is advantageous to deposit the carbon in the form of a bed through which the liquid is either forced or allowed to percolate.

Activated carbons are also now employed in water purification, in the removal of bad tastes and odours, and of excess chlorine after chlorination of water, and for the extraction of, for example, benzol and phenol from liquors.

Silica Gel is a hard, clear and glassy substance with a chemical composition of approximately 100 per cent. SiO_2, very carefully pre-

pared in order to give a definite physical structure. It is inert chemically and strong mechanically, so that large masses of the granular material may be employed without serious loss by attrition and may be continually heated without detriment to the adsorptive properties. The extremely large surface of the pores, with the addition of their capillary action, combined with its other properties, render silica gel particularly suitable for a wide variety of purposes.

The industrial applications of silica gel may be conveniently grouped under three headings :

1. Adsorption from the gas phase.
2. Adsorption from the liquid phase.
3. As a catalyst or as a support for catalytic agents.

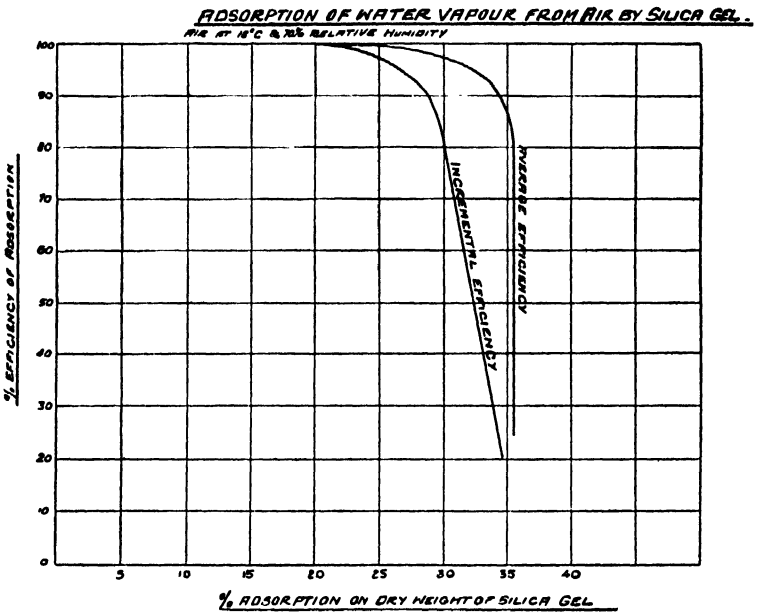


FIG. 213.

Adsorption from the Gas Phase.—Silica gel selectively adsorbs vapours of volatile liquids, such as water, acetone, benzene, petrol, etc., from air and similar gases. If an air vapour mixture of this nature is passed through a bed of silica gel, vapour will be adsorbed until the break point—when the air leaving will contain gradually increasing quantities of vapour. The curve shown in Fig. 213 shows the adsorption of water vapour from air under definite conditions of temperature, humidity and rate of flow and indicates a number of points of general interest in connection with vapour adsorption. It will be noticed that under these particular conditions the break point is reached when the silica gel has adsorbed water from the air to the

extent of 20 per cent. of its weight. On continuing to pass air through the silica gel, water vapour will be present to an increasing extent in the air as it leaves, and the two curves shown represent alternative methods of expressing the efficiency of adsorption. The average efficiency is calculated from the ratio of the total amount of vapour adsorbed and the total amount of vapour present in the air vapour mixture that has passed through the gel. The incremental efficiency, on the other hand, represents the ratio of the total amount of vapour adsorbed and the total amount of vapour present in the air vapour mixture passing through the gel at any given moment. In other words, the incremental efficiency is the actual efficiency of adsorption measured at one particular instant during an adsorption cycle, whilst the average efficiency is the average for the whole period of the adsorption cycle. It will be seen that there is an appreciable difference in the adsorptive capacity between these two curves and it is important to bear this in mind when considering efficiencies. High adsorption figures may be obtained under certain conditions, based on adsorption for complete equilibrium under static conditions, but these are apt to be misleading and hardly represent results that are of value from the industrial point of view.

A number of arrangements of plant can be adopted employing silica gel for adsorption purposes which will naturally depend upon the specific requirements, such as the quantities, concentration, temperature, etc., of any given problem. A typical plant would consist of two adsorbers, each containing the requisite quantity of silica gel, arranged so that one is adsorbing whilst the other is being regenerated. Regeneration will comprise removal of the adsorbed material in such a way that the silica gel has its original low condensed vapour content and is ready for a further adsorption cycle. The adsorbed liquid after removal from the gel may be condensed and recovered. Any number of adsorbers may, of course, be arranged so that they are worked in a convenient cycle of operations.

It will be seen that the adsorptive properties of silica gel from the gas phase afford a number of applications, such as, drying, the drying and purifying of compressed gases, dehydration of coal gas, etc. etc. The treatment of compressed gases, such as compressed air, oxygen, nitrous oxide, carbon dioxide, etc., not only deals with the small residual amount of moisture remaining after compression, but also purifies the gas by removing contamination due to noxious vapours.

A special case of air drying by silica gel is the dehydration of coal gas, which is becoming increasingly important. When coal gas is passed over silica gel, the latter adsorbs water vapour and benzene. After a time, however, owing to its selective adsorptive properties, a certain amount of the adsorbed benzene may be replaced by water

so that by varying the conditions it is possible that varying ratios of water and benzene adsorbed by the gel may be obtained.

The results obtained from a plant at a gas works showed that when obtaining the required dehydration of some 60 per cent., the ratio of water to benzene adsorbed was approximately 3–1, whilst, at the same time, naphthalene was almost completely removed from the gas, and the very slight diminution in the calorific value of the dehydrated gas was more than off-set by the value of the benzene recovered. Apart from the advantages of dehydrating the gas to such an extent that water deposition in mains and services is prevented, the removal of naphthalene is a very definite advantage.

It will be appreciated that great flexibility is possible when utilising silica gel for this purpose, as the amount of benzene adsorbed can be varied so that, if required, practically complete recovery of all the benzene present may be carried out. Fig. 214 shows a large Silica Gel equipment for the dehydration of hydrogen gas.

As an example of the use of silica gel as a support for catalytic agents, platinised silica gel, or gel impregnated with other suitable catalyst, is of great value in the contact process for the manufacture of sulphuric acid. The impregnated silica gel may be used in existing plant and thus give rise to increased yields.

Activated Alumina.—The Aluminium Company of America has been one of the pioneers in the development of activated alumina, and among other uses of this material as an adsorption agent, one of the most important is the removal of moisture from air and gases.

The Pittsburgh Lectrodryer Corporation manufactures a wide range of apparatus for use with activated alumina, and Fig. 215 shows an apparatus made by this organisation for drying carbon dioxide gas under high pressure. Apparatus is also manufactured for the dehumidification of the air supply to storage rooms, and for general industrial processes. As in the case of other adsorptive materials the adsorbed moisture is driven off by heating, so that continuous operation necessitates a duplication of the adsorption unit.

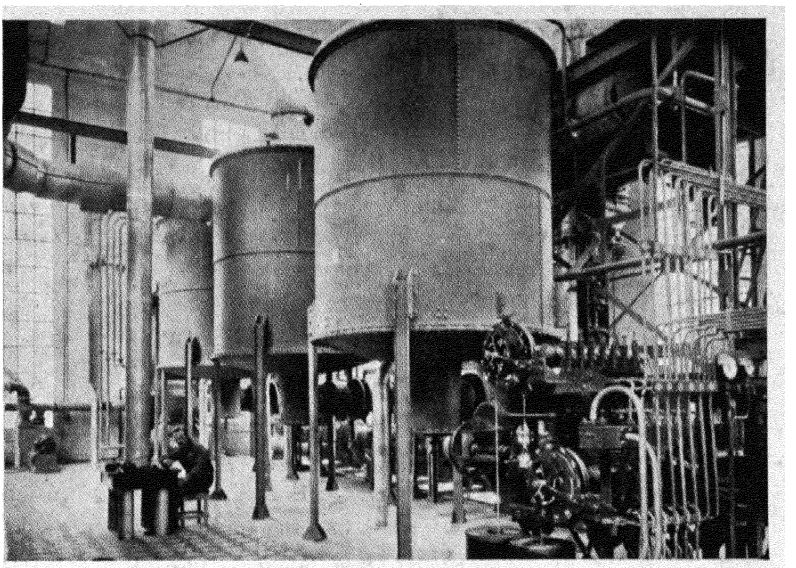


FIG. 214.—Silica gel hydrogen gas dehydration plant at the Norsk Hydro-Electric Works, Norsk, Norway.

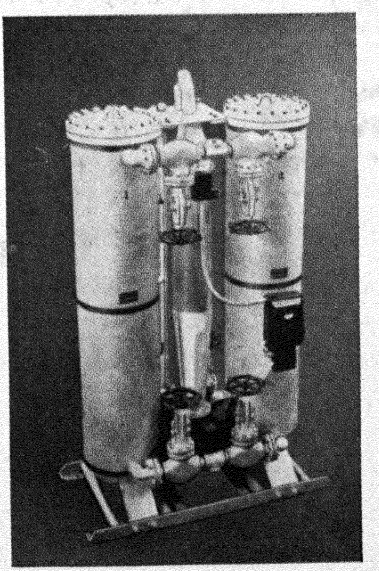


FIG. 215.—"Lectrodryer" activated alumina twin adsorber to remove moisture from carbon dioxide under high pressure in the manufacture of solid carbon dioxide.

[*To face page* 430.

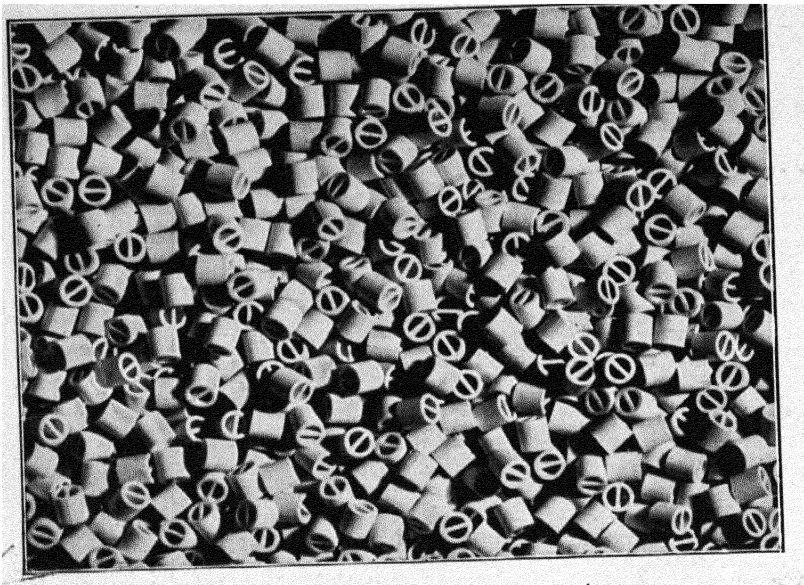


FIG. 216.—Lessing's patent contact rings.

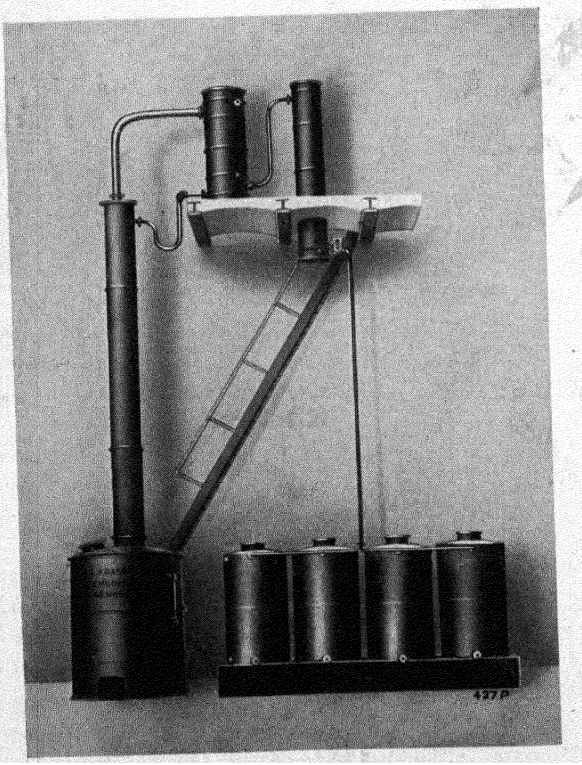


FIG. 216A.—Crude turpentine rectification plant by W. J. Fraser & Co., Ltd.

[*To face page* 431.

*

CHAPTER XIII.

DISTILLATION.

THE term *distillation* in chemical engineering is applied usually to those operations where vaporisation of a mixture of liquids gives rise to a vapour phase containing more than one constituent, and where it is desired to recover one or more of these constituents in a nearly pure state. The fundamental requirement of a successful distillation operation is that the composition of the vapour shall be different from that of the mixture of liquids from which it is derived. If the composition of the vapour is the same as that of the liquid, separation cannot be effected by distillation methods.

Distillation cannot yield a perfectly pure product, but in practice in many instances it is possible to obtain a product sufficiently pure for commercial purposes.

Distillation processes depend upon the fact that the more volatile constituents of a mixture of liquids when partially vaporised occur in increased concentration in the vapour phase. By repeated simple distillation, or by distillation through specially designed fractionating columns, the components of many vaporable mixtures of liquids can be effectively separated.

Usually simple distillation methods are confined to work of the laboratory type, and industrial distillation operations involve the use of fractionating columns, which may be (1) plain packed columns, (2) sieve plate columns, or (3) bubble-cap columns. A packed column comprises a vertical pipe attached to the still head and in which refractory earthenware chips, short hollow cylinders of metal or ceramic material, or special designs such as Lessing, Raschig, and other rings are used. Examples of Lessing's patent contact rings are seen in Fig. 216, from which it will be noted that they consist of short hollow cylinders with a more or less diametral partition connected on one side with the cylinder but not in contact with the other side. They are disposed indiscriminately in the tower or column at angles which they find when dropped promiscuously into the vessel (see Lessing *J.S.C.I.*, 1921, **XL**, pp. 115T–118T). These rings may be made in metals, ceramics, and carbon. Raschig rings are merely plain hollow cylinders (E.P. 6288 of 1914). Fig. 216A shows a standard crude turpentine rectification plant by W. J. Fraser & Co., Ltd.

of Dagenham. The still is coil heated by Dowtherm vapour and the dephlegmating column is ring packed.

Sieve plate columns are designed on lines illustrated in Fig. 217. It will be seen that these columns consist of a number of perforated sheet metal or wire screen plates P. Vapour from the still rises as shown and partly condenses on the first plate P_1, from which some of the more volatile constituents will be vaporised, so that the liquid-condensing on the plate P_2 will be considerably richer in the more volatile constituents than the liquid in the still. The same reasoning will apply to the higher plates, so that eventually the vapour passing through and evolved from the final plate will yield a product of the desired purity.

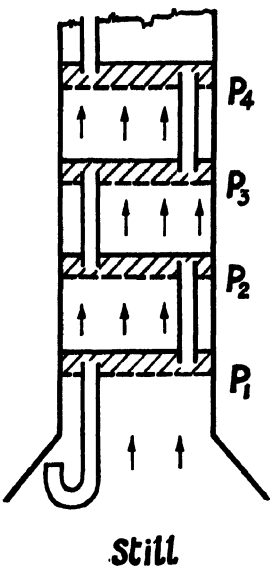


FIG. 217.—
Sieve plate column.

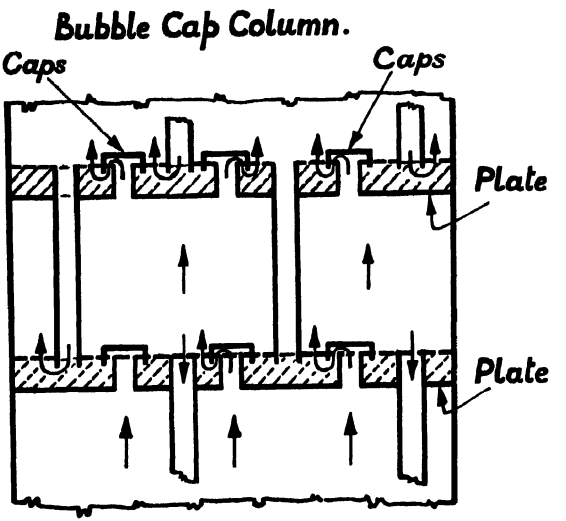


FIG. 218.

This type of still has several disadvantages, chiefly that at low rates of vaporisation the liquid runs down from one plate to the next below and so on, so that the desired equilibrium to ensure a good uniform product cannot be maintained. At high rates of flow of vapour entrainment is unavoidable, and the friction through the sieve plates is often excessive. When worked at the optimum capacity, however, such columns give quite good results on many mixtures.

A small section of a bubble-cap plate column is shown diagrammatically in Fig. 218.

The ascending vapour mixture is caused to pass through a series of bubble caps so placed that their lower ends are immersed in condensed liquid. As the vapour rises through successive plates it becomes

richer and richer in the more volatile constituent until, with a sufficient number of plates, the desired degree of purity can be effected as the vapour passes the final uppermost plate.

In effect, each successive plate becomes a small still, and the higher the position of the plate the more of the more volatile constituent will there be within it. The heat necessary for vaporisation on each plate is obtained from the condensation of ascending vapours.

In all fractionating columns the efficient separation of the constituents depends in no small degree upon the provision of reflux or a return of part of the condensate down the column. Reflux at any point of the column will be richer in the more volatile component than the ascending vapours, and condensation of relatively greater amounts of the less volatile component will occur, followed by vaporisation of liquid richer in the more volatile component. In this way, the less volatile component is " washed " out of the ascending vapour.

In continuous distillation by fractionation, the feed to the column is either wholly liquid heated to near the boiling point or partly liquid and partly vapour, and the feed enters above the bottom of the column so that the lower plates act as stripping plates to remove the last traces of the more volatile constituent.

The study of the distillation of mixtures of more than two components is highly complex, so to facilitate the discussion of the fundamental principles of distillation, in the first instance only binary of mixtures of two components will be considered.

Types of Binary Mixtures.—Mixtures of two liquids may be non-miscible, partly miscible or miscible in all proportions. The following discussion will deal mainly with the distillation of binary mixtures of miscible liquids which do not have a constant boiling point, since such binary mixtures represent by far the greatest proportion of industrial distillation problems. The important subject of azeotropic distillation is discussed on pages 471 to 476.

Boiling-Point Diagrams—Vapour Pressure Relationships.

Now, when two liquids are mutually soluble the vapour pressure of each is decreased by the presence of the other ; and, consequently, the sum of their vapour pressures is *less* than the sum of the vapour pressures of the two liquids taken separately. The composition of the vapour in such cases is not independent of the relative amounts of the components of the mixture of liquids, but is markedly influenced thereby.

From the foregoing it is clear that it is important in any distillation problem to know the equilibria between the liquid and vapour phases of the mixture to be distilled.

Fig. 219 shows the boiling point and equilibrium composition relationships, at constant pressure of all mixtures of liquid X (boiling

point t_x) and liquid Y (boiling point t_y), and liquid X is to be regarded as the more volatile. The diagram consists of two curves, both ends of which coincide, and any point (e.g. point a) on the upper curve has for abscissæ the composition of vapour (e) that will just begin to condense at the corresponding temperature t_1 with liquid of composition d.

Any point such as b on the lower curve has as abscissæ the composition of liquid which will just begin to boil at the temperature t_1, giving vapour of composition e. Any two points on the same horizontal line (e.g. [a and b]) represent compositions of liquid and vapour in equilibrium with each other at the temperature given by the hori-

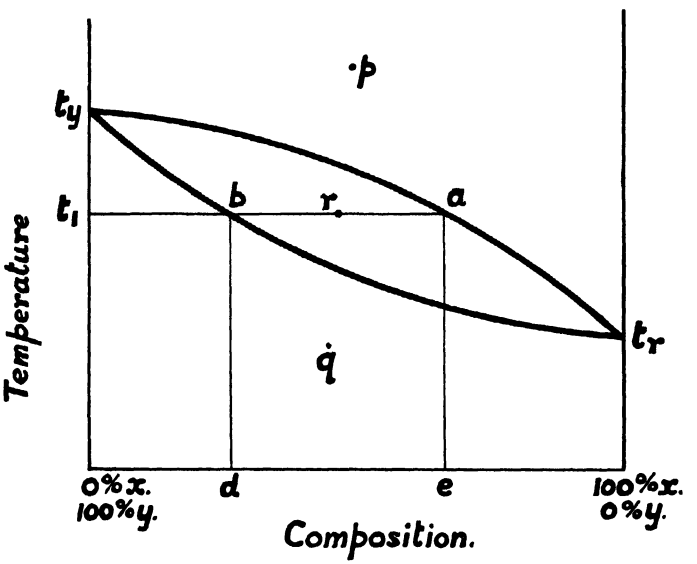


FIG. 219.—Boiling point and equilibrium composition relationships.

zontal line through them. At all points above the upper curve, e.g. p, the mixture is entirely vapour, whereas at all points below the lower curve, e.g. q, the mixture is completely liquefied. At points between the two curves, e.g. r, the system comprises partly vapour and partly liquid.

If a liquid mixture of composition d is heated slowly, it will begin to boil at t_1, and the vapour first produced will have a definite composition represented on the diagram by e. As soon as an appreciable amount of the vapour has been formed, the composition of the liquid will no longer correspond to d because the vapour is principally composed of the more volatile component than the liquid and the point b tends to move towards t_y.

It will be realised that the boiling-point diagram must be de-

termined experimentally in all cases. The diagram will vary with total pressure conditions, but the whole diagram will move up or down as a whole, and the relation between the vapour and liquid curves is not greatly affected.

There are two laws in this connection which are worthy of note, i.e. Raoult's Law and Henry's Law, which although not strictly applicable to the exact solution of distillation problems, yet are worthy of consideration in that they do provide a real guide to fundamental principles of practical distillation.

Raoult's Law states that at any given constant temperature the partial pressure of one component of a mixture is equal to the mol fraction of that component multiplied by its vapour pressure in the pure state at the temperature under consideration. (By mol fraction is meant that fraction of the entire number of molecules making up the liquid which is represented by the molecules of the component under consideration.) Hence, according to this law the partial pressure of the component concerned varies directly from zero to the full vapour pressure as its mol fraction varies from zero to unity.

It is to be noted that Raoult's Law applies in practice to but few mixtures, and, in general, only to those in which the constituents are chemically similar, and wherein there is no molecular interaction. Benzene and toluene, therefore, follow Raoult's Law closely, whereas, for example, acetic acid and water, and alcohol and water do not.

Let

p_a = partial pressure of component A over a binary mixture wherein the mol fraction A is x.
P_a = vapour pressure of A in pure state.
p_b = partial pressure of component B.
P_b = vapour pressure of component B in pure state.
P = total pressure exerted by mixture at a given temperature.

Then Raoult's Law may be expressed in the following way :—

$$p_a = P_a x$$
$$p_b = P_b(1 - x)$$
$$P = p_a + p_b = P_a x + P_b(1 - x).$$

Let y = mol fraction of A in the vapour.

Then
$$y = \frac{p_a}{p_a + p_b} = \frac{P_a x}{P} \qquad (1)$$

If it is known that the mixture closely follows Raoult's Law, and the vapour pressures at various temperatures of the component are also known, it is practicable to draw upon graph as Fig. 220, which gives the boiling-point diagram of the mixture of benzene-toluene. It is obtained from the above separation, and the following additional data.

TABLE 52.

Temperature (° C.).	Vapour Pressure in mm.	
	C_6H_6	C_7H_8
80	753	290
80·6	760	—
85	877	345
90	1016	405
95	1168	475
100	1344	557
105	1532	645
110	1748	743
110·7	—	760

From the above equations we get :—

TABLE 53.

Temperature (° C.).	Partial Pressure Benzene (x)	Mol Fraction Benzene (y)
90	0·58	0·78
95	0·41	0·63
100	0·26	0·46
105	0·13	0·26
110	0·02	0·04

To clarify the foregoing, take a mixture of 20 per cent. benzene and 80 per cent. toluene. It will boil when the mixture attains a temperature of 102° C. (point E on the curve), and the vapour coming off will have the composition represented by F on the upper curve. If condensed this vapour would yield a liquid containing 38 per cent. benzene and the rest toluene. Naturally, the liquid remaining in the still will now contain less than 20 per cent. benzene, and the boiling point will gradually rise. It follows that since the distillate will at all times be richer in the more volatile component than the liquid remaining behind in the still, proper separation of the constituents is impracticable under these conditions. If, however, the liquid condensed from the vapour with 38 per cent. benzene were removed from the system, and heated again separately, the boiling point would be now G, and the vapour would be as shown at H—namely, approximately 62 per cent. benzene and the rest toluene. If this richer vapour be condensed, removed and again heated it will yield a liquid boiling at K, with a composition of 82 per cent. benzene, and by repeating this process it is clear that eventually practically pure

benzene can be obtained. This principle is used in all types of distillation apparatus where fractionation is necessary. As previously mentioned in the case of the sieve plate and bubble-cap plate columns, the plates may be regarded as little stills, each receiving successively a liquid with a greater proportion of the more volatile constituent and rejecting a little of the less volatile constituent, so that eventually

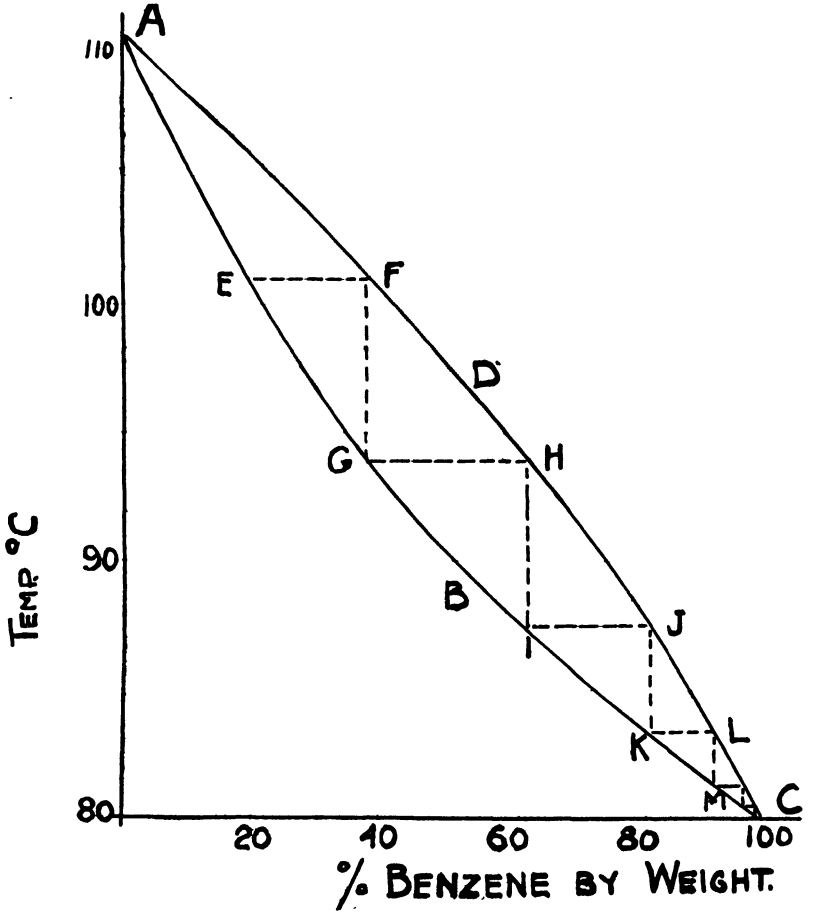


FIG. 220. Boiling point as a function of composition of liquid-benzene and toluene.

the last plate approximates to the point C in Fig. 220, i.e. yielding practically pure material. The conditions under which each plate is working may be illustrated by the dotted lines on the graph, i.e. a plate E is yielding a product of 38 per cent. benzene, which is condensed on the plate G, giving rise to a product I of 62 per cent. benzene and so on. (Walker, Lewis and McAdams, " Principles of Chemical Engineering," McGraw Hill Book Co., reproduced by permission.)

Henry's Law states that the partial pressure of a component over a solution is proportional to its mol fraction in the liquid

$$p_a = Cx,$$

where p_a is again the partial pressure of component A over a liquid mixture wherein the mol fraction of A is x and C is the Henry constant. It is to be noted that Raoult's Law is really a special case of Henry's Law wherein the constant C becomes the vapour pressure P_a, etc., of the component.

The Design of Fractionating Columns.

The design of fractionating columns has been the subject of much practical and mathematical research. The first detailed study of binary miscible mixtures was by Sorel (*Compte Rendus*, 1889, **58**, 1128–1204–1317, and 1894, **68**, 121), and many workers have based their analysis on Sorel's original work (e.g. Lewis, *Ind. Eng. Chem.*, 1922, **14**, 492 ; Peters, *Ind. Eng. Chem.*, 1923, **15**, 402 ; McCabe and Thiele, *Ind. Eng. Chem.*, 1925, **17**, 605).

A good design of fractionating column should meet the following requirements :

(1) Descending liquid at any level should not be mixed with liquid from any other level, and it should be of identical bulk composition throughout any horizontal cross section of the column.

(2) Liquid at the interface in contact with the vapour should be mixed as rapidly as possible with the bulk of the liquid at the same level in order to prevent accumulation of the less volatile constituents in the liquid at the interface. This applies in a like manner to the ascending vapours.

(3) The column should provide maximum contact between liquid and vapour, including the factor of extended area as well as that of an active surface as possible, and uniform distribution of both liquid and vapour throughout the available cross section of the column. In addition, means should be provided to prevent liquid passing down via the column wall. The column should retain a minimum amount of liquid, of compact design, with minimum back pressure, and of material unaffected by service conditions. This last requirement is highly important since corrosion of bubble caps, for example, may lead to serious restriction of the openings.

Theoretical Column Plate.—The performance of any practical column is more easily understood if it is compared with a theoretical ideal column composed of theoretical plates, which fulfil the requirement that the vapour rising from one plate to the plate above is in equilibrium with the liquid leaving the upper plate passing to the plate below.

Mechanism of Fractionation.—Considering one perfect plate, four streams of material are involved—namely, a stream of liquid from above and a stream of vapour from below, and also a stream of liquid leaves the plate and is delivered to the plate below, and a stream of vapour is delivered to the plate above. Assuming a boiling-point diagram of the form shown in Fig. 221, component A is the more

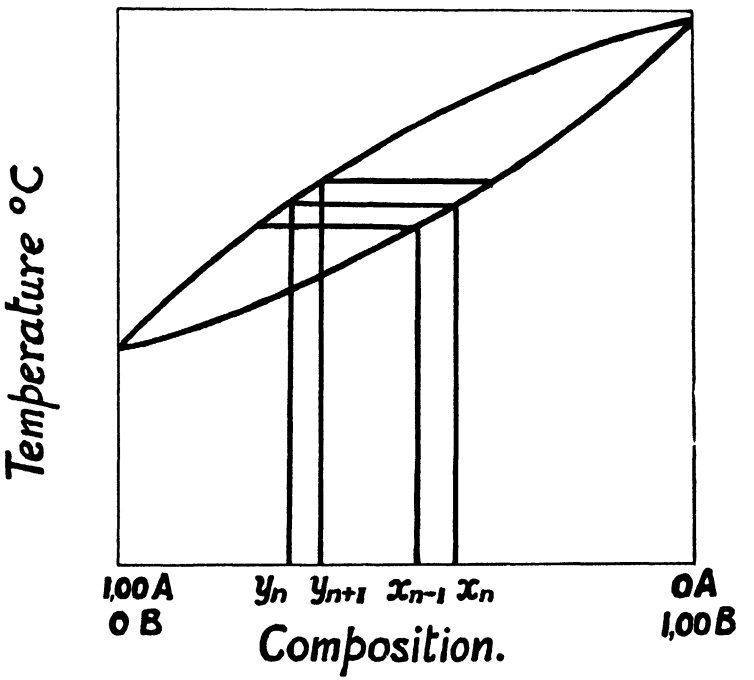


FIG. 221.

volatile, x is composition of liquid in mol fraction of A, and y is composition of vapour. The composition of the four streams are represented by x_n, x_{n-1}, y_{n+1} and y_n, and the plate is receiving liquid of composition x_{n-1} from the plate above, and vapour of a composition y_{n+1} from the plate beneath. The plate delivers vapour, composition y_n, to the plate above and liquid, composition x_n, to the plate below. (By definition these two latter streams are in equilibrium.) The liquid falling from the plate above has composition x_{n-1} and is richer in the more volatile component A than is the liquid leaving the plate and passing to the plate below, whereas the vapour rising from the plate, composition y_{n+1} below, is richer in the less volatile component B than is the vapour from the centre plate. Since by definition the streams x_n and y_n are in equilibrium, the streams x_{n-1} and y_{n+1} cannot be in equilibrium, and hence, when brought

into contact, they tend to approach equilibrium. Some of the more volatile component A is vaporised from the liquid, and hence its content of A is reduced from x_{n-1} to x_n, and some of component B is condensed from the vapour increasing its content of A from y_{n+1} to y_n. In other words, the more volatile component is transferred from the liquid stream to the vapour stream, and hence it moves up the column, whereas the less-volatile component is transferred from the vapour stream to the liquid stream and hence falls down the column. (Badger and McCabe " Elements of Chemical Engineering," McGraw Hill Book Co., Inc., reproduced by permission.)

Material and Heat Balances for Ideal Plate.

Referring to Fig. 222, it is assumed that the theoretical plate is the nth down from the top in a column consisting of ideal plates, and wherein the feed is at a point below this plate. From the $(n+1)$th plate below is rising a stream of vapour of mass V_{n+1} mols per hr., and it is taken that the mol fraction of the more volatile component A in this rising vapour is y_{n+1}. The plate (n) yields V_n mols of vapour per hr. to the $(n-1)$th plate above the theoretical plate, and the composition of this vapour (in terms of A) is y_n. From plate $(n-1)$ falls a stream of liquid as reflux in quantity L_{n-1} mols per hr., and this contains x_{n-1} mol fraction of A. The theoretical plate (n) delivers to the lower plate $n+1$, L_n mols of reflux liquid per hr. of composition x_n.

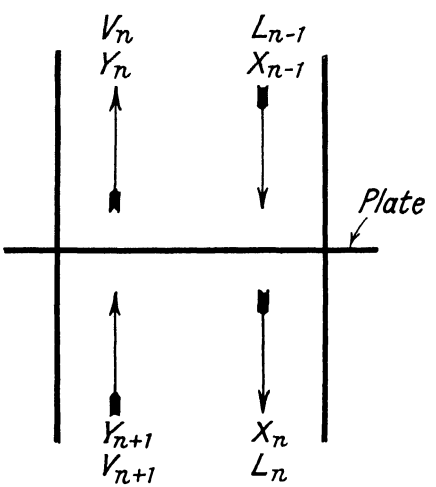


FIG. 222.

The material equations are as follows: in terms of total material under consideration

$$V_{n+1} + L_{n-1} = V_n + L_n \qquad (2)$$

In terms of component A

$$(V_{n+1})(y_{n+1}) + (L_{n-1})(x_{n-1}) = V_n y_n + L_n x_n \qquad (3)$$

If the working temperature of the liquid in the theoretical plate is taken as the standard of comparison, the temperatures of the vapour leaving the plate below will be a little higher because the vapour is leaner in the more volatile component A, and similarly, since the falling liquid L_{n-1} is richer in component A it will have a lower boiling point.

Let

Latent heat in vapour V_{n+1} be designated	a
Sensible heat in vapour V_{n+1} above datum be	b
,, ,, ,, L_{n-1} below ,, ,,	c
Heat of mixing of components be	d
Latent heat in vapour V_n	e
Radiation be	f

Then the heat balance of the operation is

$$a + b - c + d = e + f. \tag{4}$$

It is to be noted in the above that the important factors are a and e, that is the two latent heats, and in comparison the rest of the items are negligible for practical purposes. So that the equation may be written

$$a = e. \tag{5}$$

Constant Molal Overflow.—The empirical approximation known as Trouton's Rule states that the molal heat of vaporisation divided by the absolute temperature of the boiling point is constant for large groups of chemically similar liquids. In other words, it can be taken that a mol of component A on the theoretical plate (n) requires as much heat to vaporise it as a mol of B on the same plate. (If the two components of the mixture do not have the same Trouton Rule constant a fictitious molecular weight may be assumed for either component so that Trouton's Rule is applicable. In this case the boiling-point diagrams and equilibrium diagrams must be calculated on the basis of the assumed molecular weight. This aspect is fully discussed by (Peters, *Ind. Eng. Chem.*, 1922, **14**, 476.) The heat of vaporisation of a mol of *any* mixture of A and B is, therefore, taken as independent of the relative composition of the mixture, if temperature changes are neglected.

From this, it follows that

$$V_{n+1} = V_n. \tag{6}$$

Since plate n is any plate above the feed plate this equation is of general application. It is also apparent that $L_{n-1} = L_n$, and these latter equations define the terms constant molal vaporisation and constant molal overflow respectively.

Calculation of the Number of Theoretical Plates in a Fractionating Column.

The following analysis of the design of fractionating columns for use in the distillation of miscible binary mixtures is that of McCabe and Thiele, as this is now generally recognised as an effective and convenient method. (McCabe and Thiele, *Ind. Eng. Chem.*, 1925, **17**, 605).

The column under consideration is assumed to have both stripping and fractionating sections, and is shown diagrammatically in Fig. 223,

(It is assumed in the following discussion that the plate efficiency, or the height of column equivalent to one theoretical plate for the type of column and the mixture under consideration, is known.) A " general " plate is given as n, if in the rectifying column, or $\bar{n}$ if in the stripping column. Where any quantity is given a subscript, the latter refers to

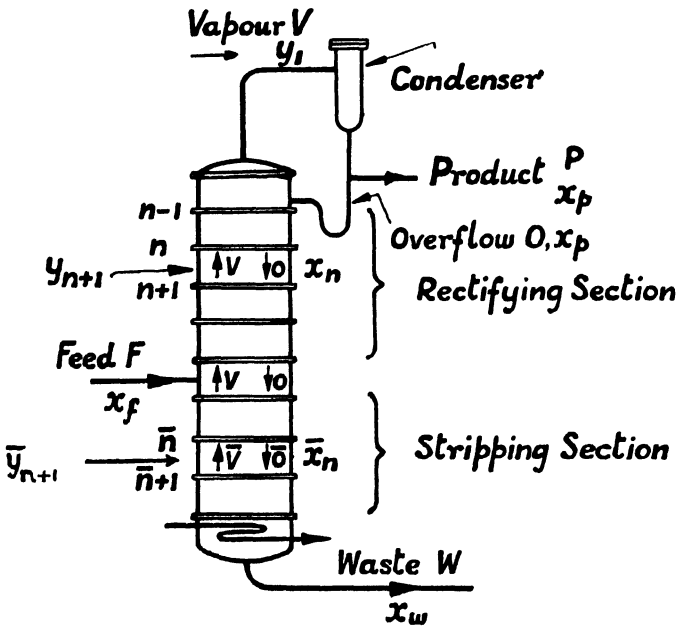


FIG. 223.

the point of origin of that quantity, e.g. y_n means the composition of the vapour rising from plate n and x_{n+1} gives the composition of the liquid descending from plate $\bar{n} + 1$. Other symbols are :—

P = mols of distillate or product withdrawn in a given time.
x_p = composition of product.
F = mols of binary mixture fed to the still in given time.
x_f = composition of feed.
O = mols overflow from any plate in the rectifying column.
$\bar{O}$ = mols overflow from any plate in the stripping column.
W = mols of waste withdrawn in a given time.
x_w = composition of waste.
V = mols of vapour rising from any plate in rectifying column.
$\bar{V}$ = mols of vapour rising from any plate in stripping column.
AA′ BB′ coefficients in enrichment equations. (In the whole discussion the basis will be 1 mol of product, i.e. P = 1.)

The following assumptions are made in the first part of the discussion, and later the effect of the restrictions so imposed receives attention.

(1) Sensible-heat changes throughout the column are negligible compared with the latent heat.
(2) The molar latent heats of the constituents are equal.
(3) The heat of mixing of constituents is negligible.
(4) The number of mols of vapour ascending the column and the molal overflow is constant from plate to plate.
(5) The feed enters the column at a temperature equal to the boiling point of the liquid on the feed plate.
(6) The only condenser is a simple condenser, so that the composition of the product is the same as the vapour from the top plate.
(7) The heat supplied to the base of the column or still is by means of a closed steam or liquid heating pipe.

The following standard equations then follow:—By means of balances of total material and more volatile component it can be shown that for the rectifying section,

$$y_{n+1} = \frac{O}{O+1} x_n + \frac{x_p}{O+1} \tag{7}$$

or if

$$A = \frac{O}{O+1} \text{ and } B = \frac{x_p}{O+1} \tag{8}$$

then

$$y_{n+1} = Ax_n + B, \tag{9}$$

which equation, when plotted with y as ordinate and x as abscissæ, is that of a straight line with y axis intercept of B and a slope A. This equation will now be known as the enrichment equation of the rectifying column, and the straight line representing it as the enrichment line of the rectifying column.

Considering the apparatus of Fig. 223, below a section drawn between the plates $\bar{n}+1$ and n it can be shown that

$$\bar{x}_n = \frac{\bar{O} - W}{\bar{O}} \bar{y}_{n+1} + \frac{Wx_w}{\bar{O}}, \tag{10}$$

and taking into account the assumption (4) and (5) above a heat balance shows

$$\bar{V} = V, \tag{11}$$

and a material balance about the feed plate (Fig. 223) shows that

$$\bar{O} = F + O. \tag{12}$$

Also by a material balance on the whole apparatus

$$F = W + 1 \tag{13}$$

Substituting values for $\bar{O}$ and W in the appropriate equations above we get

$$\bar{x}_n = \frac{O+1}{O+F} \bar{y}_{n+1} + \frac{F-1}{O+F} x_w \tag{14}$$

Let

$$A' = \frac{O + 1}{O + F} \text{ and } B' = \frac{F - 1}{O + F} x_w \tag{15}$$

we get

$$\bar{x}_n = A'\bar{y}_{n+1} + B', \tag{16}$$

which again is the equation to a straight line with, in this instance, a slope of $\frac{1}{A'}$ and an x axis intercept of B'. This equation will in future be known as the enrichment equation of the stripping column and the straight line representing it as the enrichment line of the stripping column.

Use of the Two Enrichment Lines.

For every binary mixture there is a definite relationship between x the composition of the liquid phase, and y the composition of the vapour phase in equilibrium with it. The equilibrium curve resulting from this relationship and equations 9 and 16 are all that is necessary to calculate theoretically the composition of liquid and vapour corresponding to each plate and consequently the *number* of theoretical plates required to effect the desired separation, provided that the composition of feed, waste, and product, and magnitude of feed and waste have been selected.

NOTE.—*All concentrations are expressed as mol fractions of the more volatile component.*

Analytical Method.—Plot the equilibrium curve as in Fig. 224. Since the condenser is a simple one, y_1, the concentration of the vapour from the top plate is equal to x_p, the composition of the product, and therefore is known. From this the value of x_1, the composition of the liquid on the top plate, can be read directly from the equilibrium curve, since it is represented by the abscissa of the point on the curve having the ordinate y_1. The coefficients A and B of equation $y_{n+1} = Ax_n + B$ are calculated from x_p and O. If the equation is written as $y_2 = Ax_1 + B$ and if the known values of A, B and x_1 are substituted therein, y_2, the composition of the vapour rising from plate 2, can be calculated. Again, since y_2 is known, x_2 can be read from the equilibrium curve by finding the point thereon with ordinate y_2 and reading its abscissa. The value of x_2 is substituted in the equation $y_3 = Ax_2 + B$, and y_3 calculated. This process is repeated for each plate, and for each plate it is necessary to read one value from the equilibrium curve and carry out one calculation by the equation $y_{n+1} = Ax_n + B$.

Assuming that this process has been carried out for a number of plates and x_1, y_1, x_2, y_2, x_3, y_3, etc., have all been so determined, and that the following points are plotted, a-co-ordinates x_1y_1, b-co-ordinates x_1y_2, c (x_2y_2), d (x_2y_3), e (x_3y_3), these points can be connected by

short horizontal and vertical lines as in the figure. It is to be noted that the points b and d lie on a straight line, the equation to which is $y = Ax + B$.

The foregoing graphical construction can therefore be made much more simply without the necessity for analytical calculations by drawing the line to equation $y_{n+1} = Ax_n + B$, starting with point a, and drawing a series of steps composed of alternate vertical and horizontal

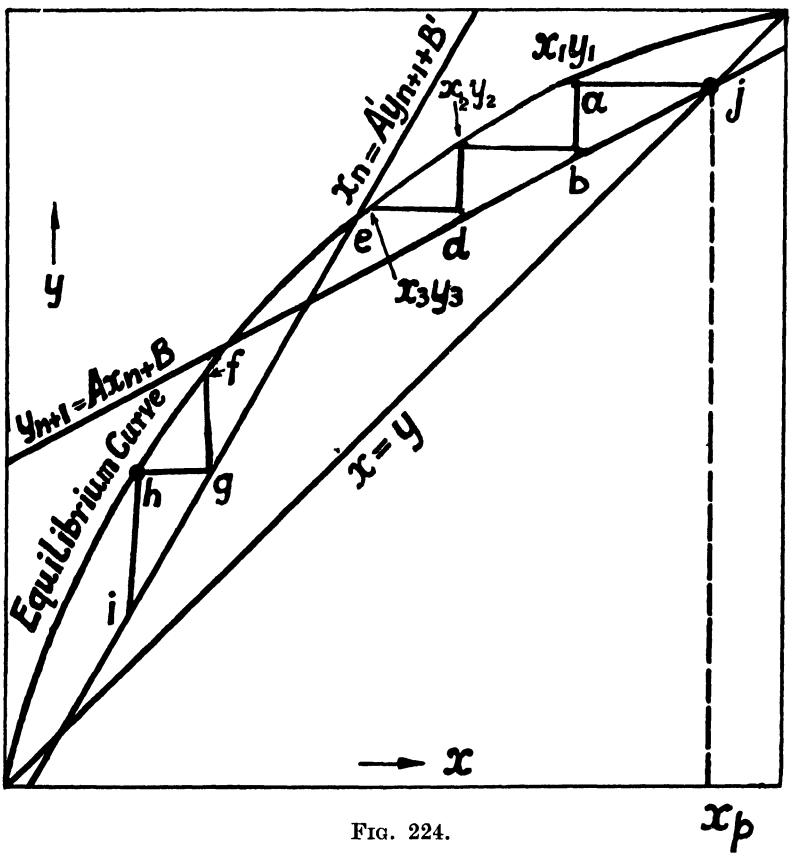


FIG. 224.

segments. Each step represents a perfect plate, and defines the composition of the liquid on each plate and the vapour rising upwards to that plate.

In a similar manner, the enrichment from plate to plate in the stripping column can be determined by plotting the stripping line to conform with the equation $\bar{x}_n = A'\bar{y}_{n+1} + B'$ and moving up or down in a stepwise manner. Thus, if the co-ordinates of the point f are $\bar{x}_{n-1}$, $\bar{y}_{n-1}$, those of point g will be x_{n-1}, $\bar{y}_n$, and so on.

The diagonal line $x = y$ is drawn for convenience, since the point a is thus easily located by drawing the vertical line $x = x_p$, finding its intersection with the diagonal (point j) and drawing a horizontal line (ja).

Plotting the Enrichment Lines.

Inspection of equations 7 and 14 shows that the orientation of the enrichment lines, if plotted on rectangular co-ordinates, depends only on the reflux O for given values of F, x_p and x_w. If the subscripts are dropped from equation 7 and $x = y$, O vanishes, and hence $y = x = x_p$, i.e. the rectifying line crosses the diagonal ($x = y$) at the composition of the product for any reflux. Again, if

$$x = \text{zero}, y = \frac{x_p}{O + 1} = B, \tag{17}$$

and so for any given overflow, the rectifying line is plotted by finding the value of B, plotting as in Fig. 225 and drawing the line AB.

It can be similarly shown that the stripping line crosses the diagonal where $x = x_w$.

The intersection of the two enrichment lines is obtained as follows: the locus of this intersection is found by eliminating O from equations 7 and 14 and solving for x as follows:—

$$x = \frac{(F - 1)x_w + x_p}{F}. \tag{18}$$

By material balance over entire apparatus

$$F = W + 1 \tag{19}$$

$$Fx_f = Wx_w + x_p \tag{20}$$

Eliminating W and solving for F we get

$$F = \frac{x_p - x_w}{x_f - x_w}. \tag{21}$$

Substituting for F in equation 18 and simplifying

$$x = x_f, \tag{22}$$

or the enrichment lines intersect on the vertical line $x = x_f$ whatever the reflux may be.

The enrichment line for the stripping column is plotted by drawing a straight line connecting the intersection of the rectifying line, and the vertical line $x = x_f$ with the intersection of the $x = y$ line and the vertical line $x = x_w$ (line CD, Fig. 225).

Location of the Feed Plate.—If it is desired to separate a mixture of composition of x_f into a product of composition x_p and a waste of composition of x_w using as reflux O, the lines ACB and CD should be plotted as in Fig. 225. The point A will have the co-ordinates $x_p y$· and the stepwise procedure is started from that point. Inspection shows that the rectifying line must be used as far as the point b, but can be used as far as the point c. The change to the stripping line must be made between these two points, that is the feed must be introduced on a plate where the composition is between c and b, if the column is to function as desired. Practical considerations necessitate that the

enrichment per (plate and therefore the average length of segment) must be as large as possible. It is seen that the rectifying line should be used as far as the point c and the stripping line from there upwards. Consequently the feed should be introduced on that plate whereon the composition of the liquid is just less than that of the feed, and in Fig. 225 the feed plate is the fourth from the top. The steps are then carried below c, using the stripping line until one of the *horizontal* segments crosses the line $x = x_w$. Each step represents a perfect plate, and in the figure the total number of plates is $6\frac{2}{3}$.

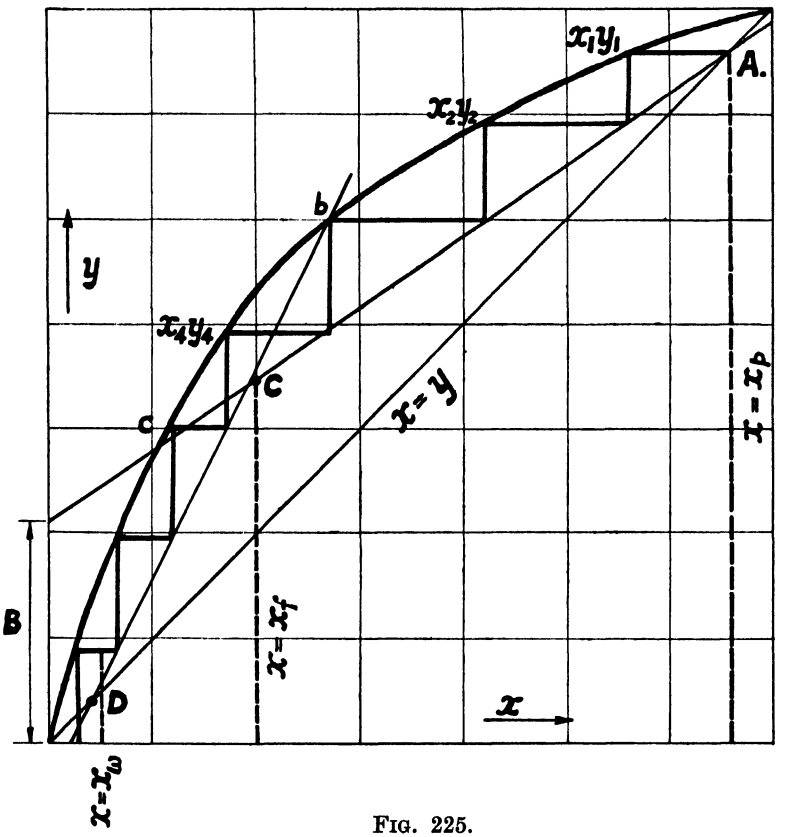


FIG. 225.

In this connection Lewis (*Ind. Eng. Chem.*, 1922, **14**, 492) points out that there are two limiting conditions in the design of a fractionating column, depending on the overflow or the amount of reflux. On the one hand, there is a theoretical minimum overflow which will effect the required separation in a perfect column containing an infinite number of plates. On the other hand, if an infinitely large reflux is taken, the separation would be effected in a column consisting of a minimum number of perfect plates. In the first case the cost of the column

would be infinite, but the cost of heat would be a minimum, since the minimum amount of vapour is generated at the foot of the column because of the *minimum* theoretical quantity of overflow. In the second case, the number of plates in the column is a minimum, but the cost of heat is infinite, as an infinite amount of vapour must be generated.

The designer must choose an optimum overflow between these two extremes such that the sum of the plant charges and heat requirement is a practical minimum.

Minimum Overflow.—Let the concentrations of waste, feed and product be plotted as Fig. 226. It has already been shown that the

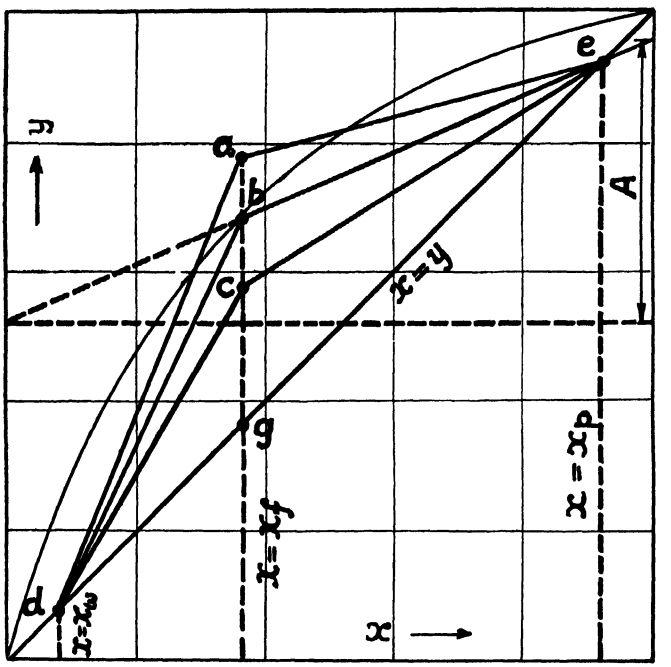


FIG. 226.

enrichment lines pass through the points d and e respectively, and intersect on the line $x = x_f$. The slope of these lines is solely dependent upon the overflow since F, the weight of feed in a given time, is determined. From Fig. 226 it is evident that if the lines intersect above the equilibrium curve as at a, the desired separation cannot be effected, whereas if the lines intersect at the intersection of the equilibrium curve and the line $x = x_f$ as at point b, the separation can be attained, but it necessitates an infinite number of plates. Finally, if the lines intersect at any point above the $x = y$ line, and below the equilibrium curve as point c, the separation can be effected with a finite number of plates. As the only method of shifting the inter-

section from a to c is by increasing the overflow, by definition the minimum overflow is that quantity for which the rectifying line will intersect the $x = x_f$ line at point b. The magnitude of the *minimum* overflow is found by measuring the distance A and finding O from the equation.

$$O = \frac{A}{1 - A} \tag{23}$$

$\left(\text{which is obtained from the equation } A = \frac{O}{O + 1}\right)$.

Maximum or Infinite Overflow.—Inspection of equations 7 and 14 shows that as O increases indefinitely the slopes of the enrichment

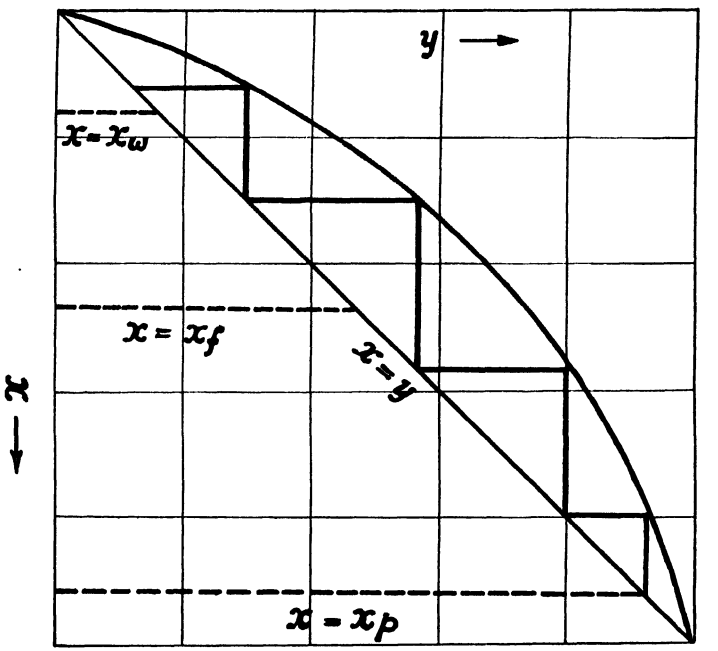


FIG. 227.

lines approach unity and for an infinite overflow the lines coincide with the $x = y$ line. The minimum number of plates is determined by steps as in Fig. 227.

Application of the Method of McCabe and Thiele to an Actual Case.—An alcohol water mixture (10 per cent. alcohol by weight 4·17 mol per cent.) to be separated, giving a product 94·5 per cent. alcohol by weight (87·05 mol per cent.), with waste containing not more than 0·1 per cent. alcohol by weight (0·04 mol per cent.). The reflux or overflow in the rectifying column is assumed for this purpose to be 5 mols per mol of product.

When the equilibrium curve for alcohol water mixtures is plotted as

Fig. 228, and values of x_p, x_f and x_w plotted thereon, it is clear that the whole operation cannot be carried out on a single diagram of reasonable size. Hence, three enlarged diagrams are drawn as in Figs. 229, 230, 231, and used with Fig. 228, Fig. 229 being an enlargement between the limits $x = 70$, and $x = 90$ mols per cent., and Figs. 230, 231 from $x = 5$ to $x = 0$ per cent. The enrichment lines are then drawn, the rectifying line passing through the point P (co-ordinates $x_p y_1$, Fig. 228) and with a slope of $\frac{5}{5+1} = 0{\cdot}833$, and the stripping line passing

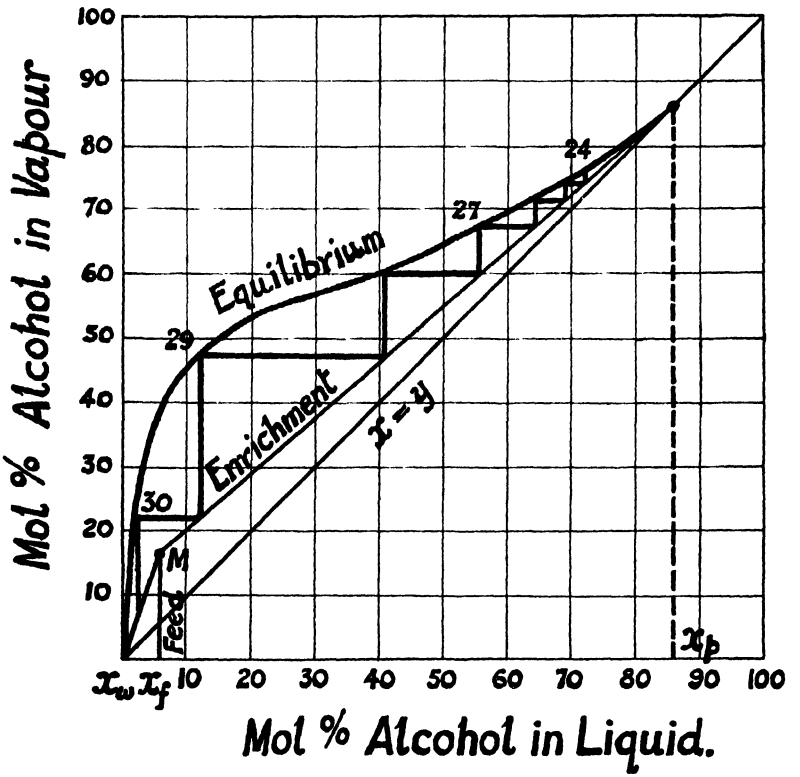


Fig. 228.

through the point M (intersection of the line $x = x_f$ and the rectifying line, Fig. 228) and the point N (co-ordinates x_w, x_w, Fig. 231). The stepwise procedure is started at P (Fig. 229) and carried through Figs. 229, 228, 230, 231 in turn, until the composition of the waste is reached with, as this case, the thirty-fifth step, so that in this case the entire column contains 34 $\frac{1}{3}$ perfect plates. The change from the rectifying line to the stripping line occurs at the thirtieth plate from the top.

Most of the plates are within the range represented by Fig. 229, and

a small error in the equilibrium curve in this range will be seen to introduce a relatively large error in the number of plates.

Effect of Removal of Restrictions Imposed by Assumptions.—The effect of using a partial condenser in place of a total condenser is that the vapour rising from the top plate is weaker than the product. The enrichment equation is unaffected if the composition of the product is known. Hence, with a partial condenser, instead of beginning the step corresponding to the first plate along the line $y = x_p$ it is begun at a

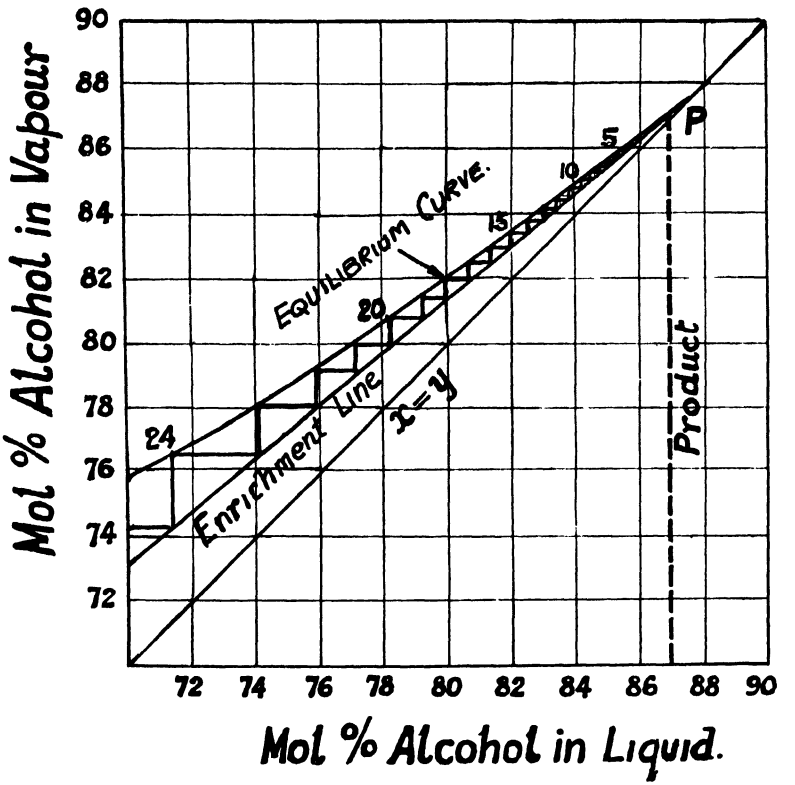


FIG. 229.

line $y = y_1$, where y_1 is less than x_p, and must be calculated from a knowledge of the working particulars of the partial condenser.

Variation of Molal Overflow.—The molal overflow may not be constant for the following reasons :—

(1) *Difference in Molal Heats of Vaporisation of Two Components.*—Allowance may be made for this by computing all quantities in " latent heat units " instead of mols, i.e. the quantities of liquid evaporated by any definite quantity of heat. Thus, if the liquids have heats of vaporisation of 969 and 305 cals per gm. the basis may be 969 calories and the latent heat units will be 969/969 and 969/305 gms. of the two

liquids respectively. They will then be treated as if they had molecular weight of 1 and 3·177. If these values are chosen they must be used throughout—in the construction of the equilibrium curve as well as expressing the compositions on each plate and of the feed, product and waste.

(2) *Change of Boiling Point of Liquids on Successive Plates.*

(3) *Heat Losses from the Column.*

These effects are usually small and rarely require consideration.

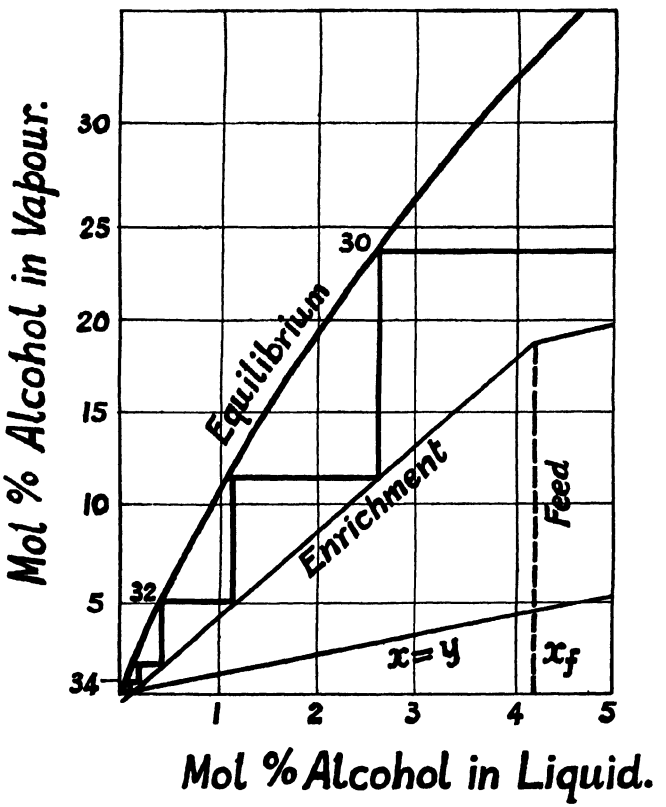


FIG. 230.

Note.—Ponchon, *Tech. Moderne*, 1921, 13, 20, 55, and Savarit, *Chim. et Ind.*, 1923, Special No., 737–56, discuss variation of overflow in a graphical manner, but the methods are rather complicated.

The foregoing calculations result in the solution of the problems in respect of the number of theoretical plates required to effect the desired separation. One of the assumptions made in the discussion was that the vapours rising from any plate are in complete equilibrium with the liquid on that plate. Such equilibrium is not attained in

practice ; the number of theoretically perfect plates is corrected by multiplying by an efficiency factor to obtain the actual number of plates required in practice.

Plate Efficiencies in Practice.—In commercial towers plate efficiencies vary from 40 to 90 per cent., but with good design and attention to detail the range should not exceed 60–90 per cent. In general, the plate efficiency can be increased by attention to the design and spacing of bubble caps, by arranging for maximum permissible depth of immersion of the caps, care in ensuring uniform and good distribution

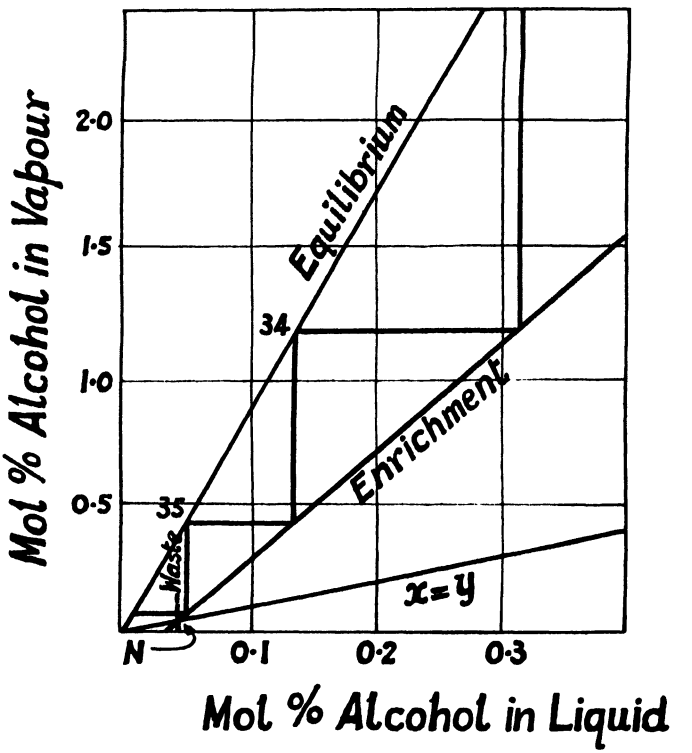


FIG. 231.

of reflux flow to prevent short circuiting of the rising vapours, prevention of excessive entrainment by baffling a limiting velocity of vapour.

The discussion of fractionation so far has been limited to binary mixtures. For terniary or more complex mixtures the treatment is naturally much more complicated. An excellent summary of various proposals for the solution of the distillation of complex mixtures has been given by Underwood (*Trans. Inst. Chem. Eng.*, 1932, **10**, 112), who deals at considerable length with this aspect of the subject.

Frequently, the method of handling mixtures of more than two com-

ponents is to remove one component in one column, and send the remainder to another column for the separation of another component and so on. To completely separate a mixture of x components $(x - 1)$ columns will be required.

There are important exceptions to the above general practice ; for example, a system comprising alcohol, fusel oil and water. Alcohol and fusel oil are miscible in all proportions, as are alcohol and water, whereas fusel oil is only slightly miscible with water. The order of volatility is alcohol–water–fusel oil, on the basis of their individual boiling points. When this mixture is distilled in a fractionating column the alcohol concentration is at the top and, at first, the fusel oil and water remain near the bottom. Due to the steam distillation action of the water upon the fusel oil, the latter is driven up the column a little, and in such columns the fusel oil-water mixture containing alcohol must be withdrawn from this point. The product will separate into two layers, a water-alcohol layer and an alcohol-fusel oil layer. The first layer may be returned to the column for recovery of the alcohol, but the second layer must be sent to a separate column. (See also p. 471.)

Again in the distillation of crude petroleum, which contains a wide variety of mutually soluble substances, there is but little difference between the boiling point of many of the individual materials, and as a consequence it is impossible to even approximate to a clear-cut fractionation. The various fractions of petroleum used in industrial work are not pure substances, but mixtures often of a large number of materials. If distilled in a single fractionating column, the low boiling constituents will predominate at the upper end of the column, whereas the high boiling ones will tend to remain at the bottom. Thus, such fractions as may be desired can be withdrawn at intermediate plates in the column.

Before continuing the theoretical discussion it is desirable to describe an actual distillation plant and Fig. 231A shows an experimental distillation unit by the Vulcan Copper & Supply Company of Cincinnati. This unit is suitably designed for operation as follows :

1. As a simple still involving the use of the kettle and condensers only, with the fractionating column by-passed entirely.

2. As a discontinuous fractionating unit involving the use of kettle, column and condensers. The operation, in this case, is analogous to the ordinary batch distillations commonly met with in practice.

3. As a continuous fractionating unit involving the use of the column and condensers with the kettle by-passed entirely.

(*a*) As a continuous exhausting column only, in which case the feed is entered on the top plate of the column by means of a feed manifold.

(*b*) As a continuous compound exhausting and rectifying column, in which the feed is entered on whatever intermediate plate is called

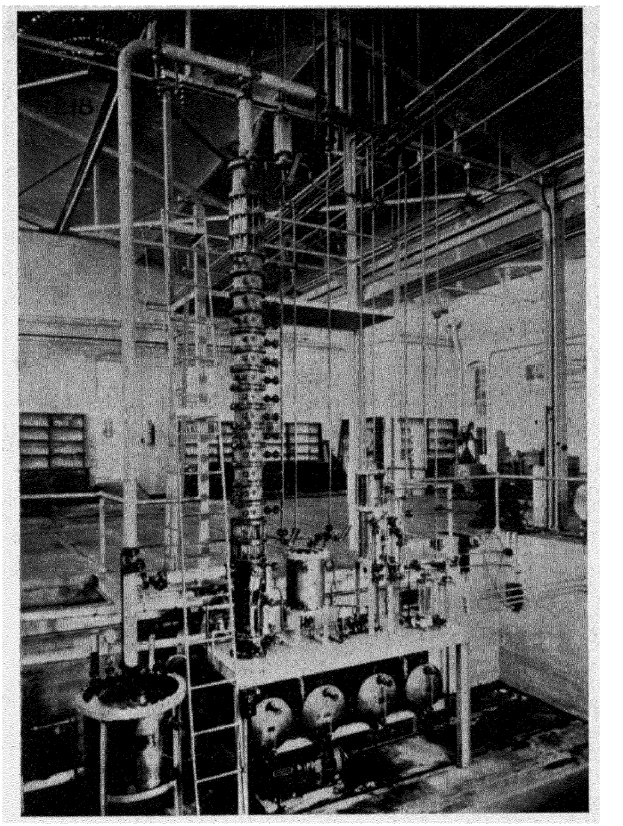


FIG. 231A.—Experimental distillation unit by the Vulcan Copper and Supply Company of Cincinnati.

[*To face page* 454.

for by the particular distillation design in question, and as obtained from equilibrium data; composition of feed, product, residue, etc.

4. Design of the equipment is such as to permit carrying out the methods of operation, as listed under Nos. 1, 2, 3(*a*) and 3(*b*) with the use of either direct or indirect steam. In order to do this the kettle is provided with a steam coil and a direct-steam sparger pipe; and the column is provided with an internal tubular calandria and a direct-steam sparger pipe.

5. A continuous decanter is included as part of the equipment and is so connected as to permit the study of distillations involving heterogeneous constant boiling mixtures of either the binary or ternary types.

6. The condensing and cooling apparatus is of modern high-velocity design for independent heat transfer study. For this reason their capacities are in considerable excess of what is actually required when operating the fractionating column. For the purpose of studying the effect of partial condensation during distillation, separate condensers are provided for reflux and for product distillate. The reflux condenser may, by means of suitable valved connections, be used as a preheater for the feed when operating continuously, or as a water-cooled condenser when running batch distillations. In order to obtain the maximum efficiency from the heat transfer apparatus, the reflux and final condensers are designed for condensing only. Therefore, a suitable vent condenser, of high-velocity tubular design, and a condensate cooler of the coil type are also provided.

7. Indicating meters of the orifice type are provided for measuring the rates of liquids flowing in all parts of the system. These include meters for feed and reflux, and combination meters and testers for the final product distillate and decanter layers.

8. Five of the plates in the fractionating column are enclosed by Pyrex Glass sections, for the purpose of permitting direct observation of vapour and liquor interaction on these plates, and also to permit the study of the weir effect of the liquid flowing over the top of the overflow pipes. Special bubbling caps with Pyrex Glass domes are provided for these five plates.

9. A complete set of indicating instruments, consisting of thermometers, pressure gauges, etc., are provided. Sampling cocks for obtaining liquid and vapour samples at all points in the system are also provided, so that complete experimental data may be obtained for calculating the actual enrichment from plate to plate in the fractionating column.

10. To permit the handling of the organic acids, as well as the alcohols, ethers, esters, aldehydes, ketones, aromatic compounds, etc., the construction of the entire equipment is of heavy copper and bronze. No solder or rivets are used in the construction; seams,

wherever necessary, are brazed with pure silver or tobin bronze. All joints are of the flanged type. This flanged type of construction applies not only to the various pieces of apparatus, but to the connecting piping, valves, and instruments as well.

11. Design of the equipment is such as to permit thorough experimental study, either singly or in combination, of the following fundamental Chemical Engineering Operations :—

(*a*) Flow of Fluids
(*b*) Flow of Heat
(*c*) Evaporation
(*d*) Distillation

12. Design of the equipment is such as to permit carrying out any of the above methods of operation either under a vacuum, or at atmospheric pressure, or under pressures up to 40 lbs. gauge. Operation under elevated pressures up to 200 lbs. gauge are permissible when metal sections are substituted for the Pyrex Glass sections in the fractionating column, and when suitably designed high-pressure indicating meters and sight glasses are substituted for the standard meters and sight glasses furnished with the apparatus. The manufacturer is prepared to furnish these substitute column-sections, meters, and sight glasses, designed for high-pressure operation, and having the same overall dimensions as those which they replace. In other words, the substitution of such parts may be done without in any way disturbing or changing the original arrangement of connection-piping on the equipment.

13. The arrangement of the interconnecting piping is such as to permit changes in the methods of operation corresponding to those outlined under Nos. 1, 2, 3(*a*), 3(*b*), 4, 5 and 6, solely by opening and closing the proper valves. In other words, it is not necessary to blind off openings, insert new piping and valves, etc., when it is desired to change to a different equipment set-up.

14. The flexibility of the unit is further enhanced due to the fact that all plates in the column are between flanges permitting the addition of one, or any number of additional plates at a future time with a minimum outlay of expense and time.

Batch Distillation.—The discussion of distillation principles has so far been confined to continuous distillation. Often batch distillation is desirable, and it is to be noted that there are important differences between the two methods of separation.

In continuous distillation the composition of the product and waste material is decided upon after consideration of the rate and composition of feed, and so the design of the necessary equipment depends upon an economic balance between reflux, number of plates and diameter thereof, and heat requirements. Again for a constant rate of distillation the composition and quantity of vapour and liquid streams are constant at any given point in the system.

In batch distillation, however, a batch of liquid is charged into a still and heated. When the vapours have reached the condensing arrangements a portion of the liquids are returned to the column as reflux. Further, there is a continuously decreasing quantity of the more volatile constituent or constituents in the still, leading to continuously changing conditions of feed, reflux and product.

For example, if the charge consists of ethanol and water, and it is desired to remove as much alcohol from this mixture as is economically desirable, the continuous removal of the alcohol from the still necessitates a continuously increasing reflux rate to maintain the desired purity of the product.

It is usual to arrange for the rate of vaporisation from the still to be constant and to increase the reflux rate by decreasing the amount of product withdrawn from the condenser so that more and more is used as reflux. The following table is taken from Sorel, " Rectification de l'alcohol," 1895, p. 55, and gives the alcohol content per cent. of the liquid on the plates of a discontinuous rectifying column.

Number of Plates from Bottom.	*Alcohol Volume (per cent.).*
49	96·3
44	95·9
39	95·6
29	95
19	94
14	93
9	92
4	87·5
Still	33·6

Determination of Number of Plates in Batch Rectification.

The principles of the McCabe-Thiele method may be applied to determine the relationship between reflux rate and number of plates at any given instant in the distillation cycle.

For different residual concentrations various combinations of reflux flow and column height may be taken, and these will serve as a basis for computing the final still concentration to which it is practicable to exhaust, and the number of plates desirable.

Steam Distillation.—Steam distillation may be carried out in one of two ways : the first is when a mixture of water and an organic liquid is boiled at atmospheric pressures. The second is when steam is generated in a separate vessel and blown into the liquid to be distilled. In the latter case the latent heat of the steam may be the only source of heat, when a layer of water will form within the still because of the condensation of the steam, or the steam may be superheated to avoid such condensation, or if saturated steam is supplied the still may be heated by, say, a steam jacket to effect the same result. It is to be

noted that steam distillation can only be applied when the product is completely, or almost completely, immiscible with water.

Steam distillation is used for the distillation of materials having a relatively high boiling point at atmospheric pressure or which are liable to decompose at the ordinary boiling point. This process is used in connection with substances such as turpentine, in which case, direct fire heating, one other method available, would be dangerous on account of the fire risk, or fatty acids which would decompose at the

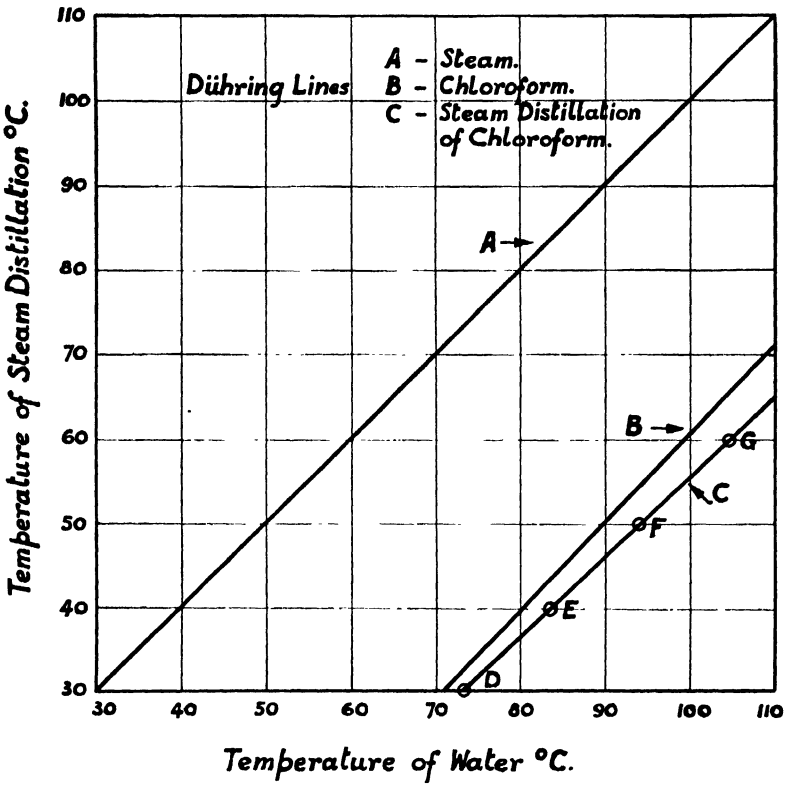


FIG. 232.

ordinary boiling point, nitrobenzene, anilin, etc. Steam distillation may be used to separate ortho- and para-phenols and the separation of many essential oils and compounds of high molecular weight.

The principle of steam distillation is that in the case of mixtures not mutually soluble the vapour pressure of the components are additive. The boiling point of the mixture of water and the other component is thus lowered. Hence, the temperature at which the liquid distils is lowered, and in addition the injected steam keeps the mass thoroughly agitated. In the case of anilin, which boils at 180° C., at ordinary atmospheric pressure, if steam is injected the anilin is heated to only

98°, when the combined vapour pressures of anilin and water are equivalent to atmospheric pressure. Thus, boiling commences and the mixed vapour of anilin and steam comes away.

In industrial practice steam distillation is effected in cylindrical pans usually externally heated by steam jacket, with steam injected through a perforated pipe around the lower interior of the inner pan. A plain condenser is used to collect the distillate, and since the water and material are immiscible, separation is easily effected.

A graphical method for calculation of steam distillation problems

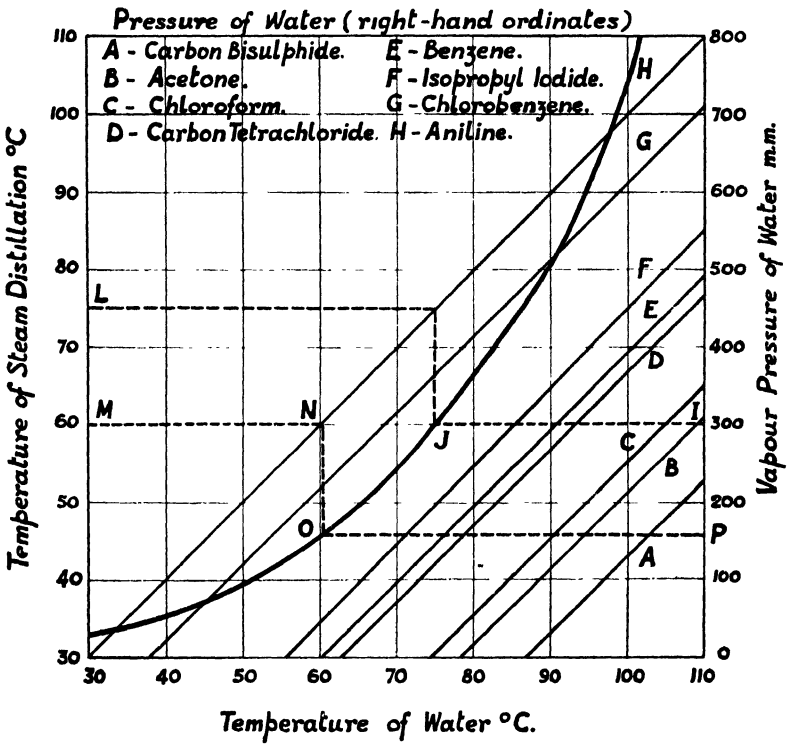


FIG. 233.

has been proposed by Baker and Pettibone (*Ind. Eng. Chem.*, 1929, **21**, 562), which is briefly as follows :—

The method is based on the use of "Dühring lines" ("Neue Grundgesetze zur Nationelle Physik und Chemie," Erste Folge, Leipzig, 1878), which are obtained by plotting the temperature at which a substance exerts certain vapour pressures as ordinates, against the temperatures at which some suitable reference liquid such as water exerts the same pressures as abscissæ. It is found that the relationship is linear, and this depends upon the fact that the vapour pressure temperature curves of nearly all substances are similar in shape.

It has already been noted that the pressure at a given temperature is the sum of the partial pressures of the steam and substance being distilled. Most substances follow Dühring's rule closely when plotted against water, and water plotted against itself, naturally, gives a straight line. Hence, it is to be expected that if the temperature required for steam distillation were plotted against the temperatures at which water exerted vapour pressures equal to the sum of the partial pressures of steam and the substance being distilled, the result would be a straight line. In Fig. 232 curve A is the Dühring line for steam, curve B for chloroform and curve C for the steam distillation of chloroform. Curve C is obtained as follows :—At 30° C., the vapour pressure of chloroform is 246 mm., of water is 31·7 mm.—total pressure 277·7. If steam distillation is to be carried out at 30° the pressure therefore would have to be 277·7 mm. which is the pressure of water at 74° C. Point D, Fig. 232, is plotted with these co-ordinates. Similarly, at 60° C., the vapour pressure of chloroform is 739·6 mm. and of water 149·2 mm. Water exerts a pressure of 888·8 mm. (739·6 + 149·2) at 104·4° C. The point G is then plotted and a straight line drawn between D and G (points E and F are check points). At any given steam distillation temperature, therefore, from this graph can be found the corresponding temperature at which water has a vapour pressure equal to that necessary for carrying out the distillation. The pressure of the distillation process can then be obtained from the usual steam tables.

DATA FOR STEAM DISTILLATION (WITH SATURATED STEAM) OF VARIOUS SUBSTANCES.

Substance being Distilled.	Slope and Intercepts on Dühring Lines.		
	Slope.	Intercept on 100° C. H_2O Line.	Intercept on 50° C. H_2O Line.
Carbon bisulphide . . .	0·994	43·2	— 6·5
Acetone	0·972	52·3	3·7
Chloroform	0·984	55·6	6·4
Carbon tetrachloride . .	1·000	67·0	17·0
Benzene	0·992	69·5	19·9
Isopropyl iodide . . .	0·986	74·7	25·4
Chlorobenzene	0·968	91·0	42·6
Anilin	0·980	98·6	49·6

Fig. 233 gives Dühring lines for the steam distillation of a number of substances plotted against water as a reference liquid. For convenience, there is also plotted the vapour pressure curve of water OJ. To find the pressure at which any of the substances may be steam distilled

at a particular temperature, go horizontally across the chart to the Dühring line, then down to the vapour pressure curve of water and across to read the pressure. Line MNOP illustrates this by determining the pressure at which anilin would steam distil at 60° C. Point M is the temperature of distillation (60° C.), point N is the corresponding temperature at which water exerts the same vapour pressure, and point O (or P) this pressure, which is 152 mm.

This method is equally applicable to the steam distillation of complex mixtures which obey Dühring's rule, e.g. octane and hexane, hexane-heptane, heptane-octane.

Practical Distillation Plant.

The following notes on the practical design of fractionating columns for batch stills are taken from an article by Bewsher (*Industrial Chemist*, 1937, **13**, 424). Three representative types of columns are discussed, and the first two are illustrated in Figs. 234 and 235. A common design in the tar industry (Fig. 234) comprises a mild steel still body; with either cast iron or mild steel column. Such stills are used for the preparation of benzol, and for such purposes they are made in sizes up to 10 ft. 6 ins. dia. by 40 ft. long. Fig. 235 is the familiar pot still, and is commonly used for general batch distillation.

Fig. 235A shows a batch distillation plant specially designed for the close cutting in the rectification of benzene, toluol, and the like. The plant includes a horizontal still, a bubble cap or ring-packed fractionating column, dephlegmating and condensing equipment for the production of reflux. Dowtherm vapour or high-pressure steam is used for heating the still.

The above stills (Figs. 234 and 235) are fitted with the following types of column :—

(1) *Perforated Deck Column.*—This is seen in Fig. 236. Each column section consists of three decks, and the construction will be clear from the figure.

In this perforated deck column the liquid stream is split up by allowing it to flow through a large number of small holes in the column decks, and the ascending vapour to pass back and forth from side to side by passages made in the decks on opposite sides. If sufficiently high these columns are effective for rough distillation work such as the preliminary distillation into components of lighter coal-tar fractions.

The usual dimensions of this perforated deck column with closed overflow as in Fig. 236 are as follows :—

Distance between decks	= 0·166 × column dia., but not less than 6 ins.
Height of each section	= 3 × above distance.
Aggregate area of holes in deck	= 1 sq. in. for every 75 sq. in. of column cross section.

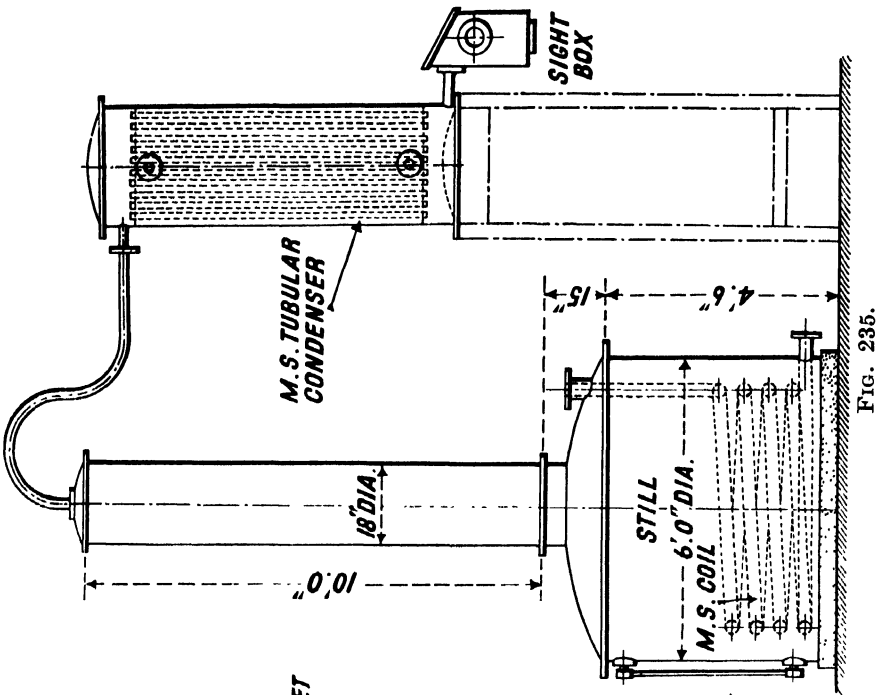


Fig. 235.

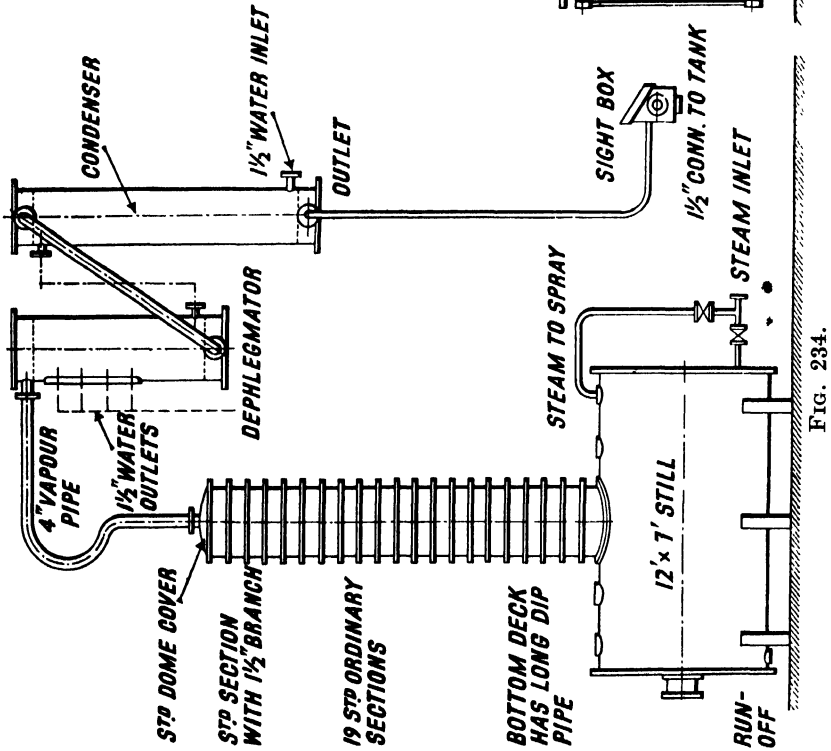


Fig. 234.

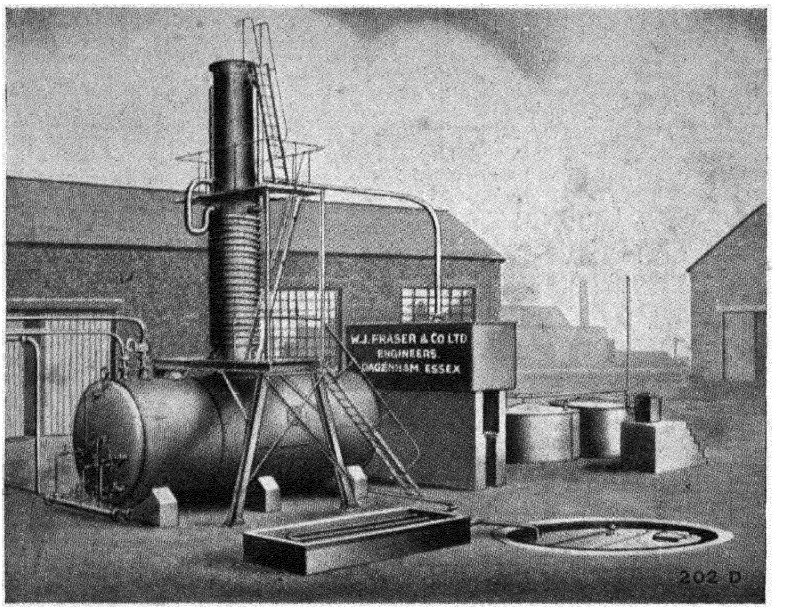


FIG. 235A.—Periodic distillation plant by W. J. Fraser & Co., Ltd., of Dagenham.

[*To face page* 463.

Dia. of holes in deck = 4 mm.
Dia. of overflow pipes = 0·08 internal dia. of column.
Dia. of vapour inlet and outlet connections = 0·166 × internal dia. of column.

This perforated deck type of column can be made more cheaply by omitting the closed overflow arrangements, and it then becomes practically a sieve plate column (see Fig. 217). The type with closed overflow is, however, much more efficient.

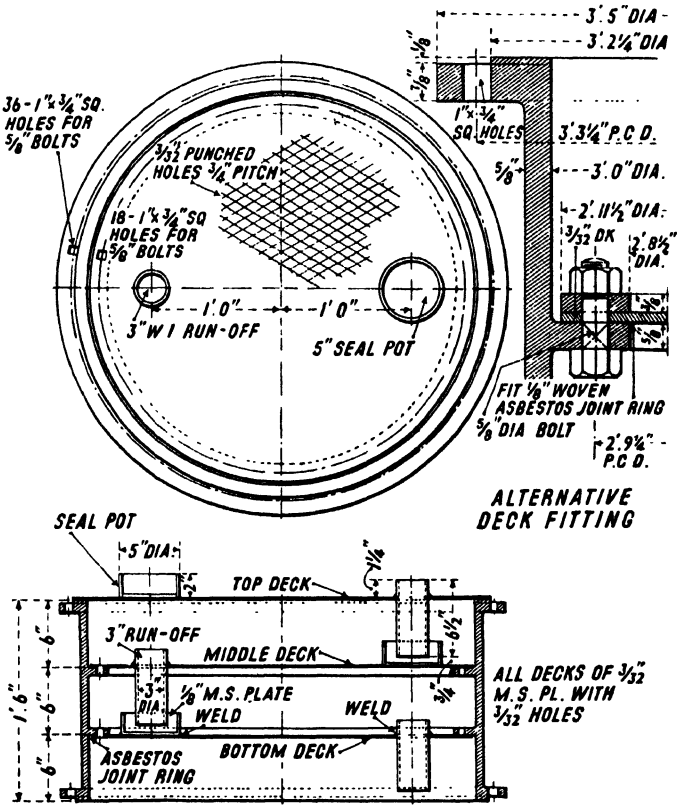


FIG. 236.—Standard section of perforated deck fractionating column.

(2) *Bubble Cap Columns.*—Much has been written about the principles of design of bubble cap column, but in practice it is found that such equipment permits of great flexibility provided that it is reasonably well proportioned and operating within its capacity. There are three principal types of design of bubble cap column :—

(*a*) Multiple nozzle type, which embodies a number of nozzles per deck of comparatively small diameter, with small circular bells.

(*b*) Single nozzle type, in which only one large bell and nozzle are fitted to each deck.

(*c*) The oblong nozzle type, which comprises one or more long narrow nozzles extending in most cases across nearly the full width of the deck, and fitted with bells of similar shape.

The first type is most generally used, and in practice nozzle dia-

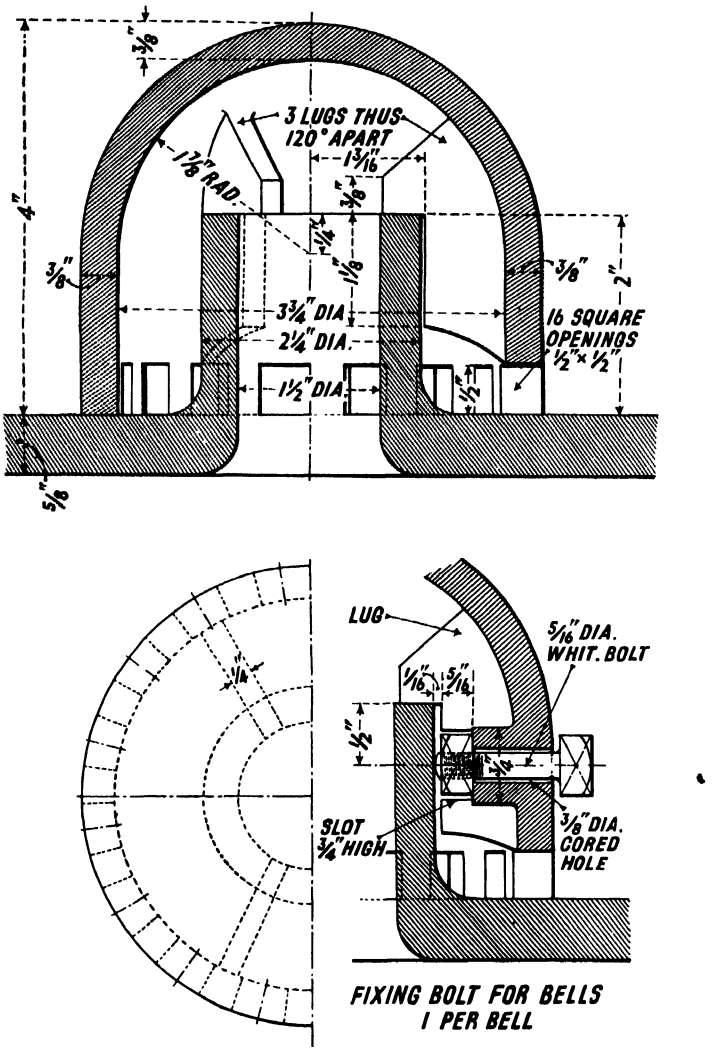


FIG. 237.

meters vary between 1¼ to 4½ in. The larger sizes are suitable for stripping stills where a considerable amount of steam is injected, whereas the smallest sizes, viz. 1¼ in., 1½ in., 2 in., are ordinarily used for close fractionation. The optimum size for many problems is about 1½ in. dia., and the principal dimensions of this size are given

in Figs. 237 and 238. The Table at the foot of this page gives details of standard columns with this type of bell.

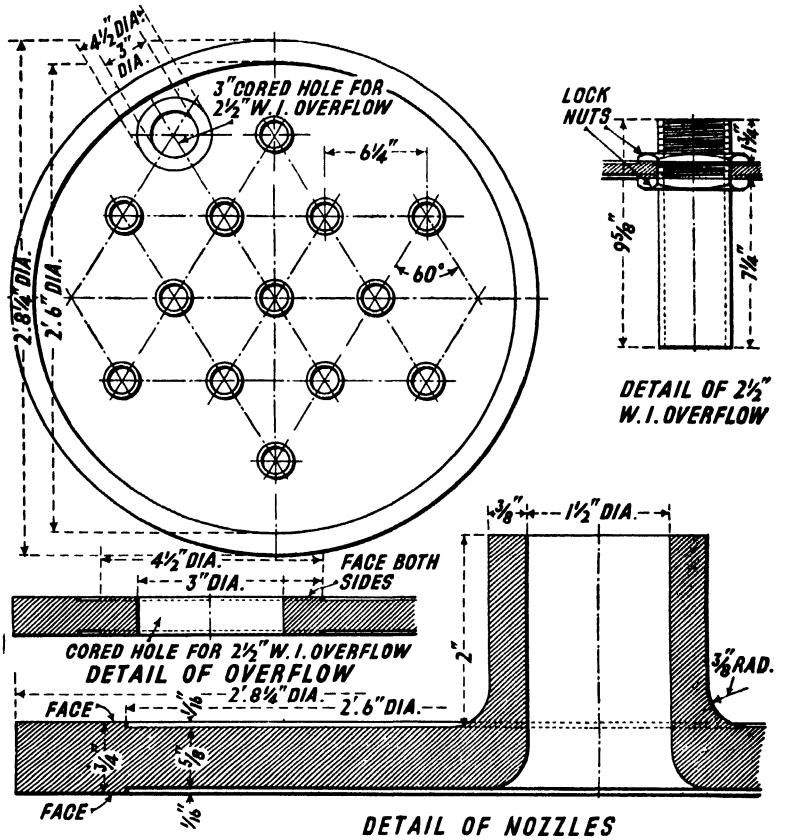


FIG. 238.

Column dia. (ins.).	No. of Bells per Deck.	Gross Length of Barbotage per Deck (ins.).	Gross Area of Deck (sq. ins.).	Ratio of sq. in. of Deck to 1 in. Barbotage.
9	1	14·14	63·6	4·5
12	2	28·3	113	4·0
15	4	56·6	177	3·1
18	5	71	254	3·6
21	7	99	346	3·5
24	7	99	452	4·6
30	13	184	707	3·8
36	19	268	1,018	3·8
42	27	382	1,385	3·6
48	33	467	1,809	3·8
		Average of 10		3·83

The number of bells per deck is best calculated on a basis of so many sq. ins. of gross deck area per lineal inch of barbotage. Bewsher states that in his experience practical bubble cap columns vary between 3–6 sq. ins. of gross deck area for every lineal inch of barbotage. From centre to centre of nozzles, Bewsher recommends 1·5 times the bell dia. The above spacings of bells are seen in Fig. 239.

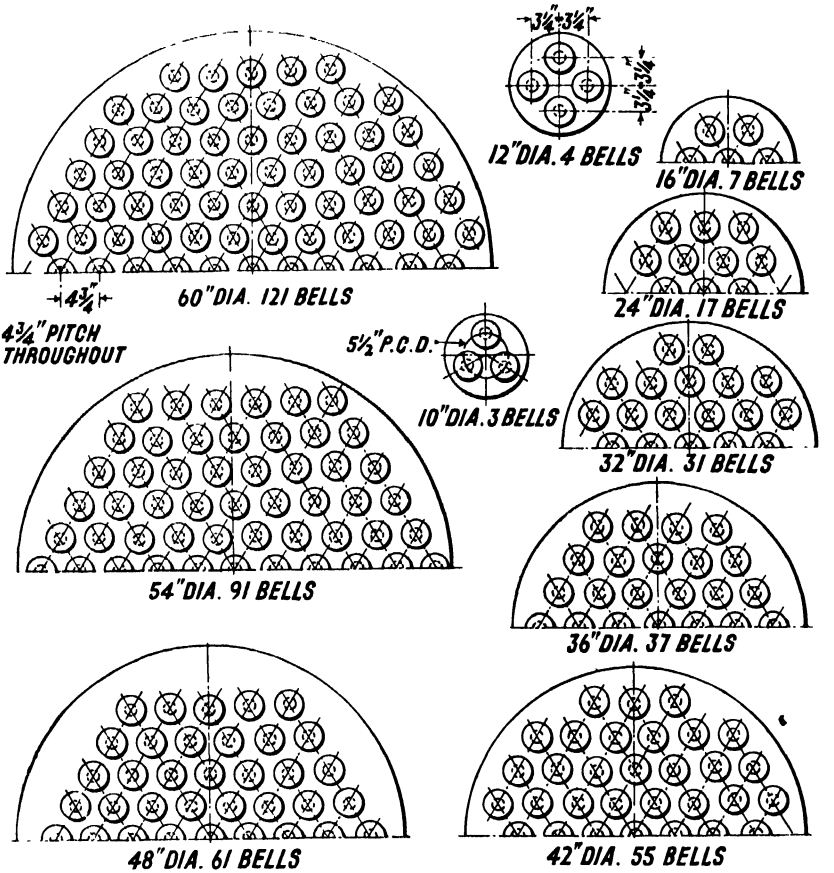


FIG. 239.

Bewsher also gives some interesting details of the construction of columns in non-ferrous materials, and concludes the series of articles with some particulars about packed columns.

(3) *Packed Fractionating Columns.*—The packed column consists essentially of an empty vertical cylinder filled with one of the various types of cylindrical packing such as the Lessing contact rings illustrated in Fig. 216. In long columns the packing may, if necessary, be supported at intervals upon perforated grids.

One of the greatest advantages of the packed column is the ease

with which it may be constructed and if necessary modified, and Fig 240 gives typical dimensions of a column in mild steel. This is conveniently divided into four sections, each 4 ft. long, with a perforated deck at each section-flanged connection.

Another advantage of the packed column is that it permits of a wide choice of materials of construction and does not involve expensive fabrication. For example, the column shown in Fig. 241 is constructed in the well-known high silicon iron " Narki," and it is fitted with spigot

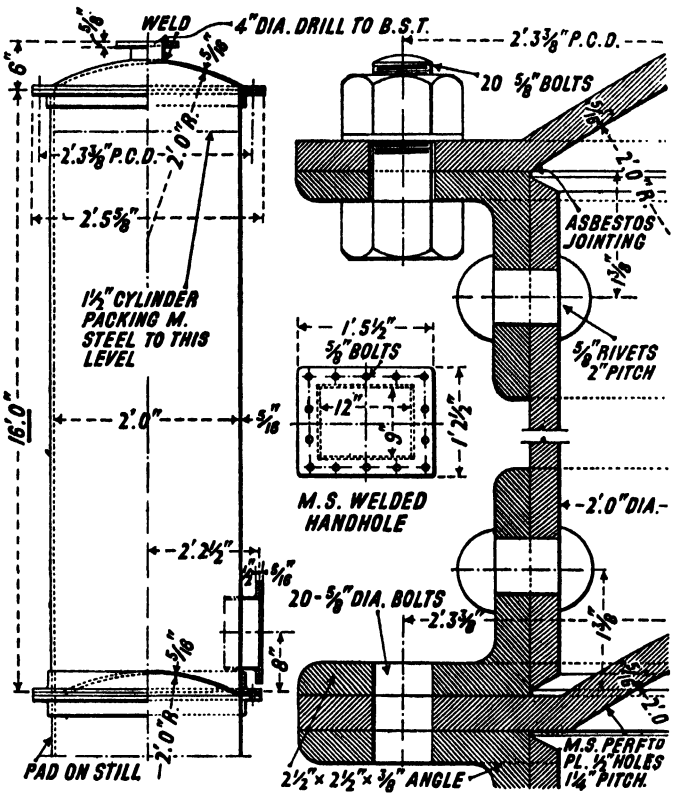


FIG. 240.—Column construction for use with mild steel packers.

and socket joints so that no difficulty is experienced as would be the case if flanging, etc., were necessary. The packing rings may be of stoneware or other non-corrosive material.

Fig. 242 shows a typical copper or non-ferrous metal column much used for handling the distillation of fermentation products and the like. Naturally the number of decks and plates depends upon the nature and quality desired from the distillation operation, but the dimensions given provide apparatus suitable for a surprisingly wide range of operations. Examples of nozzles and bells used in

these copper columns are seen in Figs. 243 and 244, and the dimensions of the bells, etc., are arranged as in the Table below.

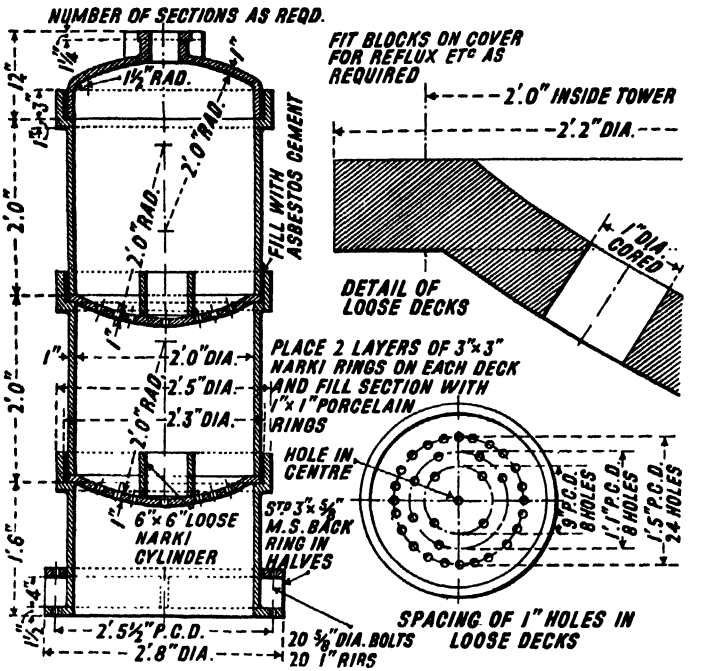


FIG. 241.—A column constructed with socket and spigot joints.

RATIO OF DECK AREAS TO LENGTH OF BARBOTAGE COLUMN IN NON-FERROUS MATERIAL FOR USE IN THE FERMENTATION INDUSTIES.

Column dia. (ins.).	No. of Bells per Deck.	Gross Length of Barbotage per Deck (ins.).	Gross Area of Deck (sq. ins.).	Ratio of sq. in. of Deck to 1 in. Barbotage.
10	3	33	78·5	2·38
12	4	44	113	2·57
16	7	77	201	2·61
24	17	187	452	2·42
32	31	341	804	2·35
36	37	407	1,018	2·50
42	55	605	1,385	2·29
48	61	671	1,809	2·70
54	91	1,001	2,290	2·28
60	111	1,221	2,827	2·31
			Average	2·441

Methods of Separating Constant Boiling Mixtures.

Sunier and Rosenblum (*Ind. Eng. Chem. An. Ed.*, 1930, **2**, 109), discuss the separation of constant boiling mixtures by distillation under reduced pressure. The ethyl alcohol-water system allows of much better separation by distillation under reduced pressure, which is explained as follows: At 760 mm. pressure the alcohol-water

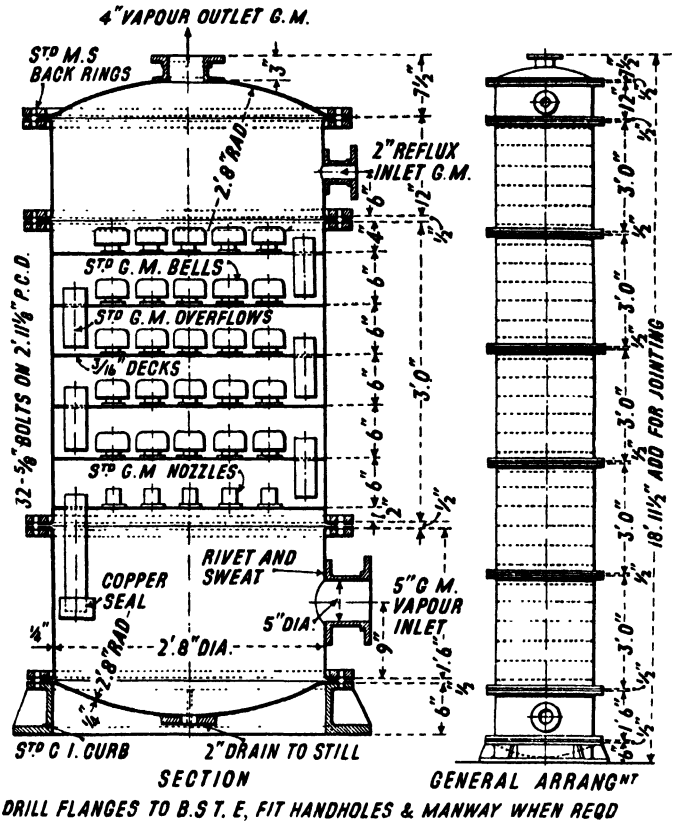


FIG. 242.—Dimension of a multiple-deck copper column.

mixture contains 4·4 per cent. water, but a complete separation takes place under a pressure of 70 mm. (27·96° C. is the boiling point of absolute alcohol under these conditions). Thus fractionation of the minimum constant boiling mixture at moderately reduced pressure will produce absolute alcohol, and this principle has been adopted in the well-known Barbet patent (see Patart, *Bull. Soc. Enc. Ind. Nat.*, 1924, **136**, 188–201).

Freezing out may also be used as a method of separation, and silica gel. has been found to split up azeotropic mixtures (Grimm, *Z. Angw. Chem*, 1928, **41**, 98, 104).

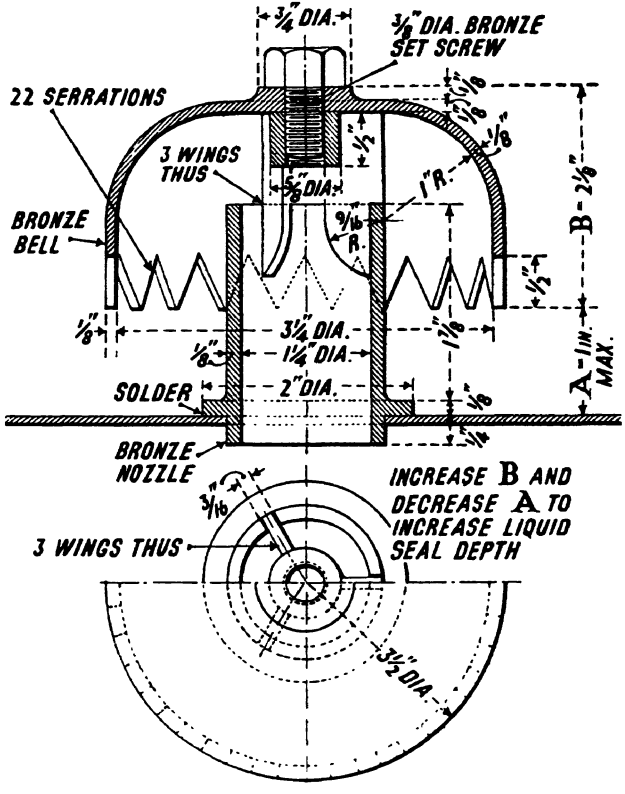


FIG. 243.—A serrated-edge cast non-ferrous metal bell.

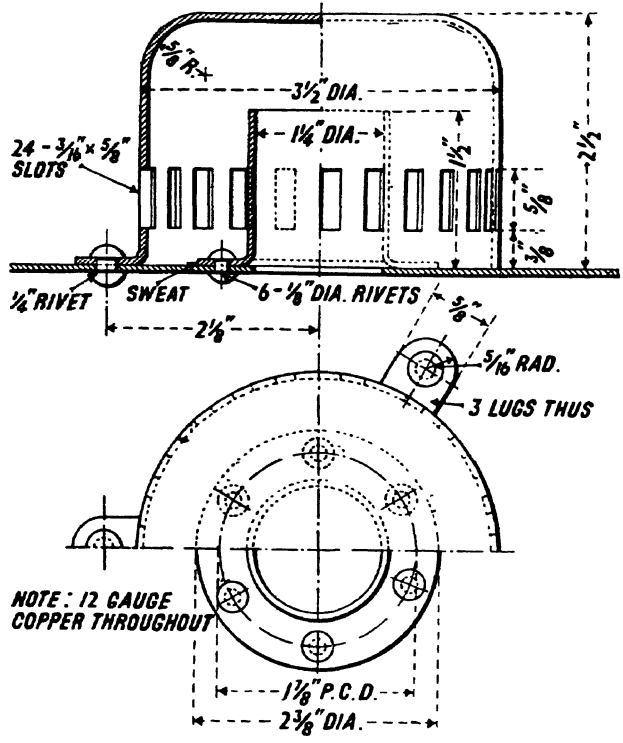


FIG. 244.—Another type of non-ferrous bell employing a riveted construction.

Azeotropic Distillation.—The following notes on this subject are given from a recent paper by Guinot and Clark. (*Adv. Proof Inst. Chem. Eng.*, Nov. 1, 1938):

Azeotropic Mixtures, binary and ternary, or, in other words, mixtures of constant boiling point containing two or three constituents have long been known. They are of two types, namely those in which the boiling point of the mixture is:—

(*a*) lower than that of any of its constituents.
(*b*) higher than that of any of its constituents.

It seems to be a fair statement that the possibility of making practical use of azeotropic mixtures was not realised until Professor Sydney Young prepared absolute alcohol by making use of the ternary azeotropic mixture, ethyl alcohol—benzene—water, the composition of which is:—

Alcohol	18·5 per cent.
Benzene	74·1 „ „
Water	7·4 „ „

The boiling point of this mixture is 64·85° C.

Professor Young carried out this work during 1902, using a discontinuous process. Until some twenty years later, when the first continuous processes for manufacture were evolved, and plant was subsequently designed in which these processes could be carried out, no real progress was made in the art.

During 1918, Lecat published his interesting and valuable book, "L'Azeotropisme." The following extracts from this book, both of which refer to the preparation of absolute alcohol by Young's process, are significant. The first on page 60, at the end of paragraph 54, reads as follows (translation): "In passing it may be said that the process is not a practical one and it has not been given as such. The preparation is difficult and there is a considerable loss of alcohol." Again, on page 61, the statement is made that: "The losses of alcohol are much greater than those in the lime process, which is still the most practical."

Despite the above statements it is interesting to note that Young, in his book "Distillation Principles and Processes" (page 194, second edition), states that: "The (azeotropic) method has been employed since 1908 by Kahlbaum of Berlin for the production of absolute ethyl alcohol from strong spirit."

Two of the most interesting commercial applications of azeotropic distillation are as follows:—

Manufacture of Absolute Alcohol

It was not until the year 1923 that Backus, Keyes and Stevens in the U.S.A., and Guinot in France, almost simultaneously developed

continuous processes for the manufacture of absolute alcohol, the ternary azeotropic mixture, ethyl alcohol—benzene—water, being involved. This was the real starting point of all commercial development of azeotropic distillation processes.

Since then hundreds of such plants have been installed, and to-day upwards of 40,000 hl. (880,000 gal.) of absolute alcohol are produced daily by azeotropic processes. Certain of these plants are capable of producing upwards of 1000 hl. during 24 hours.

Less than 15 years ago only a few hundred hectolitres of absolute alcohol were produced each year—mainly by the lime process—for use in pharmacy and in laboratories.

The following facts, as determined by Young, are involved in the continuous processes, as they were in his discontinuous process, though entrainers other than benzene are used in certain cases. The underlying principles are, however, the same as those about to be described.

(1) When the ternary azeotropic mixture (boiling point 64·85° C.), alcohol—benzene—water, is distilled and condensed, it separates into two layers. The top layer represents 84 per cent. of the volume of the distillate and has approximately the following composition (at 20° C.) :—

Alcohol	14·5 per cent.
Benzene	84·5 „ „
Water	1·0 „ „

The lower layer, representing the remaining 16 per cent. of the mixture, has the following approximate composition :—

Alcohol	53 per cent.
Benzene	11 „ „
Water	36 „ „

The composition of the layers varies greatly with the temperature of the decanted mixture. When this is effected at a temperature close to that of the boiling point of the azeotropic mixture, the volume of the lower layer is greatly diminished, but its water content is increased to almost 50 per cent.

(2) The binary azeotropic mixture, benzene—alcohol, contains 67·6 per cent. of benzene and boils at 68·2° C.

The process is carried out by passing the 96 per cent. alcohol, with the requisite quantity of entrainer, into Column A (Fig. 245). On heating by means of the closed steam coil shown, the ternary azeotropic mixture is formed at the head of the column whilst absolute alcohol is obtained at the base. In the intermediate zone a mixture of entrainer and alcohol containing only a little water is obtained. In theory the entrainer, which is added initially, serves indefinitely and is added in quantity sufficient to allow of rapid dehydration, but not in such excess that it contaminates the absolute alcohol produced. Actually it is necessary to make good the inevitable small losses of

entrainer which occur, but the quantity involved should not exceed 0·05 per cent. of the volume of the absolute alcohol produced.

The vapours of the ternary azeotropic are condensed and passed in part to the decanter B, in which the mixture separates into two layers. The upper layer, rich in entrainer, is returned to the head of column A, and the lower aqueous layer is passed to a small column C, in which the entrainer is recovered (as azeotrope) and returned to the head of column A.

At the base of column C, aqueous alcohol is obtained and this is passed to column D at the head of which 96 per cent. alcohol is produced and passed to column A for dehydration. From the base of column D, water free from alcohol flows away.

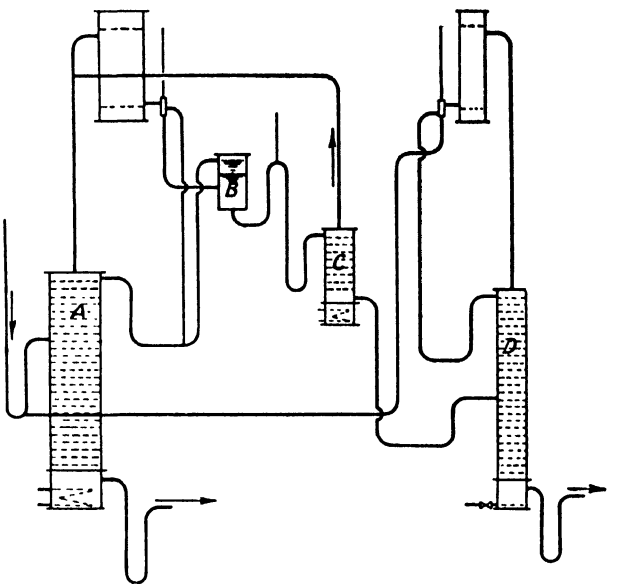


FIG. 245.—Manufacture of absolute alchohol from 96 per cent. spirit.

Numerous liquids may be used as entrainers. Those which have been employed are benzene, trichlorethylene, cyclohexane, and, finally, certain special fractions of petroleum spirit. In practice the entrainer most generally used is a mixture of benzene and a petroleum spirit with a boiling range between 95° and 100° C. The successful use of the latter, despite its high boiling point, provides an example of the surprising results obtained when dealing with azeotropic phenomena.

By making certain modifications in the plant it is possible to produce absolute alcohol direct from distillery wash or fermented wines. The arrangement of the plant for this purpose is shown in Fig. 246.

These wines, or washes, are distilled in column A in the ordinary

way, so that wash free from alcohol (spent wash) is eliminated at the base, while 96 per cent. alcohol is obtained at the head. If an entrainer is added to this last, the contents of the column are classified, as shown in Fig. 246, with the ternary azeotropic mixture at the head of the column. After condensation a portion of this mixture is passed into a decanter B and it separates into two layers. The upper layer

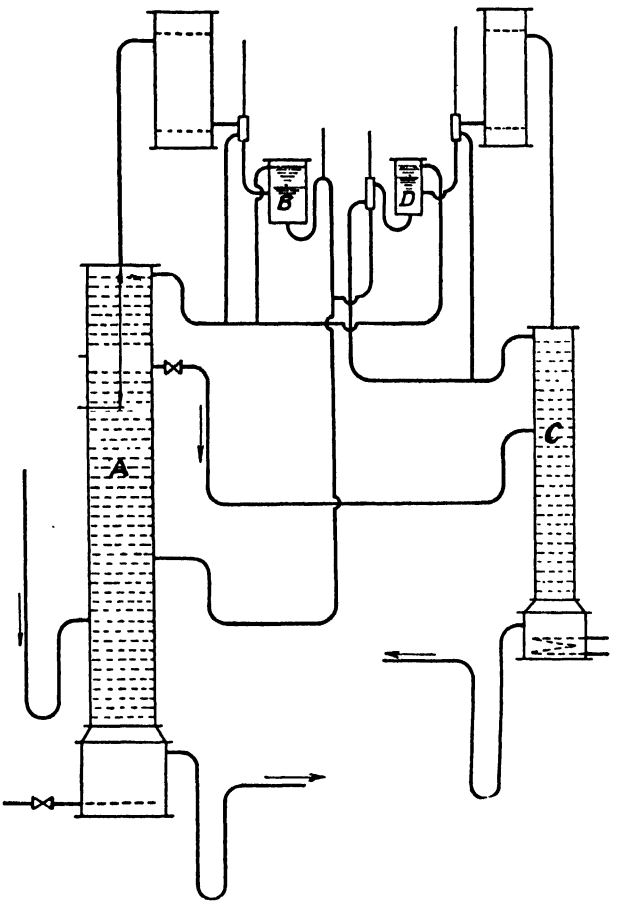


FIG. 246.—Manufacture of absolute alcohol from wines or washes.

is passed back to the head of column A and the lower layer is passed to the lower part of the column.

Virtually, anhydrous alcohol is drawn, together with some entrainer, from a point just below the zone in which the ternary azeotropic mixture is produced. This alcohol is led to column C, at the base of which absolute alcohol is obtained. The vapours at the head of this column, which in the main consist of the binary azeotrope, alcohol-entrainer, are condensed and passed in part to a second decanter D

from which the upper layer is sent to the head of column A, and the lower layer is passed to the lower part of the same column.

The working of column A is very interesting. In the first place the plates charged with alcohol in the zone of concentration prevent the water on the lower plates from rising. Secondly, the entrainer in the upper part of the column removes the major part of the water (through the agency of the ternary azeotropic mixture) from the binary azeotropic mixture—alcohol water. By this technique, under certain conditions of working, it is possible to obtain an alcohol of 99·4 per cent. strength from the zone in which the entrainer is separated from alcohol. Such a result is somewhat paradoxical, as water in quantity is present at the same time both at the base and head of the column. This demonstrates in a striking manner the remarkable results obtainable by use of the artifices of distillation involving the use of azeotropic methods. With their aid, absolute alcohol is obtained as easily as 96 per cent. alcohol, and at approximately the same cost.

Manufacture of Ethyl Acetate.

The process about to be described furnishes a characteristic example in which distillation processes contribute in influencing a reversible reaction in a favourable manner.

A still is charged with ethyl alcohol, containing a small quantity of a strong mineral acid as catalyst, and the mixture is boiled. An equimolecular mixture of ethyl alcohol and acetic acid is then added continuously, whereupon, owing to the large amount of ethyl alcohol present, ethyl acetate is produced almost instantaneously. The ethyl acetate and water produced by the reaction must be quickly removed, otherwise the reaction is slowed down and finally ceases.

To effect this removal the still is attached to a column A (Fig. 247) and in this the ternary azeotropic mixture, ethyl acetate—alcohol—water, is built up. This mixture boils at 70·3° C. and has the following composition :—

Ethyl Alcohol	7·6 per cent.
Ethyl Acetate	84·5 „ „
Water	7·9 „ „

From this mixture it is impossible to obtain pure ethyl acetate by simple rectification. Instead, it is necessary to make use of a method called " hydro-selection," which is carried out as follows.

The vapours of the ternary azeotropic mixture are passed into the centre of column B, into the top of which is led water at the temperature of 70·5° C., this being the boiling point of the binary azeotropic mixture, ethyl acetate—water.

In this way ethyl acetate rises to the head of the column as the binary azeotrope, whatever may be the composition of the vapour mixture. It is quite different with the alcohol, as the composition

of the vapours furnished by boiling a mixture of alcohol and water varies according to the alcoholic content of the mixture. In any case mixtures of alcohol and water cannot boil at a temperature below 78·3° C.

The wet ethyl acetate vapour from the head of column B is condensed and passed to a decanter, from which ethyl acetate containing 3 per cent. of water is passed to column C. Here the ethyl acetate is dehydrated, owing to formation of the binary azeotropic mixture, ethyl acetate—water, which contains 8·6 per cent. of water, and boils, as stated earlier, at 70·5° C. Anhydrous ethyl acetate is withdrawn from the base of the column.

The weak alcohol flowing from the base of column B is passed to column D and there concentrated to give 96 per cent. alcohol. This

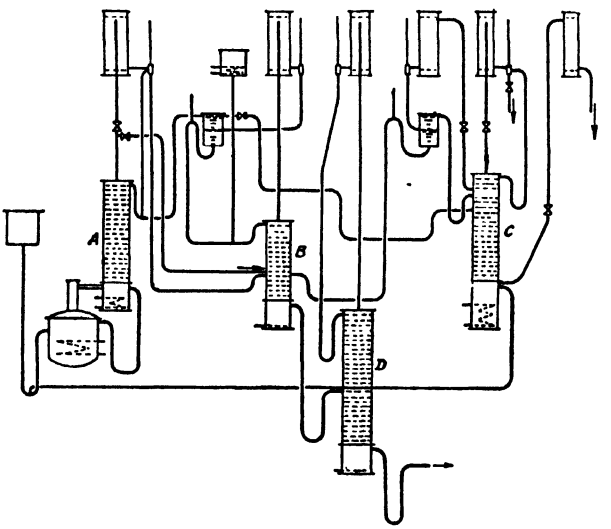


FIG. 247.—Manufacture of ethyl acetate, etc.

is returned to the still, and water containing a mere trace of acetic acid is run to waste from the base of the column.

By making modifications in the operation of the same plant other esters may be produced, for example, butyl and amyl acetates, ethyl, butyl and amyl formates, ethyl, butyl and amyl propionates, ethyl, butyl and amyl butyrates. In every case use is made of azeotropic mixtures.

Other examples of azeotropic distillation in industrial chemistry are in the manufacture of ethers, diethyl acetate, concentration of acetic acid, and acetic anhydride.

Vacuum Fractionation—Evaporation Distillation.

Burch (*Proc. Roy. Soc.*, 1929, **123**, 271) describes an evaporation still for the high vacuum distillation and fractionation of organic

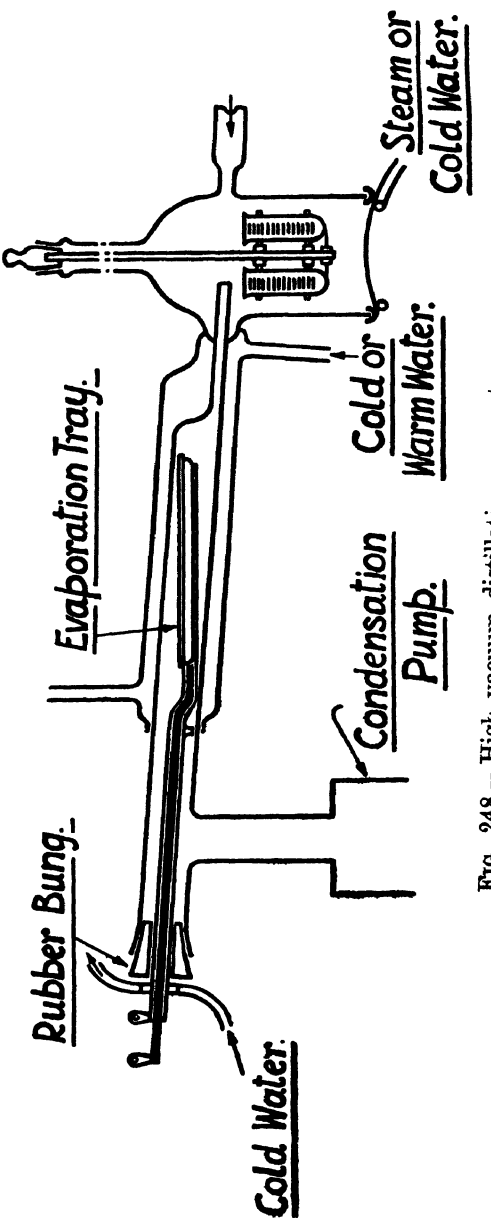


FIG. 248.—High vacuum distillation apparatus.

substances without decomposition. The underlying principle is that a cold condensing surface is placed a very short distance above the liquid to be distilled, so that a vapour molecule rising from the heated liquid will in general make no collision during its passage to the con-

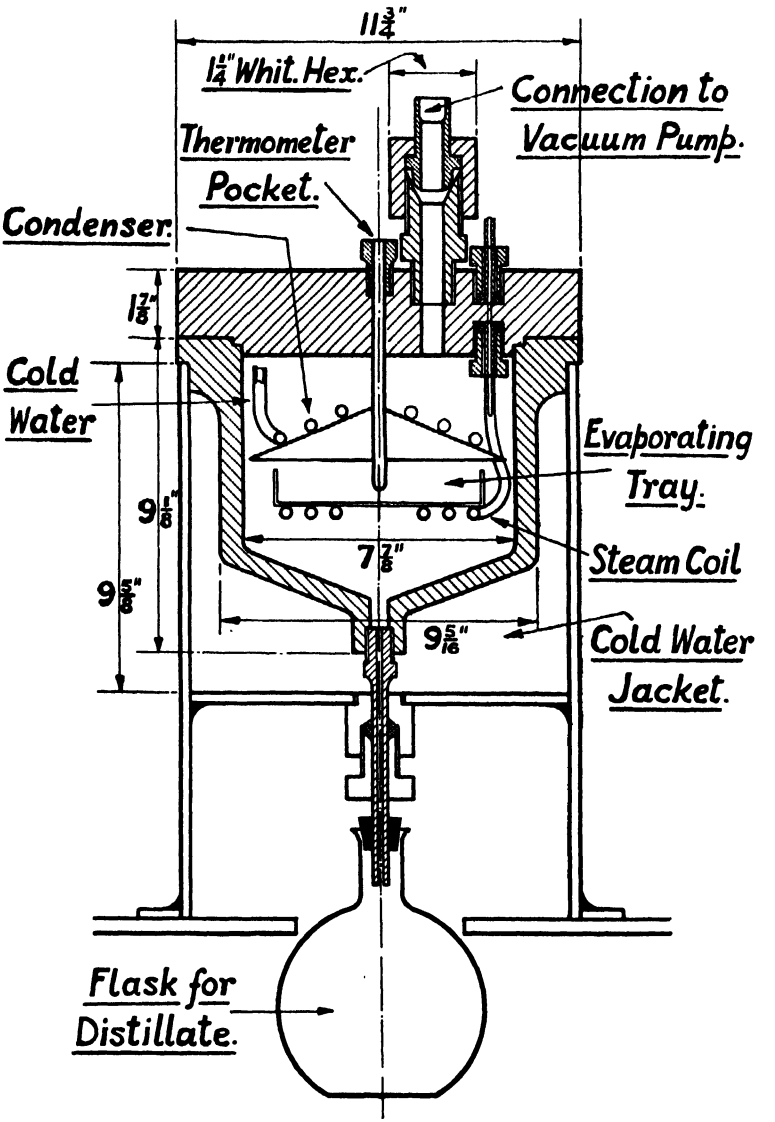


FIG. 249.—High vacuum distillation apparatus.

densing surface. In this way a high speed of distillation is possible from a given evaporating area with minimum temperature requirements (see Fig. 248). An adaptation of Burch's apparatus is seen

in Fig. 249, and it was constructed at the Chemical Research Laboratory, Teddington, for separating the resinous constituents of low temperature tar from the crystallisable components of this material. The latter are distillable under these conditions, whereas the resins remain in the residue. The distillation is carried out at temperatures not exceeding 130° C.

The apparatus consists of a metal vessel within which is a circular steam-heated evaporating tray of about 300 c.c. capacity. The condensing surface is a copper cone cooled by a closely wound water cooled copper coil. The ultra cathode ray vacuum is obtained by a

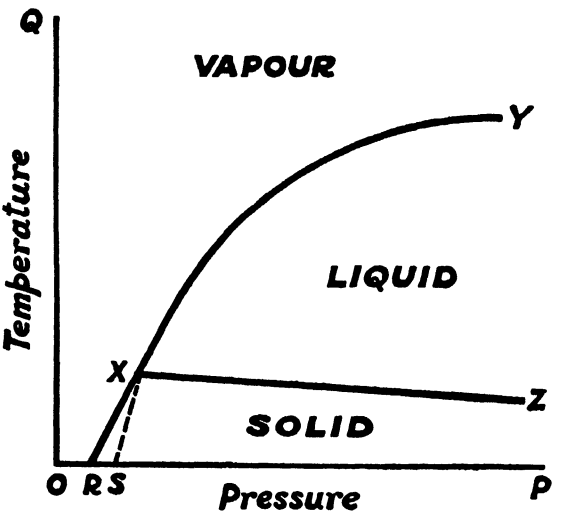


FIG. 250.

Cenco Hyvac rotary pump and with a Kaye mercury pump (Morgan, *Proc. Inst. Chem. Eng.*, 1933, **11**, 142).

Sublimation.—This term is applied to substances which pass directly from the solid to the vapour state at ordinary pressure, and the condition which determines whether a substance will sublime is illustrated by Fig. 250.

The curve represents the boiling point of a substance, the portion RX its subliming points and XZ the melting point thereof under varying pressure. Note that the boiling and subliming points vary widely with pressure whereas the melting point changes but little. The three curves intersect at X, which is known as the triple point, and at the corresponding pressure and temperature the three-phases —solid, liquid and vapour—can exist in equilibrium. If the pressure is less than this triple-point pressure the substance will pass directly from the solid to the vapour state, as it cannot melt under these conditions. The dotted continuation of the curve X indicates that

when the pressure is lowered below the triple-point pressure a liquid may be cooled below the ordinary freezing point at atmosphere pressure without solidifying.

Comparatively few substances are known to sublime at ordinary pressures because in the great majority of cases the triple-point pressure is far below atmospheric pressure.

In the laboratory, substances which sublime at atmospheric pressure can be purified by quite simple apparatus. Two watch glasses clipped together with a perforated filter paper between are sufficient in most cases. The lower glass containing the substance to be purified is heated, and the upper glass kept cool. The function of the filter paper is to prevent the sublimate falling back into the unpurified material. Among the more common organic compounds which sublime at atmospheric pressure are the following :—

Alizarin.
Ortho- and para-Amino phenol.
Anisic Acid.
Anthracene.
Anthraquinone.
Caffein.
Carbanilide.
Dimethyl glyoxime.
Iodoform.
Isophthalic acid.
Naphthalene.
Quinone.
Salicaldehyde (para).
Salicylic acid.
Para Di-nitro benzene.
Phthalimide.
Propionamide.
Pyrogallic acid.

CHAPTER XIV.

FILTRATION.

FILTRATION may best be described as a process in which relatively small quantities of solid matter are removed from liquids in which the solid is suspended. There are many types of filtering appliances which may be classified as follows :—

(1) Filter presses of various types.
(2) Pressure or vacuum filters in which pressure or vacuum is used to force the liquid through filtering material such as sand, or of the " streamline type," e.g. Metafilter.
(3) Leaf filters which were first developed in the metallurgical industry.
(4) Rotary continuous filters.
(5) Pulp filters including sterilising filters.
(6) Hydro-Extractors and Centrifugals.

In the following description of filtering practice I am indebted for much practical information to Mr. Eustace A. Alliott, of Manlove Alliott & Co., Ltd., Nottingham.

(1) Filter Presses.

A filter press is a frame in which a number of loose slabs of filter surface may be clamped to form a series of hollow chambers capable of withstanding internal pressure. This arrangement gives a large filtering surface for a given volume of apparatus, and such appliances when properly constructed of suitable materials give long service with a great degree of reliability.

Two forms of filter press are in general use—namely, the chamber and frame types.

Chamber Presses.

In this type (see Figs. 251–2) the edges of the plates are raised so that when two are brought together a hollow chamber is formed. The filter cloths are laid over each side of the plate, forming a tight joint when the plates are clamped together. The feed passage is taken through the body of the plates, and through holes left in the filter cloths as indicated in the drawing. The liquid enters the chambers under pressure and the solid portion is retained on the cloth. The

clear liquid passes through the cloth and drains via corrugations on the chamber sides as indicated to the outlet at the bottom of the plates. Usually a tap is fitted to the outlet of each recessed plate so that any given chamber can be shut off if the filtrate is cloudy because of faulty filter cloth or other cause. If it is desired to raise the filtrate to a level higher than the press, this can be done by a sealed outlet pipe into which all the enclosed chamber discharges are led.

Chamber or recessed plate presses are usually fitted with central feed, but as will be readily understood the feed passage may be

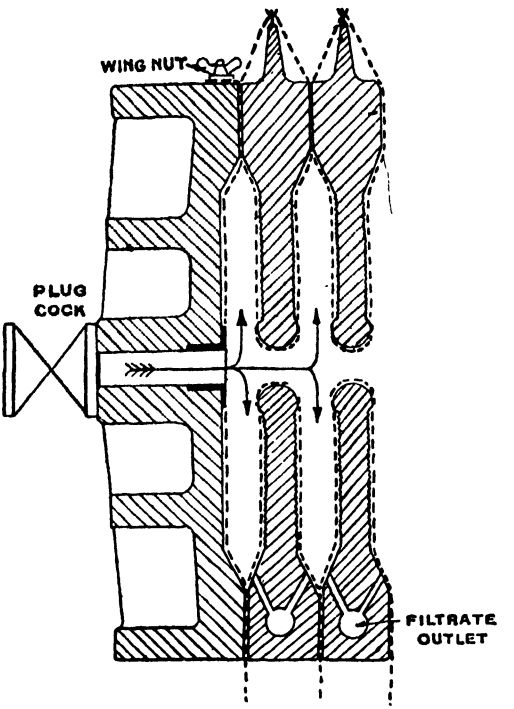
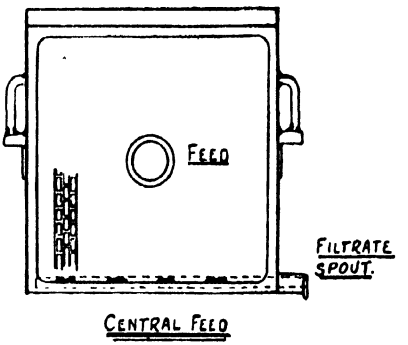
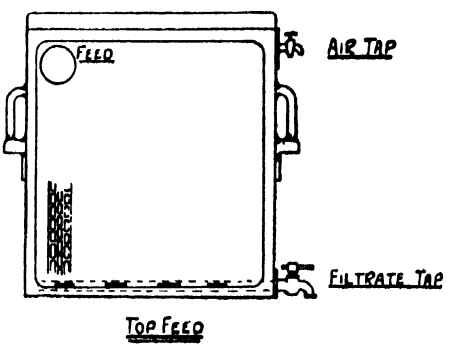


FIG. 251.—Chamber type filter press.

arranged in any other position if desired. For example, if a solid cake is not to be formed, bottom feed is convenient, as in this position the liquid contents of the chambers can be properly emptied before the press is dismantled for cleaning. Again, when heavy suspensions are being handled top feed is desirable, and sometimes in such cases two feed passages are arranged at different heights to obtain maximum density of cake.

Chamber presses are the least expensive type and require least labour to operate. It is particularly suitable for thin cakes, and the usual cake thicknesses are 1 in. for the smaller sizes and up to 2 ins. for the largest chambers.





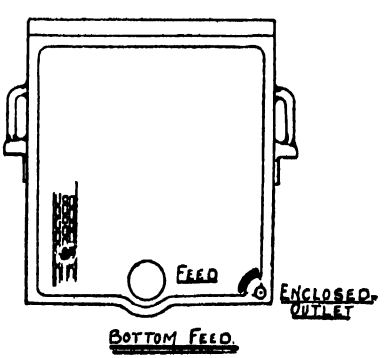


FIG. 252.—Methods of feed inlet and filtrate outlets in Chamber filter press.

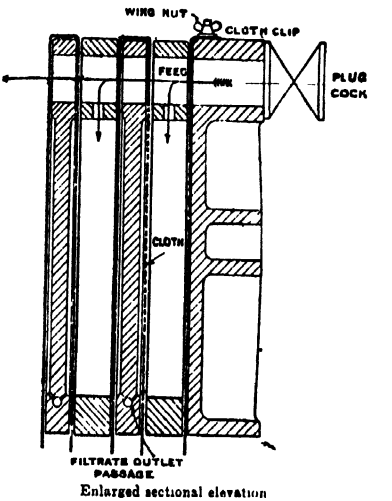


FIG. 253.—Plate and frame type of filter press.

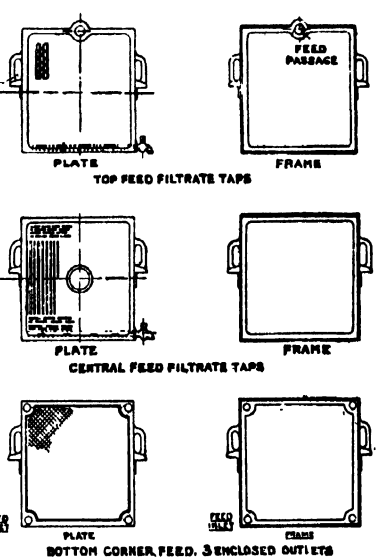


FIG. 254.—Various types of frames for above type of filter press.

Plate and Frame Presses.

This type is sometimes known as the flush plate type and is a more satisfactory and versatile type than the chamber pattern, but it is correspondingly more expensive to manufacture and requires rather more labour to handle. Figs. 253–4 show a section of a group of such plates and frame units, and it will be noted that the plates are flat with the chamber formed by introducing a hollow frame behind successive plates. This type is eminently suitable when thick cakes are desirable, and for cases where the conditions tend to rot the filter clothing, as the cloths lie quite flat on and are supported by the plate. Also the design permits of filter paper instead of cloth being used.

When handling materials which form a hard firm cake, an internal feed is desirable to avoid choking of the feed and uneven filtering pressure. In most cases passages arranged externally to the cake are satisfactory, and the usual position for the passage is at the top centre of the press ; another favourite position is in the side of the press just a little above the centre line. For sticky and gummy liquors these presses are sometimes made with four passages, one at each corner of the chamber, as by this arrangement the liquor has a minimum distance to travel through the grooved surface to get to the outlet. Also the upper passages permit of the free escape of air from the chamber.

Filter Press Plates—Materials.

Plates are often made of cast iron for neutral or alkaline liquors, or in wood for acid or corrosive conditions, or of special metals and alloys to deal with specific problems. Sometimes vulcanite, rubber or wood is used for handling strong hydrochloric acid liquors. Pitch pine is most frequently used for wooden plates, and for acetic acid liquors oak has been successfully used. In the United States cypress wood is often employed, and teak is frequently recommended for many acid liquors. Beech, maple and sycamore have been used, but the other woods described are more reliable. Paraffin wax impregnation of wood frames before use is strongly recommended, and it is important when once in service that wooden plates should be kept wet to avoid shrinkage.

Filter Press Plates—Filtering Surface.

The surface of the plates upon which the filter cloth rests takes a variety of forms depending upon the design of the plate, the position of the feed and the material to be handled. It is important that the liquor channels shall be sufficiently deep and narrow to prevent complete closure of the passage by the filtering cloth. Smoothness of

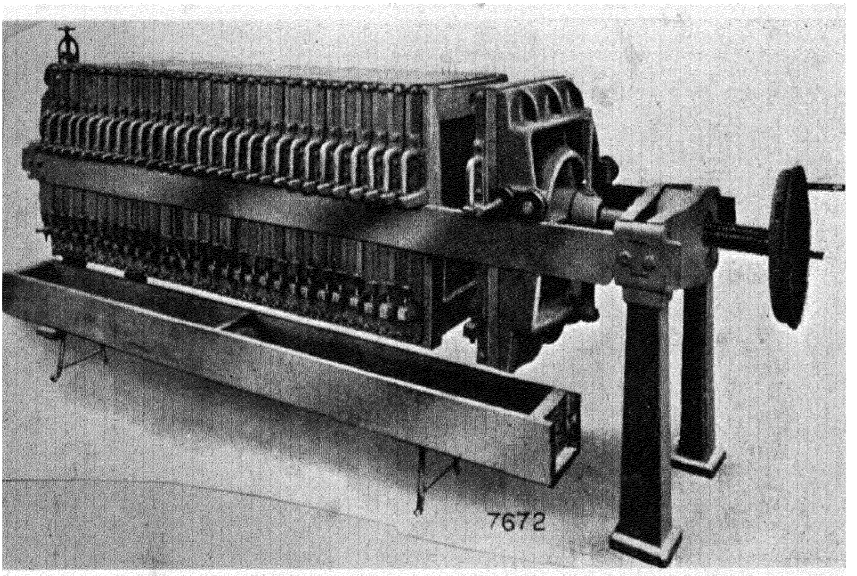


FIG. 255.—Centre screw closure of filter presses.

[*To face page* 484.

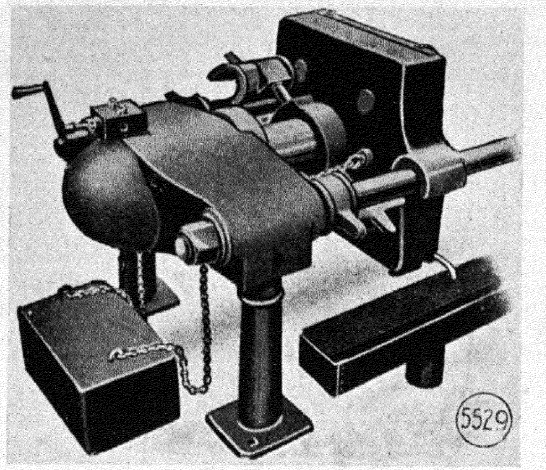


FIG. 256.—Hydraulic closure for filter presses (Manlove Alliott & Co., Ltd.).

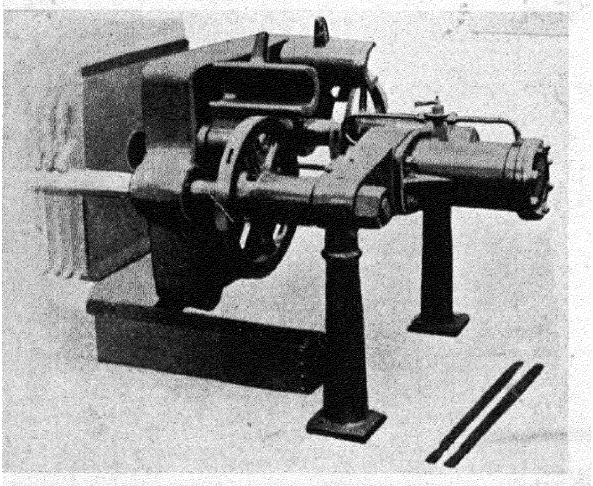


FIG. 257.—Pneumatic closure for filter presses (Manlove Alliott & Co., Ltd.).

[*To face page* 485.

surface and absence of sharp projections is most important, as otherwise the life of the cloths will be materially reduced, particularly if high filtering pressures are used. Coarse mesh gauze is sometimes used for difficult filtration, as also are perforated plates.

Filter Press Plates—Dead Plates.

A dead plate, or cutting off plate, is a desirable fitting if batches of varying bulk are to be handled. Such a plate has but one working surface, and is sufficiently robust to withstand the unbalanced end pressure, which, it must be noted, may be considerable at high filtering pressures. Such dead plates can be placed anywhere in the assembly, thus permitting a selected number of chambers to be employed, the remainder being isolated.

Filter Presses—Mechanical Features.
Closing Gear for Plates.

The usual form for small presses is shown in Fig. 255 and is of the centre screw pattern. It is not desirable to use this method for plates greater than 24 ins. square, in which case it will readily close and maintain tightness against 100 lbs. fluid pressure. Means should be provided for quick access to the plates for purposes of removal or cleaning, and this is achieved in many designs by pivoting the loose head carrying the screw so that the head may be swung clear immediately the pressure is released. Hydraulic or pneumatic closure (Figs. 256 and 257) is adopted where speed of operation is essential. Fig. 257 shows a pneumatic method of plate closure much used in sewage filtration.

The side rods or bars of the press act as supports for the plates as well as part of the press structure. Flat and round rods are equally suitable, and care must be taken to ensure that there is ample room for the plate handles and for filter cloth.

Filter Cloths.

In chamber or recessed plate presses, double cloths are used, and in such cases the cloths are stitched together at the edges of the feed opening and one cloth is passed through the feed hole in the plate. Both halves are then spread on the filter surface and fastened at the top by means of clips, or they may be stitched. Another way is to take a strip of cloth long enough to cover both sides of the plate with two holes cut to correspond with the position of the feed passage. This assembly is then hung over the plate and the joint around the feed passage made by clips of the screw pattern to make a fluid tight joint.

In frame presses cloths of double size may be simply hung over the plate without further attachment.

The commonest form of filtering material is cotton duck or twill. Jute and hessian cloths are frequently used in place of cotton, and these cloths are also used as undercloths to support a tightly woven twill. Filter paper may be used, but it must be well supported and of the crinkled variety, and backed by a suitable material such as hessian. Cloths with a swansdown surface are used for the filtration of yeast, and are protected against clogging by a superimposed cloth of strong twill.

For strongly acid liquors, camel hair is reported as satisfactory for 30 per cent. sulphuric and 10 per cent. hydrochloric acid. Wool or felt cloths will resist up to 20 per cent. sulphuric acid, but they are useless for hydrochloric acid. Asbestos is suitable for all strengths of acid and alkali.

Filter cloths should not be allowed to dry on the press saturated with possibly corrosive liquors and full of retained solids, but washed immediately filtration is finished, and kept moist until again required. Suitable washing machines are available for washing filter cloths under controlled conditions.

Operation of Filter Presses.

The liquor is fed to the press by gravity, by pump, or by some form of pressure egg, and in all cases the pressure of filtration should be carefully controlled.

In general, the best results are obtained with a relatively low filtering pressure with high pressures in the last stages of the run. In ordinary cases, pressures vary from 10 to 150 lbs. per sq. in. ; the higher pressures are only used for viscous liquors containing hard solids of an open granular nature. Dyestuffs and colours generally require pressures not higher than 15 lbs. per sq. in.

Washing in the Filter Press.

Washing can be carried out with great advantage in the filter press. The simplest method is to force water in through the feed passage. This is best done in the plate and frame type, and it is preferable that a solid cake should not be formed, but that a space should be left between the layers built up on each cloth. Here a bottom feed is advantageous, as the excess liquor can be drained from the chambers prior to washing, though in the ordinary type, it can generally be removed by air pressure. It is possible to wash this way in any plate and frame press or even in recessed presses, although they may not have been specially designed for the purpose. If a solid cake is not formed it is the only practicable way except re-lixiviation.

The trouble is that owing to sedimentation the cake is apt to be thicker at the bottom, and in order to keep the two sides from touching,

space may be wasted at the top. Further, the press capacity is diminished and more labour is necessary in emptying. In some cases, however, solid cakes can be rough washed if they are sufficiently permeable. General reports from users appear to show that more wash water is required, but this would depend very much upon the manner of the operation. This method of washing is usually referred to as " simple " washing. Another consists in forcing the water from one side of the cake to the other, and may be referred to as " through " washing. It is also called " back " washing, as the water is admitted to the back of the cloths.

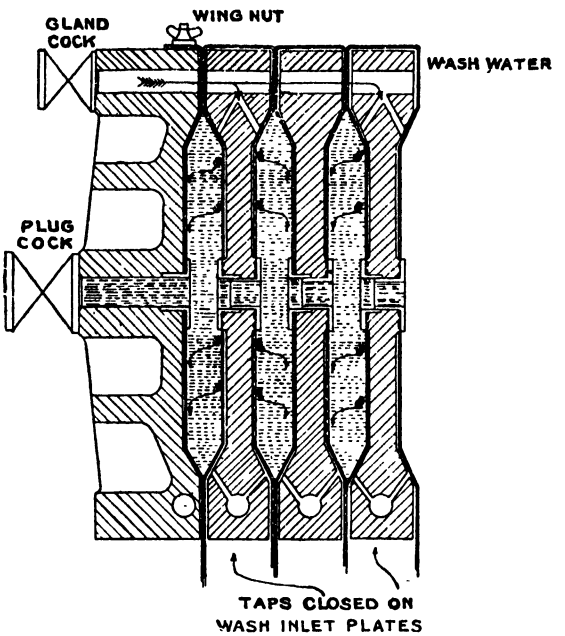


FIG. 258.—Recessed plate filter press arranged for washing.

Figs. 258–9 show this method applied to recessed plates. The wash water inlet passage forms a continuous channel in an upper corner of the rims. It has inlet ports to each alternate plate, on which the filtrate cocks must be closed during washing. The water enters behind the cloths, passes through these and the cakes to the back of the cloths on the intermediate plates, the cocks on which have been left open to permit it to escape. This is sometimes called " tap " washing, and its chief merit is its simplicity, as only one special passage is required. One disadvantage of an internal feed is that a soft core will permit short-circuiting, while a hard one may not get washed properly. For the very best results plate and frame presses should be employed, owing to the even thickness of the cake at the edges

and the fact that any soft material in the feed passage is isolated. Further, provision should be made for the escape of any air which may have leaked into the space behind the filter cloths at the conclusion of filtration, as this may prevent the water flowing through the upper portions of the cakes. Even ordinary "tap washing" is distinctly improved by the provision of air cocks. Then, again, the washings should be taken out at the top of the press, so that there is exactly the same pressure tending to force the water through the cake, whether this be measured at the top or at the bottom. The importance of these factors will be better understood when it is realised that comparatively low pressures are best for washing purposes, as will be seen later. Except where due provision has been made, time will be required under such conditions to force trapped air out of the press, and in addition, any unbalanced hydrostatic head (due to unrestricted draining on the outlet plates) will aid in causing a disproportionate amount of wash water to percolate through the bottom of the cakes.

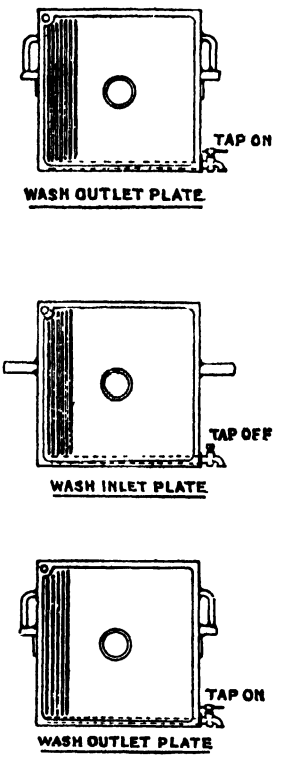


FIG. 259.—Plates used for press illustrated in Fig. 258.

A filter press in which all these points have had attention may properly be described as a "thorough" washing press (Fig. 260). The illustration shows wood plates and frames constructed on this system. At the conclusion of pressing all the filtrate taps are shut off and wash water is admitted to the enclosed channel at the bottom. This passage connects by ports to every alternate plate and permits the water to rise behind the cloths on these, driving the air before it into the special air channel which connects with the wash inlet plates only. As soon as there is any flow from this it is shut off, and the water must then pass horizontally through the cakes and cloths to the intermediate plates, where it rises in the grooves till it escapes into the enclosed outlet at the top. In this way provision is made for as perfect a displacement as possible of the strong liquors in the cake. An even better arrangement would be to have wash outlet cocks fitted on the tops of the plates, delivering into a special trough, as this would permit any chamber giving muddy washings to be shut off at will. In general practice, however, enclosed outlets are found more convenient and perfectly satisfactory.

An interesting point about presses of this type is their extreme adaptability. There are a dozen possible variations of the washing connections alone, since any passage can be used as an inlet, without counting possibilities in regard to steaming, air-drying, etc. The chief methods of washing are, however, ordinary thorough washing as above, washing in reverse direction, either through the enclosed

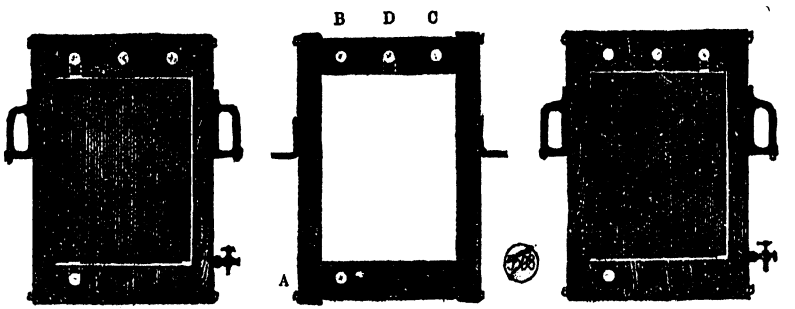


FIG. 260.

A = Wash Water Inlet. B = Air Release.
C = Wash Water Outlet. D = Feed Channel.

outlets or through the taps, and ordinary simple washing as first described. The wash water and air passages can be used as enclosed filtrate outlets. It is obvious that air, steam or water may be admitted to the wash passages when the press is empty, but closed

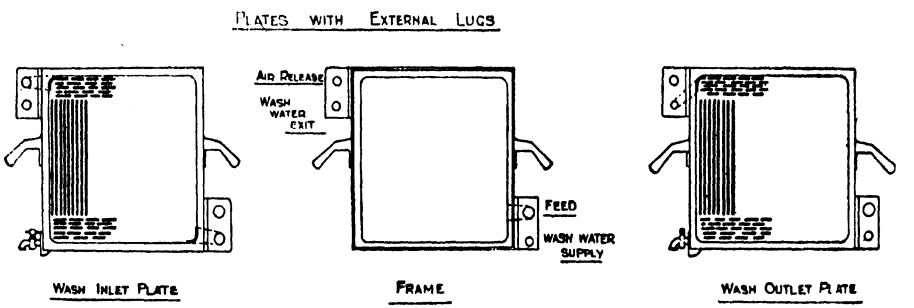


FIG. 261.

up ready to restart. By this means the cloths are given a reverse washing, and may be made to last longer before clogging.

In the case of iron plates, these wash passages are made either in the plate rims or can be in external lugs (Fig. 261), with advantage in certain cases, since this permits plain cloths without holes to be used, and there is no difficulty in fitting and keeping them in place. The joints on the lugs are often made by cloth sleeves, which are slipped over them. These must be changed with the cloth, and for

that reason rubber joint rings are often preferred. These may be let into special grooves around the wash passages, or may fit inside.

In any event, the cost of outside lugs is only justified where the filtering medium is subject to frequent washings or renewals. Normally the cloth is kept in place by adherence to the plates once it has been used, so that even where passages are in the rims no difficulty is experienced in keeping the holes in their right positions. If the cloths last a reasonable time and proper arrangements are made for cutting the port holes, the cost of this is small in proportion to the work done. A useful type of plate has two external passages in lugs which form part of the handles (see Fig. 261A). One of these is a feed passage, the other the wash water inlet passage. This form permits the outside lug plate to be made more cheaply, in a form very convenient for manipulation, but lacking some of the advantages of the type shown in Fig. 260.

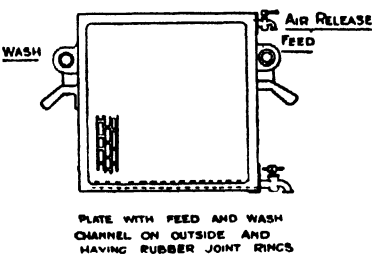


FIG. 261A.

Now, assuming that a press has been selected with all facilities for washing, as described above, and care has been taken that the filtering surface has been kept free and unchoked, giving the wash water access to every part of the cake, there are still other factors essential to satisfactory results. These are :—

(1) Care must be taken to secure a well-formed cake.
(2) The cake must be of as coarse a grain as is possible, without causing settlement in the press, and the various grades of particle must be uniformly distributed.
(3) The washing pressure must not be too high and should not fluctuate. It should be applied as quickly as possible after the cake has been formed.
(4) Care must be taken that the press is worked properly and especially that the air-taps are made use of.

Economical washing depends on even displacement, and good practice results when this ideal is approached as nearly as possible. If the cake is not complete, obviously there will be gaps, through which water can pass. Further, if the deposit is soft and not properly compacted such gaps may readily be formed during washing, while if

this operation is delayed some cakes tend to sag a little and do not fill the chamber up to the top. The frames may be fitted with an internal rib or fin to counteract the effect of this, but some users consider there is more difficulty in cleaning out the cake. Then if the grain is too fine it will be difficult to get the wash water to penetrate without undue pressure, which may cause channelling and short-circuiting. In such cases adsorption effects are also likely to hold back soluble matter in spite of even the most perfect washing. If the grains are reasonably coarse they will be more permeable, and will have less surface to retain strong liquor. A truer and quicker displacement is then likely to result. If they are not of fairly uniform size, the coarser ones will probably have settled to the bottom of the chamber, and the wash water will pass in preference through them, giving mixed or weak washing. If the particles themselves are porous, time will be needed to extract the absorbed soluble matter, quite apart from surface effects.

Finally, high pressures should only be applied with caution where absolutely necessary, as these may cause channelling and short-circuiting. The lowest which will give a reasonable flow should therefore be used. The supply must be steady, and a gravity feed or a connection to the town water supply is usually preferable to the use of a pump, where either can be employed. While the best results are usually obtained at pressures much less than those in general use for consolidating the cake, it should not be overlooked that the filtrate has only to penetrate half of its thickness, while the wash water must press through the whole depth of the consolidated mass. In order that washing may not be too prolonged, the best cake thickness is usually somewhat less than for plain filtration.

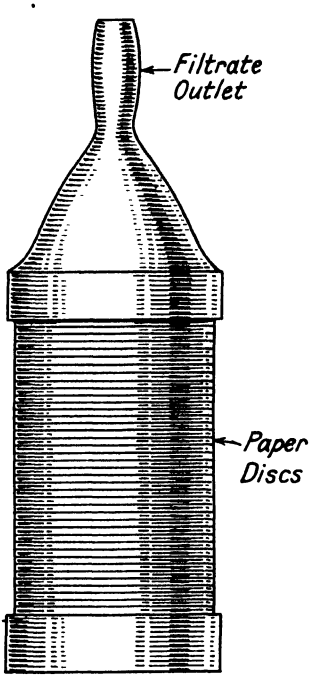


FIG. 262.

(2) Pressure or Vacuum Filters.

The application of pressure filters of the sand filter type is limited to water purification. They give rapid filtration in a small space, and are easily cleaned by backwashing combined with a little agitation.

There have been marked developments recently in *edge filtration* as exemplified by the " Streamline Filter," which is well suited to the filtration of mineral and vegetable oils. They are not suitable for

dealing with any great bulk of solids, nor where dry discharge is needed. The filter body is usually cylindrical and the filter comprises a column of specially prepared paper discs compressed together (see Fig. 262). The minute inequalities of the paper surfaces cause very fine passages to be formed between the successive layers of paper, so that when the liquid to be filtered is drawn through either by vacuum or by pressure, the solid matter is retained at the edges of the pack and it remains on the outer surface. The clean liquid passes up through the centre of the column, as seen in Fig. 263. When the elements are coated with a thick deposit and the rate of flow falls, filtration is interrupted to permit of

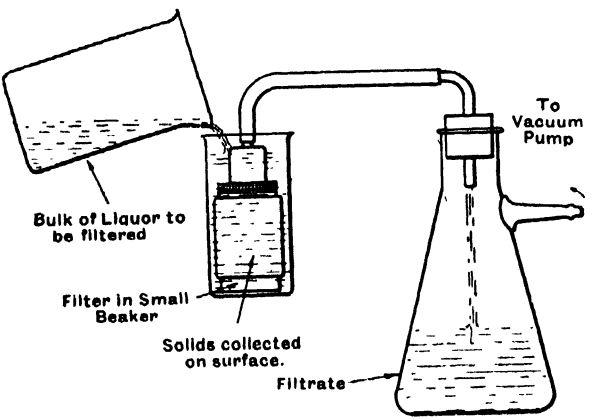


FIG. 263.

clearance by compressed air blown down the centre of the column (see Fig. 264).

Such filters are particularly suitable for handling used lubricating oil from petrol and diesel engines and in purifying transformer oils.

Another use of edge filtration is typified by the " Metafilter," which has been successfully applied to clarification problems where only small quantities of solids are to be removed. This filter comprises a number of metallic strips, grouped together to form leaves, the edges of which act as a support for a bed of filtering material, which is precoated on to them before filtration is commenced. Fig. 265 shows the plates, etc., of a typical commercial " Metafilter " in which the action is as follows :—

Strip Type " Metafilter."

This type of metafilter employs strips piled up face to face in a frame. The strip material may be metallic or non-metallic, e.g. bakelite, ebonite, etc., depending upon the conditions of filtration.

The views of the individual strip, strip frame, strip frame with a filter-bed in position, section of strip frame showing filtrate draining manifold, will make this brief description clear. (Fig. 265A, B, C, D).

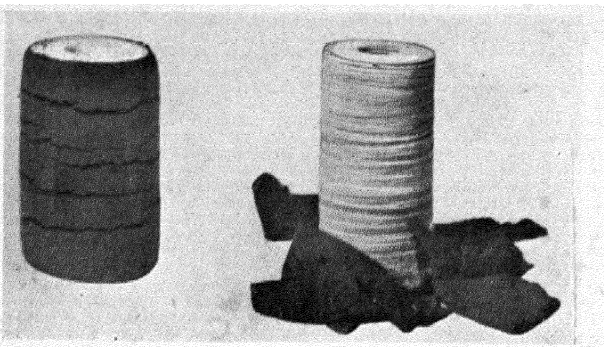


FIG. 264.

[*See page* 492.

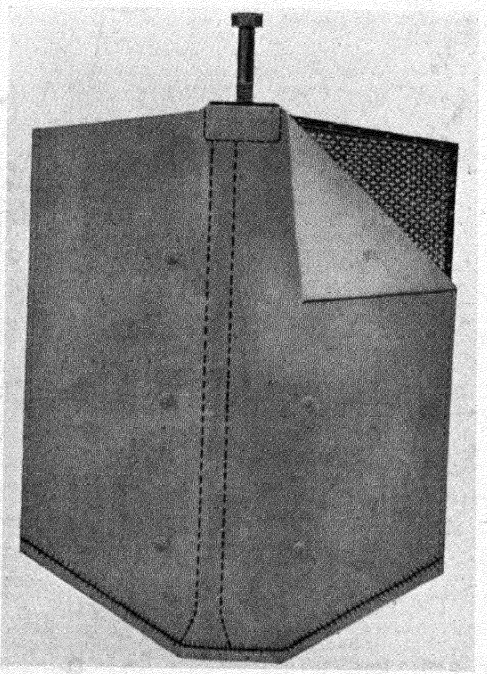


FIG. 266.—Leaf filter unit by Manlove Alliott & Co., Ltd.

[*To face page* 493.

Each strip is flat on one side with bevelled edges on the other. A rib of uniform height runs along the bevelled side slightly narrower than the diameter of the holes evenly spaced in the centre of the strip.

The length of the strip may be varied, as well as the number of strips piled and held one on another. It follows that if a number of strips are built up—flat side to bevel side, with the holes in line—the series of holes form a drainage tube in a vertical plane. The entrance to these holes is controlled by the height of the rib on the strips, and the difference between the diameter of the hole and the width of the rib.

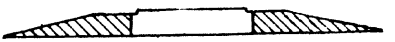


FIG. 265A.

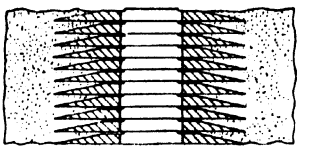


FIG. 265C.

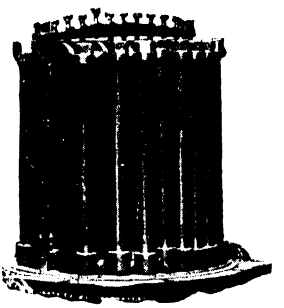


FIG. 265B.

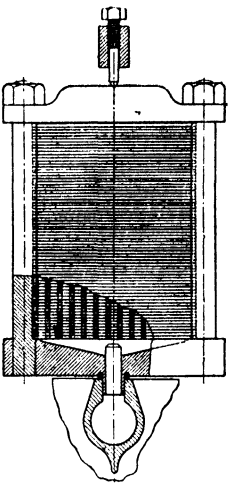


FIG. 265D.

The Metafilter.

This is at once seen from the view of the strip in Fig. 265A. The height of the rib may be varied from 0·001 to 0·005 ins. and partly determines the fineness of the filter. Fig. 265C shows a pile of strips, with a filter-bed retained in the recesses formed between the strip edges, created by the adjacent bevelled and flat faces. There are numerous methods of holding the strip in position under compression, and of connecting the series of hole-formed vertical drainage tubes to a main drainage manifold, but a simple frame and drainage manifold that has been very

effective is shown in Fig. 265B. Two, or a large number of these frames, the frame size being varied as desired, are coupled together with the draining outlet let into the main drainage manifold, as shown in Fig. 265D.

Filter-bed Formation on the "Metafilter."

The formation of a filter-bed on the Metafilter strip frame or ring packs is quite simple. A suitable material is mixed with the liquid to be filtered, the already filtered liquid, or other liquid such as water, oil, or solvent, as circumstances permit. It is necessary to keep the filter-bed in suspension and pass it through the Metafilter units by pressure or under vacuum. As the liquid and suspended filter-bed endeavour to pass through the accurate spacings between the rings or strips, the suspension is evenly strained out, and leaves a perfectly even bed over the surface of the strong retaining structure. Filter-beds comprise materials such as powdered charcoal, kiesel-guhr, silica, magnesium carbonate, etc., etc.

Simple Pressure or Vacuum Filters.

Apart from the foregoing special pressure, etc., filters, the simple form of tray pressure or vacuum filter (illustrated in Figs. 47 and 48) still retains a wide measure of popularity for many simple filtration operations. Such filters comprise a tray within a box, and the filter bed is placed upon the tray so that if liquor is forced or drawn through the bed, the solids are retained thereon.

(3) Leaf Filters.

There is a whole range of types and sizes of *enclosed pressure filters.* Among the smallest and simplest is the "Filtrall," made by Manlove Alliott & Co., Ltd., which consists of a vertical cylinder in which a number of leaves are placed. These leaves usually consist of coarse iron wire mesh, supported in a framework and covered with cloth bags or with Monel metal filter cloth (Fig. 266). The bottom edge of each leaf is fitted with a hollow conical projection which is at once a support and an outlet. These projections fit holes in a pipe (Fig. 267) placed horizontally across the filter, a small distance above the bottom. The top of the filter is fitted with a removable cover, and the sump at the bottom has a discharge door (see Fig. 268). Liquid is admitted to the filter either at the side or at the bottom, passes through the leaves and out through the horizontal pipe. When sufficient cake is built up the filter is drained and the cake scraped off the leaves into the sump, whence it is removed through the bottom door. In some clarifications it is possible to clean the leaves quickly, simply by removing the top cover and shaking them gently in the remaining liquid. The cake then

falls to the bottom and filtration can continue until the leaves are again coated. This serves to shorten the cleaning time, as the filter only needs to be emptied after every second operation.

Forms are made abroad in which scrapers are placed between the leaves, and are attached to an endless chain operable at any time from outside the filter. This complication, however, is scarcely necessary owing to the ease and speed with which the cake can be made to drop off the leaves.

One of the best-known and most-developed large pressure leaf filters is the *Sweetland filter* (see Fig. 269). This consists of a long cylindrical cast-iron body, split horizontally, the two parts being hinged to one another. The closing gear is a particularly neat arrangement. A shaft

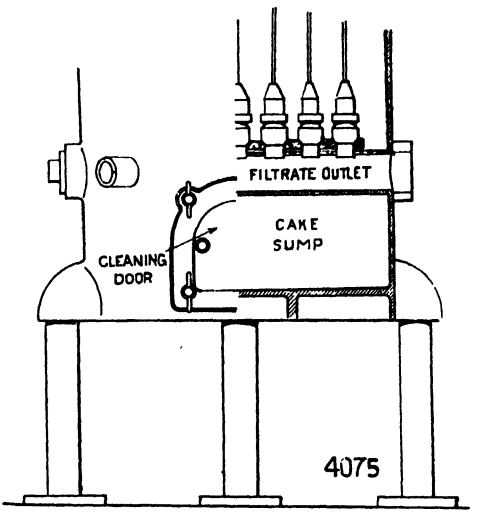


FIG. 267.—Arrangement of leaf filters.

extending the whole length of the filter is carried in bearings on the upper stationary portion, and has attached to it eccentric cams supporting a number of bolts and nuts which engage with slotted brackets on the lower hinged portion of the filter. The action of the tightening gear can best be explained by assuming that the press is in the closed position with the bolts holding the parts tightly together. The first action on commencing to turn the tightening shaft is to revolve the cams, easing the pressure on the bolts and allowing them to drop so that the heads are loose in the slotted brackets. Pins mounted on the shaft come into play and lift the bolts clear of the brackets. The lower part of the press can then be forced down or drops of its own accord, being balanced almost, but not quite, completely by a balance weight at the back. In very large presses a large hand-wheel and spur gearing is employed to give additional pressure in operating the tightening gear,

and hydraulic cylinders may be used to raise and lower the hinged portion of the body. Inside the press are mounted a number of circular leaves at suitable centres (from 2 ins. up to 6 ins.) (Fig. 270). These leaves each consist of a wire framework or drainage base which may be covered either with cloth bags or with Monel metal or other screens. The outlet, which is at the top, consists of a hollow shank which is pushed into a hole in the top of the press and secured by a nut. A hole in the side of the shank corresponds with a filtrate port which is led through a cock and a sight glass to the main filtrate outlet header. It is therefore possible to see the outlet from each individual leaf and to control it if it is not clear. The inlet to the press is at one end, where a vertical channel in the upper portion faces a similar channel in the lower portion, from which the feed is led along a passage extending the whole length of the press bottom. A deflector plate is placed above this so that the flow is directed sideways between the press casing and the leaves. A very smooth feed is thus obtained. The bottom of the press is provided with drain outlets so that any liquid remaining in the filter at the completion of filtration can be removed.

Often, and particularly in large presses for sugar work, these filters are fitted with a spray pipe by which the cake may be washed off the leaves at the completion of filtration. This spray pipe has an opening between each pair of leaves, and there is an ingenious arrangement by which the pipe may be rocked so as to cover the whole surface of the leaves, while it also moves a short distance backwards and forwards along the length of the press, so that there is a good chance of the spray of water reaching all portions of the cake. The cake, reduced to liquid mud, is run out of the bottom of the press, which is then ready to receive a further charge.

Washing, in such presses, may be carried out either by simply following up the feed with water, or at the end of filtration the remaining liquid may be blown out of the press either through the leaves or by using the draining openings under compressed air. Wash water may then be introduced without mixing with the liquid to be filtered. It is most important, however, during all these changes, always to maintain a positive pressure within the press across the leaf surface so that there is always a little liquid or air passing through the leaves and holding the cake close to them. Failing this, some of the cake may drop off, causing difficulty during washing. Unevenness of flow due to broken or cracked cakes may be avoided by mixing with the wash water a small amount of already washed cake. This is carried to any points where excessive flow of wash water is occurring and helps to fill up the cracks and even out the resistance of the cake. It should be pointed out that providing the cake is held properly on the leaves and any cracks are filled up by the methods stated, enclosed pressure filters of this and analogous forms give extremely favourable washing results.

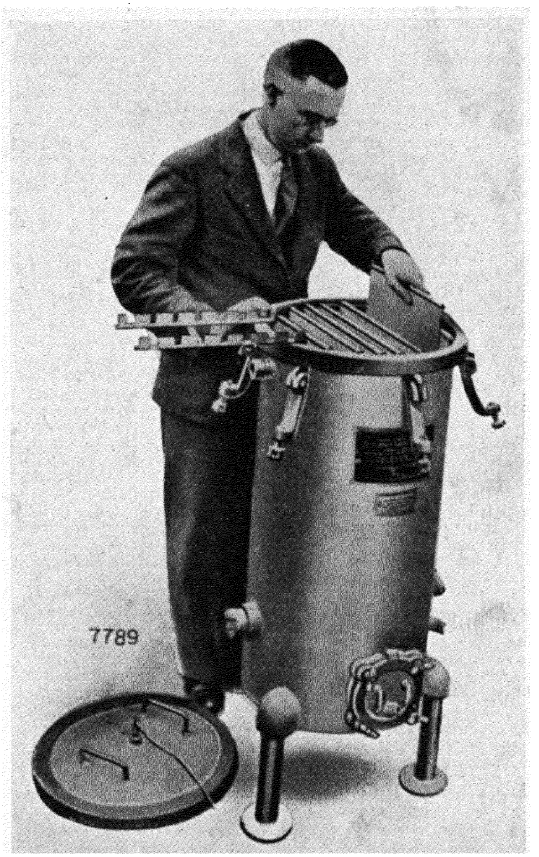


FIG. 268.—Assembly of Manlove Alliott Leaf Filter.

[*To face page* 496.

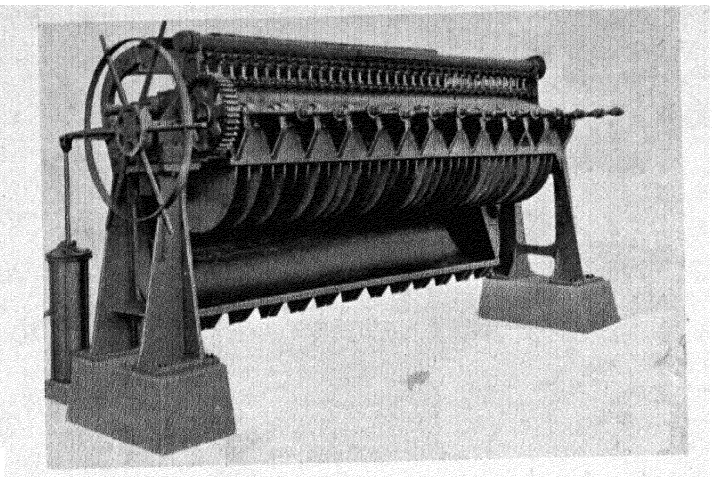


FIG. 269.—Sweetland filter.

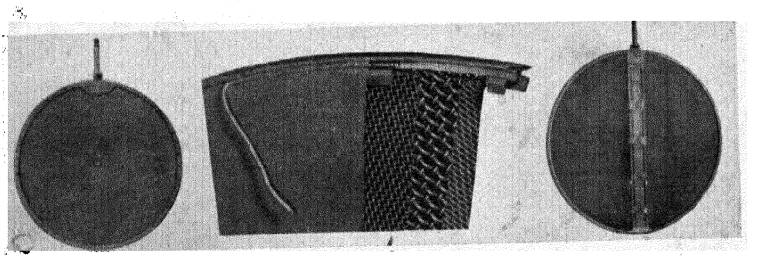


FIG. 270. Various units of Sweetland filter.

a

Top drainage leaf with smooth rim. Can be also supplied with grooved rim.

b

Later type of Sweetland Filter leaf with metal cloth as cover.

c

Bottom drainage leaf with grooved rim. Also supplied with smooth rim.

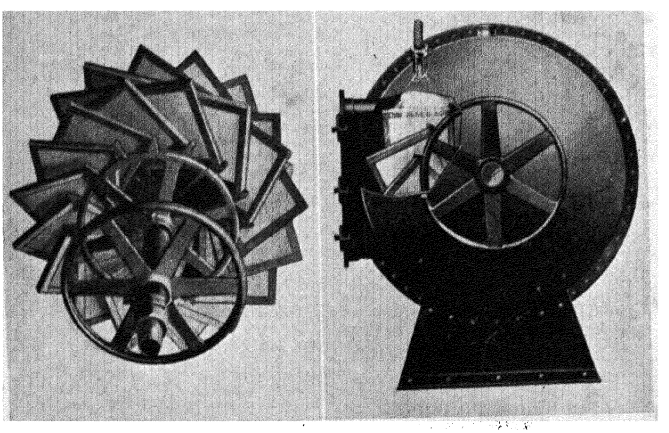


FIG. 271.

[*To face page* 497.

Since the cake is not subjected to any consolidating period (providing adjoining cakes are not allowed to meet), it follows that it is built up in an equally resisting state during filtration, and if this state is not allowed to disappear during the changes-over incidental to the introduction of wash water, practically perfect theoretical washing should take place, providing the cake is of reasonably equal thickness all over.

Leaves are obtainable with top drainage or with an internal tube giving bottom drainage, leaving a drier cake. Combinations of the two types are also available and, in another form, the stiffening rim is used as a draining channel. (See Fig. 270A, B, C).

The following data may be interesting as an example of the operation of the Sweetland filter when handling a free-filtering product such as barium carbonate, which has to be removed from a liquor containing sodium sulphide.

The body of the press was lead lined. There were 31 leaves, 33 ins. in diameter, at 4½-in. centres, 1400 gals. of liquor (gravity about 18° Tw. at 50° C.) was pumped in in 10 mins. by centrifugal pumps at a pressure reaching 35 lbs. per sq. in., an average of nearly 23 gals. per sq. ft. per hr. Two minutes were needed for draining before putting the wash on, and 6 wash liquors, each of about 600 gals., were pumped through the cake. For this a tank with 6 storage compartments was employed, 5 of which contained washings of decreasing strength from previous operations, whilst the sixth was pure water. Each wash was led back to the compartment following that from which it was taken, but the last and strongest wash went to the filtrate tank. The amount of fresh water per wash was therefore 600 gals. only. The pressure during washing was 38 lbs. per sq. in. obtained by another centrifugal pump, and the time taken was 45 mins., giving a rate of washing of about 13 gals. per sq. ft. per hr. The wash water used was about 21 displacement volume gross or 3½ net. This reduced the solubles to about 0·7 per cent. on the dry cake, while bringing on the dilution of the final wash liquor to about 83 per cent. of the original filtrate. Air drying took 10 mins. at 38 lbs. per sq. in., after which air at 10–20 lbs. per sq. in. was used to discharge the cake from the leaves. By admitting air, checking and readmitting, the bags were caused to inflate and deflate several times, so that most of the cake loosened and dropped, the remainder being freed with a long scraper. Two thousand cu. ft. of free air was used per operation (about 200 cu. ft. of free air per min. during drying and cake discharging). The labour, all told, was 1¼ man-hr. per operation. The wet cake weighed 5400 lbs. (about 100 lbs. per cu. ft.), and its moisture content was 32 per cent. The over-all hourly rate was about 18½ gals. per sq. ft. per hr., or nearly 8 lbs. (bone dry) product per sq. ft. per hr.

The "*Vallez*" is an enclosed pressure filter in which the leaves are mounted on a hollow central shaft which revolves at about 1 to 2

revolutions per min. This enables a uniform cake to be built up from slurries which are by no means free-filtering, in which there is a strong tendency for selective settlement of the solids to take place, causing tapering cakes of uneven resistance to be formed in filters having stationary leaves. This much improves washing, which becomes practically a true displacement. This claim is said to be amply substantiated in sugar refining, and is one of the principal recommendations of the filter. In some cases it means that where the filter muds would otherwise be washed in separate filters, the whole operation of filtering and washing may be carried out in a single filter with rotating leaves. The filter operates at pressures up to 40 lbs. per sq. in. On sugar work the filter usually works two cycles per 24 hrs., but on easily filtered sugars may run for 24 hrs. About 4 lbs. of Supercel Hyflo is used per ton of sugar, costing about 8d. for precoat and additions to the juice. Two men per shift serve to operate a battery of four filters, including adding the kiesel-guhr. Hot water is used for washing or sweetening off at a pressure of about 25 lbs. per sq. in. After filtration and washing the cake is dislodged by hot sprays at 60–120 lbs. per sq. in. pressure, washing it to a worm situated in the lower part of the casing, which in turn pushes it to the discharge opening. About 1½ h.p. serves to revolve the leaves. The leaves can be cleaned by filling the filter body about half full of liquid, which is then agitated by air while the leaves revolve. If a dry cake discharge is desired it is possible to employ scraper arms which travel inwards between each pair of leaves, cutting the cakes off, but this is far less in use than the spray discharge. As a rule the leaves are covered with phosphor-bronze wire cloths, which are said to have a life of 2½ to 3 years on regular daily work in a sugar refinery. These are employed with a precoat of kiesel-guhr, but there is a patented procedure employing paper pulp, which is subsequently washed and recovered.

The *Multi-leaf Auto filter* is also fitted with a rotating shaft, but in this case the filter leaves do not lie in a plane at right angles to the shaft, but are arranged in sections which are appreciably inclined to it. In effect each complete circular leaf is divided into many truncated segments, each having its own filtrate outlet connection to the hollow central shaft, and each segment is twisted to one side so that the original disc becomes in appearance somewhat like a many-vaned propeller (Fig. 271). The object of this arrangement is to permit the leaves to be withdrawn quickly from the filter for renewals, inspections, or repairs. This is effected by opening the inclined door on the outer wall of the filter casing, which is big enough to permit any leaf to be drawn through it on releasing the clamping bars which hold the leaf against the rotating shaft. Filtration, washing and air drying proceed in the usual way, while the shaft rotates at about 1½ r.p.m., after which the cake is washed off by means of spray pipes secured to the filter

casing at the required angle. One spray pipe is used for each complete set of segments. This enables the leaves to be scoured very thoroughly, and because of their inclination the cake falls clear without causing the space between adjacent leaves to be choked up.

There are various forms of *enclosed pressure filters* using special filter elements other than woven wire leaves covered with cloth or woven metal. Early examples were the various water filters of the *Berkefeld type*, employing porcelain candles.

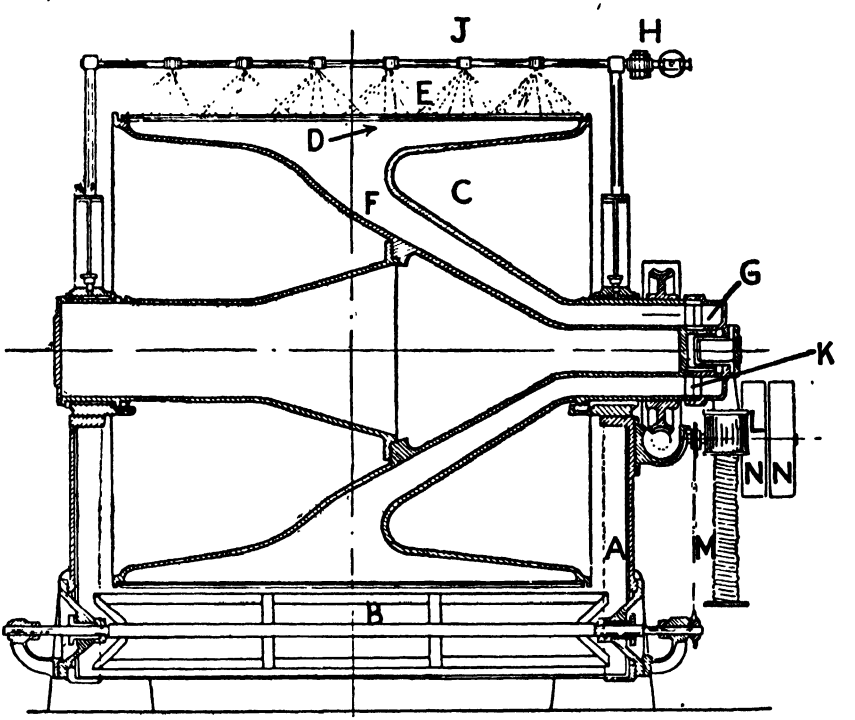


FIG. 272.—Section of " Rovac " rotary continuous filter.

A = Slurry trough.
B = Agitator.—Paddle or oscillating type supplied as required.
C = Filter drum or rotor.
D = Perforated filter plate.
E = Filter cloth, metal gauze, fabric or asbestos cloth.
F = Independent self-contained suction cells.
G = Valve head, for the automatic control of the suction in each cell, the separation of the mother and wash liquors, and the air or steam blow-back for lifting the filter cake.
H = Wash water strainer.
J = Wash water spray nozzles.
K = Renewable plate on drum trunnion.
L = Liquor sight glasses
M = Flexible filtrate discharge pipes.
N = Fast and loose pulleys. (Not required if direct coupled to motor.)

(4) Rotary Continuous Filters.

When large quantities of rapid cake-building products are to be handled, *continuous vacuum filters* of the rotary type are generally employed. In these a large drum is arranged with filter elements round its periphery, these elements communicating with a space under reduced pressure (Fig. 272).

The surface of a modern rotary filter is divided into sections which

are placed under suction, while they revolve through a tank containing the material to be filtered. They are maintained under suction as they emerge from the tank, when they are usually subjected to washing by means of spray pipes. After this, air is drawn through the cake in order to dry it as far as possible, and finally each section comes opposite the knife or " doctor," which scrapes the cake off. During this process it is usual to subject each individual section to a blast of compressed air in order to free the cake from the cloth (see Fig. 273). The heart of this arrangement is the rotary valve (Fig. 274), by means of which the outlets from the sections are connected, first to vacuum through a port connecting to a filtrate-receiving tank, then to vacuum through another port connecting to a washings receiving tank, which usually serves also for dryings. There is also a port for compressed air.

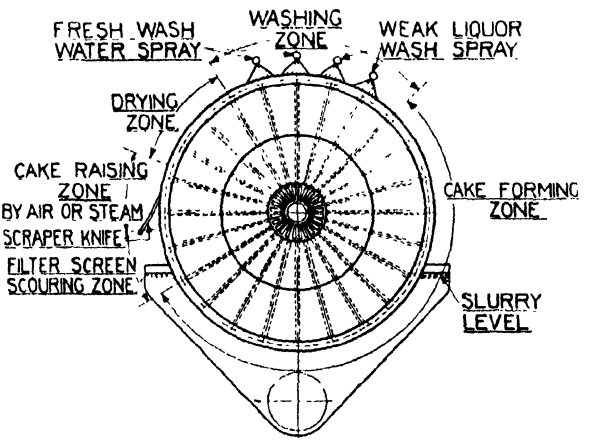


FIG. 273.—Operations during a cycle of continuous filtration.

The slurry tank is generally provided with an agitator (paddle or oscillating) (B, Fig. 272) to keep the mud from settling. The filtrate and washings are drawn to separate receiving tanks connected to a dry vacuum pump. The filtrate or washings are withdrawn from the bottom of the tanks by centrifugal or other forms of rotary pumps. It is not unusual to arrange these tanks with a float or trip device so that if they become unduly full the vacuum is broken in order to stop liquid being carried out through the vacuum pump, which alternatively is sometimes protected by a barometric tube (Fig. 275). The washing arrangements in such filters are comparatively simple, consisting of perforated pipes or sets of sprays arranged across the filter towards its top (J, Fig. 272). The filter drum may have a cast-iron or a wood periphery, divided into sectionalised chambers. In large filters, steel construction is sometimes used. These chambers support the filter cloth, which may be of any convenient kind. It is usually laid on and

bound into place by turns of wire. This wire also serves as a support for the scrapers, preventing their coming into close contact with the cloth. A more recent practice is to divide the cloth also into sections, each section being tamped into place, a device which improves the ease with which the filter can be reclothed.

In one design of rotary filter the various sections have deep grooves or slots between them, which take the ends of cloth bags which are made specially to fit these grooves. These bags can be slid over the

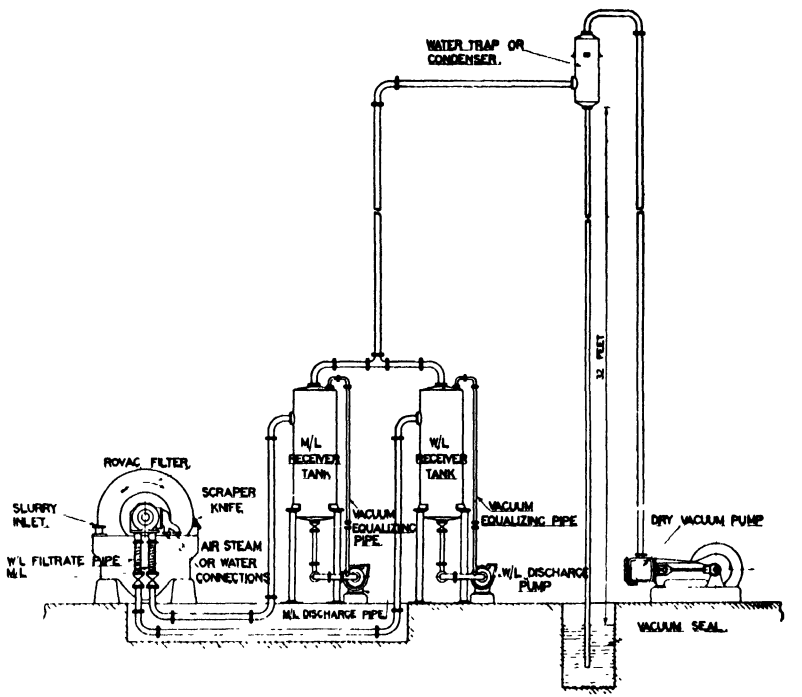


FIG. 275.

ends of the sections and bound into place, enabling the reclothing to be done section by section, practically without stopping the filter.

The filter drum is ordinarily immersed, so that about one-third of its surface is in the tank, but for paper pulp and other readily filtered products deep immersion filters are used in which the liquor surface comes well above the drum trunnions. Here vacuum pumps are often rendered unnecessary as sufficient suction can be produced by a plain barometric leg fitted to the discharge. Such an arrangement is used to filter paper pulp, and a discharge roller is also used instead of the scraper.

A difficulty occurring in rotary filters is the cracking of the cake during drying. This allows air to leak, reducing the vacuum and hindering drying. In order to prevent this it is usual to fit a number of

rollers towards the top of the filter, to squeeze the cake. A wide canvas band is sometimes stretched over these rollers in such a way that it presses on the upper surface of the filter cake, helping any cracks to close up. This is a distinct help to improved drying in some cases, and use can be made of the band to keep the cake whole and uncracked while wash water is distributed over the band. The rollers for closing the cracks are sometimes made to reciprocate in order to increase the efficiency.

A new discharge arrangement consists of a number of endless cords which are passed over the filter drum, around another smaller roller and through a kind of tooth-comb or spacer (Fig. 276). These strings or bands are placed fairly close together, and the cake clings to them and is lifted off the roller with them. As they pass over the small roller the bending causes most of the cake to break up and drop off, the remainder being scraped off the bands by the comb. This arrangement is said to be suited to handling lithophone and similar products.

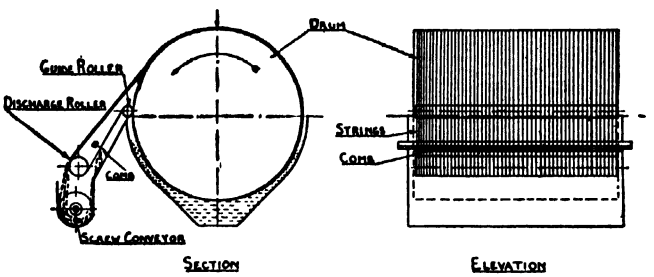


Fig. 276.

In a variation of this arrangement an endless band, consisting of a variety of closely meshed links, is passed round the filter. A cake is formed on this band and is lifted away from the roller with it. The band is taken into a drying chamber having hot-air circulation, where it travels in festoons to the outlet point, whence it returns to the filter again. The dried material falls off just prior to the return journey owing to the great bending of the endless belt which occurs at that point.

Finally, another form of rotary filter consists of a number of disc-like leaves fixed to a single revolving shaft, each disc dipping into a trough (Fig. 277). The wheels are built up of radial fan-like sections, each of which is independently clothed with a specially shaped bag. The end of each section has a pipe which fits into a recess in the shaft, connecting to the vacuum main. The filter elements and cloths are secured in position by a segmental hoop device which encircles them. This arrangement is very helpful where large amounts of filter surface have to be got into a small space. It is best suited to problems in which no washing has to be done, since the face of the cake is vertical and, in consequence, does not hold wash water very readily. Among other

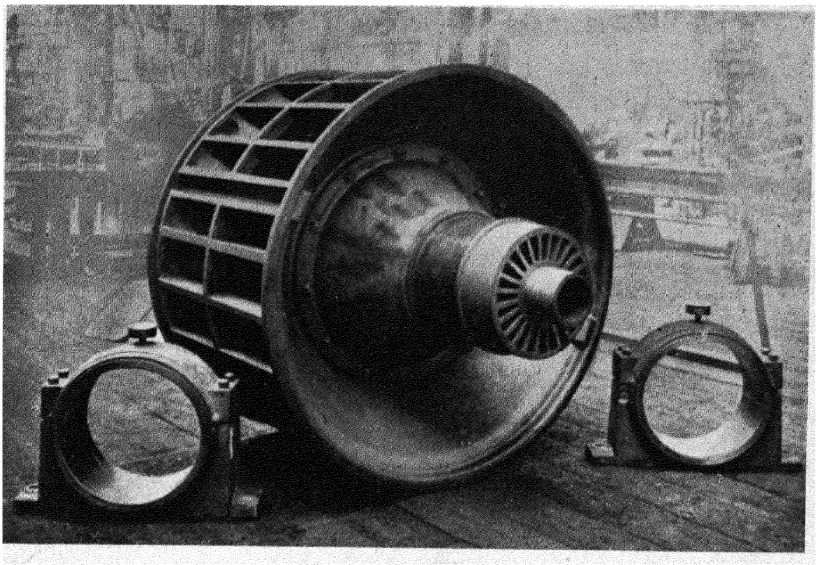


FIG. 274.—View of drum of " Rovac " Rotary Filter showing end view of Operating Valve.

[*See page* 500.

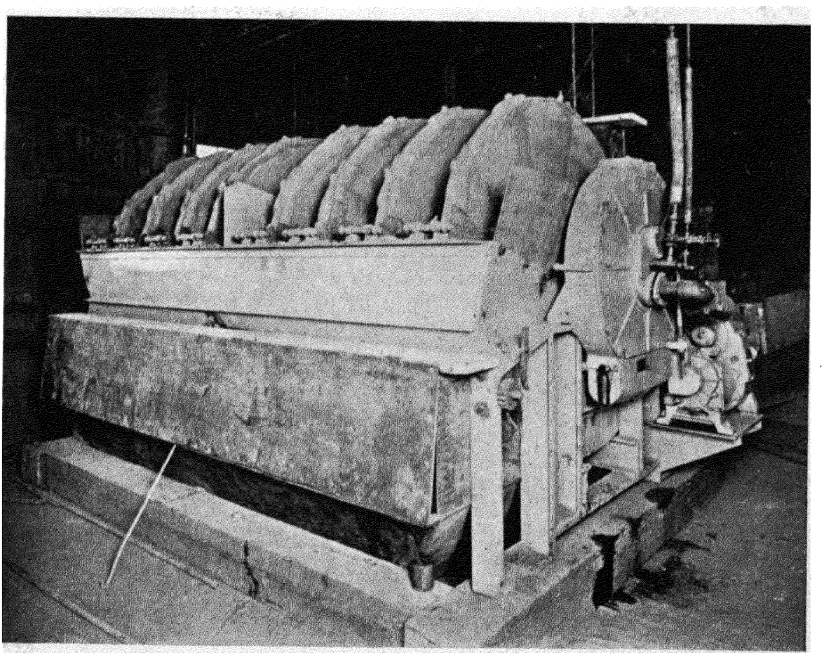


FIG. 277.

" Eimco " 6 ft. dia. disc filter with partitioned tank dewatering lead and zinc concentrates at the Combined Metals Reduction Company.

[*To face page* 502.

applications it has found favour in many starch works. Such filters can have a sectionalised trough so that each disc in a multi-disc filter can handle a separate product.

Some slurries contain particles which settle so rapidly that it is difficult to get them to adhere to the filter. Filter drums made with internal filter surfaces are intended to deal with this difficulty. The *Burt filter* was an early example of a batch filter operating on this principle. Filter elements were arranged inside the drum, with drain outlets taken to the exterior. The slurry was fed into the revolving drum until it was half full, when compressed air was applied to hasten filtration and help drying. Here, obviously, settlement helped filtration, and adherence to the filter surface, once obtained, could be maintained by air pressure.

A modern development of this idea is the *Dorrco filter*, which operates continuously under vacuum. It is in effect a rotary vacuum filter turned inside out, so that the product to be filtered is led into the hollow interior of the drum, which is fitted with sectionalised filter elements connected to a rotary valve in the ordinary manner. One end of the drum is open to admit a conveyor, which receives the cake from the upper part of the drum as it is dislodged by an internal scraper.

Another way of dealing with the difficulty is to employ a top feed, with a drum having an external filtering surface of the usual type. The internal passages are made extra large to permit generous quantities of air to be drawn through, which is necessary because of the granular nature of the solids treated in this type of filter. Such filters handle substances such as coal, salt and naphthalene crystals. It is possible to provide them with an air heater, so that hot air is drawn through the cake in the drying section, allowing moisture percentages as low as 3 per cent. or 4 per cent. to be achieved.

For products which are too coarse or granular for treatment, even on such filters, a type of drum is used in which the periphery is divided into compartments into which the material is poured and subjected to suction. As the drum revolves the compartments are turned over, and the drained product drops away. Occasionally a horizontal disc or table filter is used, but though this solves the problem of keeping difficult materials securely on the filter surface, yet it is limited by consideration of floor space, especially since the discs are necessarily one-sided, and the filters are normally made with only one disc.

(5) Pulp Filters.

Another type of deep bed filter is the pulp filter, which at one time was generally used and still is in use for filtering beverages in order to polish them and give them brightness.

A modern form of this filter, the *Kiefer*, familiar to all brewers,

consists of a vertical vessel closed by a lid on the top and having within it a pile of superimposed pulp cakes. The liquid is admitted into the body of the vessel and passes through the cakes to drainage members communicating with a vertical passage, running all down the centre, from which the clarified liquid makes its exit. The advantage of this type of filter is that the filtering material can be used again and again if it is suitably washed. The cakes are formed in a small pneumatic press.

The *Seitz-Hercules filter* achieves much the same object without any need to employ an hydraulic press for forming the pulp masses, which in this case are much thinner and are not re-used. The filter consists of a light casing, mounted on wheels and of somewhat unusual shape. The leaves consist of wire gauze stretched over a metal framework, over which wire is strung to hold the gauzes apart and form a drainage space. The front portions of the leaves have upper and lower outlet nozzles which clip to two header pipes within the filter towards the front. The leaves, which are very light, and seldom carry any real weight of deposit, are drawn out by hand for cleaning. The filter mass, which consists of a mixture of cotton and asbestos fibre, is mixed up and forced into the filter by a pump, and the liquor circulated until it runs clear. By this means a thin layer or matt is laid on the leaves, and this suffices without any continuous addition of pulp to the liquid being filtered. When this is done the liquor to be filtered is forced into the press, passing through the filter mass on the leaves and out through the filtrate openings. Since the filter is intended for use at very low pressures the outer casing is very lightly constructed, usually in tinned copper. Liquor can be admitted below a false bottom under the plates, or above them, and valves are arranged so that the flow can be shunted to the top or bottom of the press or fed equally, as required. Similarly, filtrate may be drawn from both top and bottom headers, or from one only. The top outlet only is generally used during coating of the leaves so that uneven flow, due to unbalanced static head within the filter, due to the height of the leaves, is diminished. When coating is complete there is enough back pressure to render this procedure unnecessary, and both outlets can be used. At the end of filtration the bottom outlet ensures the drainage of the leaf interiors.

The interesting part about the operation of these filters is that the filter mat or precoat is so compacted that it can be pulled intact off the filter leaf like a sheet of paper. At one time the production of this filter mass was entirely in foreign hands, but nowadays an effective replica is being made in Great Britain.

Filters having prepared pulp leaves are finding increasing application. The *Seitz sterilising filter* is especially popular. These filters use ready prepared " films " of cellulose fibre or a mixture of asbestos and cellulose, which are simply placed between the filter elements and

thrown away when done with, so that no washers are needed. The films are thick enough and fine enough to stop the passage of yeasts and other organisms, including bacteria such as *B. prodigiosum.*

Such filters find their special application for liquids from which all traces of organic life must be removed without heating being applied. The fineness of straining is effective down to about 0·8 μ or, say, $\frac{1}{30,000}$ in. This depends a little on the type of bacillus, since a long mobile, flexible type will pass more readily than one formed like a short rigid rod. Smaller filters of this class are used for handling serums, antitoxins, liver and other extracts, etc., where even a few bacteria passing into the finished product would soon ruin it.

The Hydro-Extractor and Centrifugals.—Such machines are widely used in the chemical and allied industries for the removal of

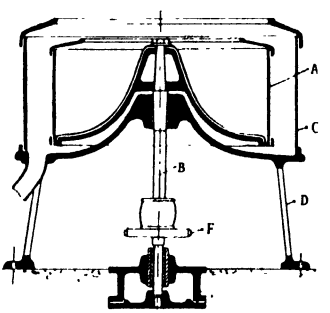


FIG. 278.

water and liquors from slurries or pastes, or from fibrous materials such as textiles.

The *hydro-extractor* in one of its simplest forms is illustrated in Fig. 278. It comprises a perforated basket (A) which is caused to revolve at high speed round a vertical axis, and under the action of the centrifugal force developed, the liquid content of the substance contained in the drum is ejected through the perforations. (To prevent the ejection of fine sediments, the perforations are covered by suitable fabric of the filter cloth type.) The machine illustrated is of the underdriven belt type, and the water or liquid removed from material in the drum leaves by the spout in the outer casing C. The brake F, is provided to bring the basket quickly to rest.

Hydro-extractors can be conveniently classified into three principal types, viz. : (*a*) fixed spindle machines ; (*b*) suspended machines ; (*c*) self-balancing machines of either the underdriven or topdriven classes.

The first of these types—the fixed spindle machine—is illustrated in Fig. 279. It is an old design and are not now in general use because the whole of any unbalanced centrifugal force due to uneven loading must be taken by the bearings of the machine and thence to the

foundations. Vibration thus caused is a serious nuisance and can be entirely avoided by the use of suspended machines, which, in the case of underdriven machines, are ordinary fixed spindle machines hung by suspension rods from columns carried on an independent base ring. These rods have hemispherical ends fitting in cups at top and bottom, and the machine is therefore free to vibrate without affecting its surroundings.

The self-balancing machine is by far the most common type now in general use, and may be of either the underdriven or topdriven class. In this design the spindle bearing is mounted in a box or casing to which a certain amount of free play is given under constraint from rubber buffers or springs. The topdriven type is illus-

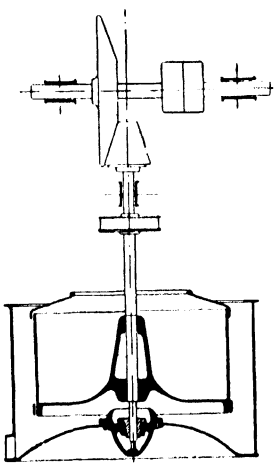


FIG. 279.—Fixed spindle type of hydro-extractor.

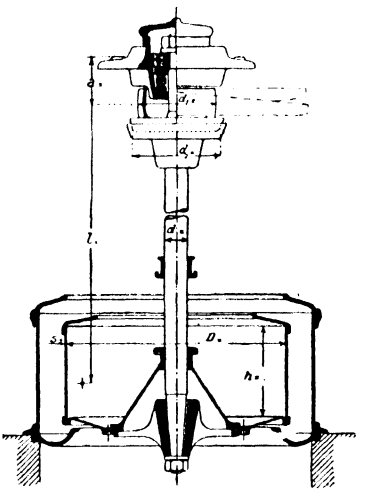


FIG. 280.—Topdriven Weston type self-balancing hydro-extractor.

trated in Fig. 280, which shows the well-known Weston pattern. There is a single top bearing contained usually in a conical rubber buffer, though sometimes a cylindrical rubber buffer is used. The underdriven type is illustrated in Fig. 281 which shows an electrically driven suspended machine of the self-balancing type by Broadbent.

The speeds at which centrifugal baskets can be run is of importance. The usual formula for centrifugal force in pounds exerted by a mass of 1 lb. is $C = \frac{V^2}{57{,}888D}$ where V is the surface or peripheral speed in ft./min. and D the diameter of the basket in feet.

From the formula it will be noted that the force exerted for a given surface speed must vary inversely as the diameter. Hence the problem is similar to that of a rotating pulley in so far as strength is concerned, and if the liquid load is proportional to the area of the

basket wall, and to its thickness, bursting will always occur at the same surface speed whatever the size of the basket and whatever the wall thickness. *Surface speed* is therefore the limiting factor in so far as strength is concerned, and it is to be noted that it is of no use to greatly increase the wall thickness because the self stress in the wall due to its own weight is a material factor.

Speeds usually vary between 8000–12,000 feet per min., though smaller machines of the separator type often run as high as 18,000 feet per min. If the surface speed is kept constant, it is shown that the centrifugal force would always be inversely proportioned to the

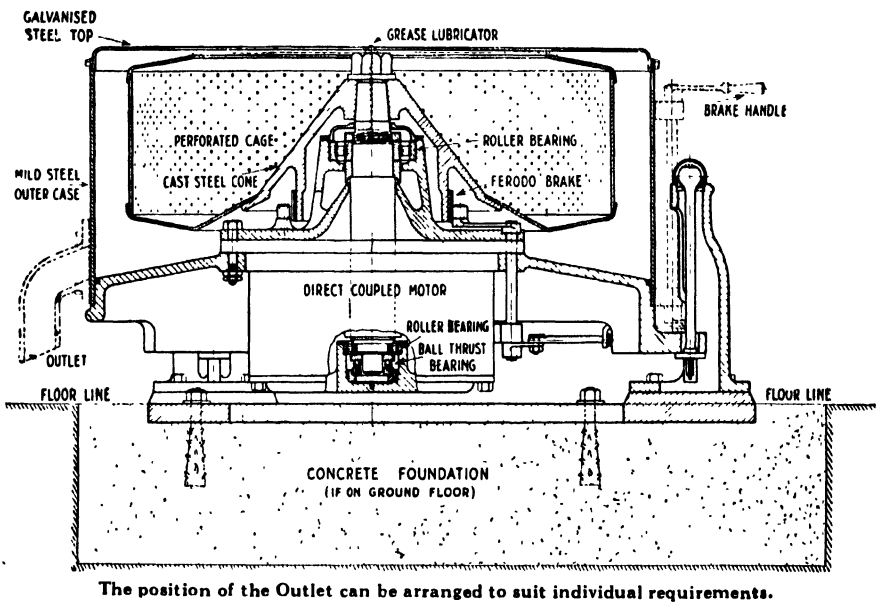


FIG. 281.—Direct coupled underdriven self-balancing hydro-extractor by Thos. Broadbent & Sons.

diameter, but in practice the running speed of commercial machines is often an average between that for equal surface speed and that for equal effect. Fig. 282 shows what the speeds of sundry sizes of basket would be if they were based in this manner on a 36-in. basket running at 1000 r.p.m. with a centrifugal effect of 512 approx., and a surface speed of 9424 ft. per min. If of steel the tensile stress in the wall of the basket would be about 3000 lb. per sq. in. depending on the nature of the perforations.

It will be seen from the figures that though the surface speed increases in the case of the larger machines, the centrifugal force decreases.

The rules for the stress in the walls of baskets due to working

conditions take into consideration the centrifugal force due to the rim of the basket, and that exerted by the load wheel is usually estimated as though it were concentrated at the full diameter of the rim.

The Balancing of Hydro-Extractors.—It is rarely that a hydro-extractor can be exactly balanced during loading, and arrangements must be made in the design of such machines to limit the harmful effect of such out of balance upon the stressed parts thereof.

Alliott (*Proc. Chem. Eng. Group Soc. Chem. Ind.*, 1924, 6A, 72) deals with this aspect of hydro-extractor design in the following interesting way.

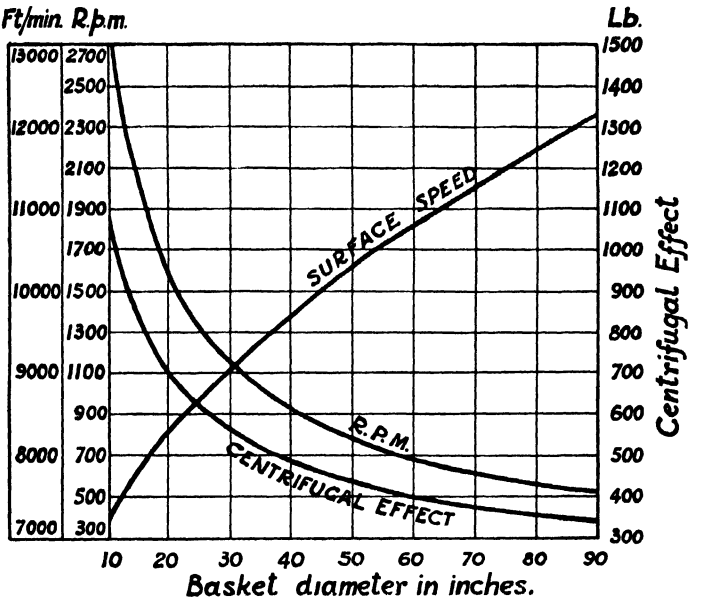


FIG. 282.

Take a weight of 4 lbs. hanging from a length (say 3 ft.) of strong catapult elastic, the ends of which are held in the hand. If the weight is displaced and permitted to vibrate by itself it does this at a certain rate, however big the vibration. This is the critical speed. If the hand is moved up and down slower than this the weight follows, and moves up and down as the hand moves up and down. Moreover as the speed is gradually increased the length of the up-and-down movement becomes greater and greater, and it is impossible to speed up to just the same rate as the weight itself vibrates if left free, for the motion would then be so violent as to break the elastic.

A curious thing happens when the speed is increased still further. The weight no longer follows but lags half-way behind moving up and down as the hand moves up and down and vice versa. Its motion

becomes less and less, and if the hand is jerked up and down very rapidly the weight scarcely moves at all. Even if the hand moves a long way up and down, so long as it does so sufficiently quickly the elastic simply stretches and the weight stays very nearly still. This exemplifies the natural motion of any elastic system when caused to vibrate more rapidly than its natural speed, and if some friction is imposed on the weight by making it say vibrate in water, its movements become much less violent even at the critical speed.

Taking now a "free spindle" centrifugal machine as seen in Fig. 280. This machine is of the self-balancing type, wherein the spindle bearing is mounted in a conoidal buffer. This type is known as the Weston type and is much used for dealing with loads of the out-of-balance type.

Considering this machine in the light of the previous discussion, the basket corresponds to the 4-lb. weight, the buffer to the elastic, the out-of-balance weight to the pull of the hand, and the speed of the machine to the rate at which the hand is moved. Such a hydro-extractor has a critical speed at which it vibrates just as the weight did, and this speed has a close relation to the rate at which the basket would swing across and back again if it were pulled hard to one side and let go. At low speed the spindle is straight or nearly so, and the out-of-balance weight is pulling it outwards. The deflection increases until the critical speed is reached. At a little above this speed the basket is still a long way out of truth but the basket lags behind in the manner common to all forced vibrations, and the out-of-balance weight is now half a turn in front. The spindle tends to move back as the speed rises, and at high speeds it returns so far that its centre of gravity comes practically into the vertical line in which the spindle would normally be. Unless the basket is very badly loaded the centre of gravity will only be perhaps $\frac{1}{8}$ in. or even less from the centre line of the spindle so that but little side stress is placed on the bearings. In the Broadbent hydro-extractor of the underdriven type (Fig. 281) the basket and all the driving gear are suspended on link buffers, as indicated on the right of the figure, and these take the place of the single conoidal buffer of the Weston type.

Centrifugals or separators are designed on lines similar to hydro-extractors but they have no holes in the baskets, which are really solid bowls. They can be used to separate from liquids solid particles so fine that they would choke filter cloths, or for separating two liquids such as water and tar, milk and cream, etc. Fig. 283 shows a typical design of centrifugal by Thos. Broadbent & Sons for the removal of fine particles from suspensions.

The mixture is fed into a solid basket, which rotates at high speed, which precipitates the solids against the circumference, and the

clarified liquid forms an interior wall. The liquor is discharged by means of a specially shaped pipe having a knife edge nozzle which is applied to the rotating liquor by means of a hand wheel. A flexible hose is attached to the end of the skimmer pipe and the surface speed of the liquor causes it to be discharged out of this pipe into storage vessels. When the cake is sufficiently thick the machine is stopped and the cake removed.

Another familiar form of centrifugal is that used for milk separation, which has a bowl 6–12 in. dia., filled with a number of metal cones or inverted dishes, which are separated from each other at short distances. Fig. 284 shows a laboratory type made by Watson, Laidlaw & Co., Ltd. The liquor to be treated falls down the inlet

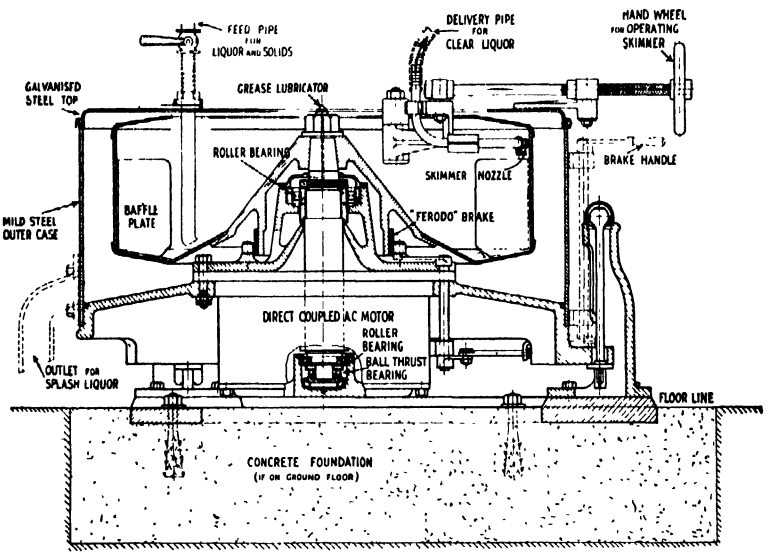


FIG. 283.

pipe through the centre of the plates, rises in passages cut through the latter and passes to the spaces between them. The object of these plates is twofold. In the first place their friction helps to bring the incoming liquor up to speed very rapidly, and secondly it acts as an extension of the separating surface, for any particle in the thin film which is contained between each pair has only a short distance to move to achieve final separation. Thus in a milk separator the heavy skim milk will form a thin layer moving outwards on the undersurface of each plate and the lighter cream a similar layer moving inwards on the upper surface of each plate. The milk comes into the outer space, passes beneath the separating lip and flows out of the lower outlet. The cream similarly passes on the inside of the separ-

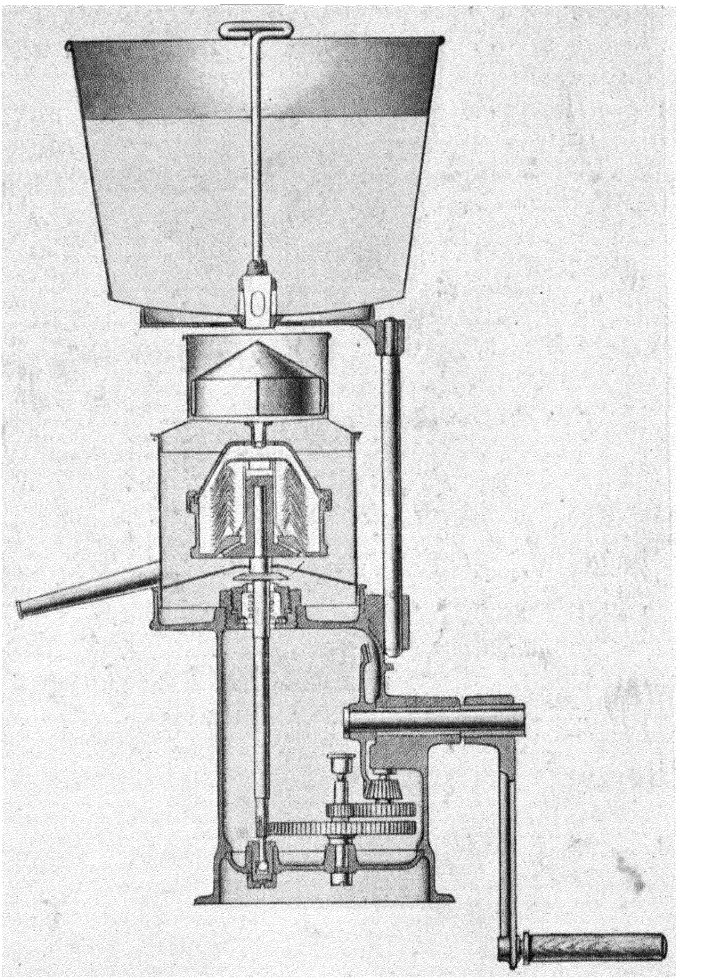


FIG. 284.—Laboratory type centrifugal separator by Watson, Laidlaw & Co., Ltd.

[*To face page* 510.

ating plate and out of the upper lip, which is slightly smaller in diameter than that over which the milk overflows.

Another class of machine (for effecting centrifugal separations) is fitted with very small bowls—down to 2 in. dia., and the speed of rotation reaches 40,000 r.p.m. Such machines are used for a wide variety of operations, such as the clarification of glue, removal of dirt, etc., from lubricating and fuel oils, handling of serums, and separating bacteria from suspensions.

CHAPTER XV.

CRUSHING AND GRINDING EQUIPMENT.

THE terms crushing and grinding are used to describe the operations of subdividing solids by mechanical means, and in general grinding means subdividing to a finer degree than crushing.

There has been a great deal of research into the theory of crushing and grinding, but it is still not possible to measure accurately the useful work done in such operations, so that the mechanical efficiency of crushing and grinding equipment must be estimated from a comparative rather than on an absolute basis.

Two proposals have been put forward to show the relationship between size reduction and power consumption. These are known respectively as Rittinger's Law and Kick's Law, and the latter may be stated as follows :—

Kick's Law.—" The energy required to produce analogous changes of configuration of geometrically similar bodies of equal technological state varies as the volumes or weights of these bodies." (F. Kick, "Das Gesetz der proportionalen Widerstande," A. Felix, Leipzig, 1885.)

Stadler (*Trans. Inst. Min. Met.*, 1909–10, **19**, 471, 478, 509; 1910–11, **20**, 420) has worked out a practical method of applying the law to crushing and suggests *ordinal numbers* corresponding to different sizes of crushed material. If Kick's Law is accepted, then these ordinal numbers should be proportional to the amount of useful work done to produce a given size of material from a certain larger unit size. Stadler's argument in this connection is as follows :—

The area of fracture over which the cohesion of the molecules has to be destroyed multiplied by a coefficient determining the resistance which the molecules oppose to their separation by the exercise of stress (crushing, tensile or shear) represents the *force* necessary to cause the fracture.

In order to perform mechanical work this *force* must act through a distance, which is the deformation which the body can stand before the breaking point is reached. (It is in this connection immaterial that this distance of deformation within the limits of elasticity and plasticity is, for not perfectly homogeneous bodies, subject to variations, which for bodies such as quartz, glass, etc., are too insignificant to be considered, and in addition they are, by the nature of our crushing appliances, arranged to such an extent that these averages are as good as exactly

defined figures.) Dealing with relative values only, we have not even to care about the exact extent of this deformation, and all we need is to be satisfied that this factor is a constant function of the diameter of the particle to be crushed.

The *mechanical work* done is represented by the product of the force by the distance, but as in a regular scale of reduction by volume the diameters of the particles decrease at the same ratio as the area of fracture increases, the product or the mechanical work for reducing the volume (or weight) of the unit from one grade to the next following is a constant for each grade and is called the crushing or energy unit (E.U.).

The volumes of the particles decrease from grade to grade in the same ratio as the number of particles, constituting in their total the volume of the unity increases, and the product of the volumes into the number of the particles of that grade is therefore constant for each grade. As in conformity with the above law the amount of energy absorbed is proportional to the volume of the body to be crushed, it follows again also that the total energy required for reducing this weight of the unit is constant for each grade.

The *ordinal numbers* of any arithmetical progression given to these grades represent consequently the relative values of the energy which has to be spent upon producing this respective grade from the initial unit or the mechanical value of the grade.

For obtaining the mechanical value of mixed sands we need only to multiply the percentages of the gradings by the number of energy units of the respective grade and add the products.

The useful work done per unit by any crushing machine is determined by the difference between the mechanical value of the sample taken at the inlet and the discharge of the machine, and for obtaining the total work done the difference has to be multiplied by the tonnage dealt with.

The relative mechanical efficiency is the value obtained by dividing the total work done by the unit of energy, i.e.

$$\text{Relative Mechanical Efficiency} = \frac{\text{Tonnage} \times \text{work done per unit in E.U.}}{\text{H.P. (Unit of Energy)}}$$

The following is an example of the application of Stadler's method to a crushing problem.

Example.—A ball mill fed with quartzite with the screen analysis shown in column 2, Table 54, is reduced to the size shown in column 3, and the tonnage handled is 36 tons per 24 hrs., and the power required 18½ h.p. Total energy units of feed = 487·82 (column 5) and of product 1376·66 (column 6). The relative work done per unit weight of feed = 1376·66 − 487·82 = 888·84.

$$E = \frac{888{\cdot}84 \times 36}{100 \times 18{\cdot}5} = 17{\cdot}3.$$

TABLE 54.

APPLICATION OF STADLER'S ORDINAL NUMBERS TO A CRUSHING TEST.

1	2	3	4	5a	6b
Screen Aperture (mm.).	Percentage on Screen.		Ordinal Number.	Energy Unit.	
	Feed.	Product.		Feed.	Product.
37·70	0·66	—	− 1	− 0·66	—
26·67	5·51	—	0	0·00	—
18·85	16·36	—	1	16·36	—
13·30	22·20		2	44·00	—
9·423	11·18	0·02	3	33·54	0·06
6·680	7·46	0·02	4	29·84	0·08
4·699	5·49	—	5	27·45	0·00
3·327	3·62	0·29	6	21·72	1·74
2·362	2·97	0·83	7	20·79	5·81
1·651	3·30	2·45	8	26·40	19·60
1·168	2·94	4·34	9	26·46	39·06
0·833	3·18	6·92	10	31·80	69·20
0·589	3·55	12·37	11	39·05	136·07
0·417	2·37	10·15	12	28·44	121·80
0·295	2·48	12·40	13	32·24	161·20
0·208	1·85	10·55	14	25·90	147·70
0·147	1·72	10·88	15	25·80	163·20
0·104	1·25	8·48	16	20·05	135·68
0·074	0·70	5·12	17	11·90	87·04
Through 0·074	1·41	15·18	19	26·79	288·42
Totals	100·0	100·0	—	487·82	1376·66

(*a*) Column 5 = Column 2 × Column 4.
(*b*) Column 6 = Column 3 × Column 4.

Rittinger's Law.

"The work required for reduction grows in proportion to the degree of reduction." In order to explain this statement, let A represent a cube of stone, homogeneous throughout, with a side of length S. Let the work required to divide this cube parallel to one of its sides be *a* ft.-lbs. [P. R. Von Rittinger, "Lehrbuch der Aufbereitungskunde," Ernst und Korn, Berlin, 1867.]

Imagine the three perpendicular sides of this cube to be divided into *n* equal parts, and the cube to be divided by planes parallel to the three perpendicular sides, as shown by A_2 and A_3 (Fig. 285).

Then we get

8 cubes of side $\frac{1}{2}$S long, by doing $3 \times 1 \times a$ ft.-lbs. of work.
27 cubes of side $\frac{1}{3}$S long, by doing $3 \times 2 \times a$ ft.-lbs. of work.

64 cubes of sides $\frac{1}{4}$S long, by doing $3 \times 3 \times a$ ft.-lbs. of work.
n^3 cubes of side $1/n$S long, by doing $3(n - 1)a$ ft.-lbs. of work.

The smaller the lateral edges of the cubes resulting from reduction as compared with the original cube (i.e. the smaller the reduction

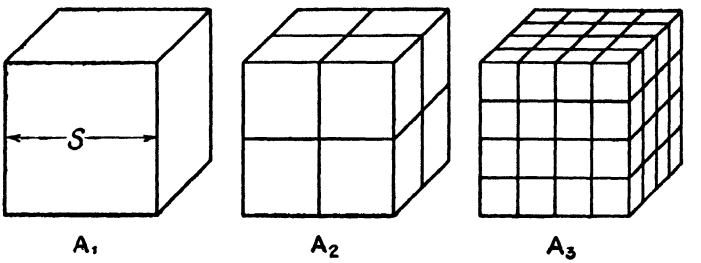


FIG. 285.

quotient $1/n$), the greater is the amount of work necessary to effect the reduction.

$$An = 3(n - 1)a.$$

The relationship between the work required to produce two different sizes of particle is

$$\frac{An}{Am} = \frac{n - 1}{m - 1}.$$

If the reduction quotients ($1/n$, $1/m$) are very small, or the degree of reduction is very great (i.e. m and n are very great), this may be written

$$\frac{An}{Am} = \frac{n}{m} = \frac{1/m}{1/n}.$$

The work done is nearly proportional to the degree of reduction, or is inversely proportional to the reduction quotients. E.g. if one produces from two 1-in. cubes of stone smaller cubes, from the one with $\frac{1}{5}$-in. sides, and from the other with $\frac{1}{20}$-in. sides, the work required in the second case is four times that required in the first case. In practice the reduction does not occur regularly, but particles of different shapes are formed, and we have in addition to the desired size many much smaller particles. The work done, therefore, in reducing to a certain size is much greater than the theoretical amount required for regular reduction, but in any two instances the work done is almost proportional to the degree of reduction. It can also be said that the energy necessary for reduction is directly proportional to the increase of surface, for, since two equal fracture planes result from each cleavage, the surface increase is directly proportional to the number of cleavages taking place, and so also is the work necessary to effect the cleavages.

It is to be noted that these two laws give widely different "efficiencies" for the same crushing or grinding result. Rittinger's Law shows a very much higher efficiency in the case of fine crushing,

as will be seen from Table 55, which summarises a series of experiments at McGill University in connection with the theory of grinding. (Bell, *Trans. Can. Men. Inst.*, 1916, **19**, 151.)

TABLE 55.

Crusher.	Diameter of Piece Crushed (ins.).	Work done per A.E. H.P. in 24 hrs.	
		Measured in Stadler Energy Units.	Measured in Rittinger Surface Units.
Gyratory	3·50	710	947
Dodge	1·20	520	1030
Rolls	0·50	286	1128
„	0·29	138	1000
„	0·18	68	1022
„	0·11	89	1187
„	0·07	52	823

From a long series of experiments Bell concluded:—

(*a*) That in the case of the reduction of any given rock there is a constant relationship between the power applied and the crushing effected.

(*b*) That Rittinger's theory appears to conform agreeably with this relationship.

(*c*) That Stadler's theory, based on Kick's law, does not so conform.

Choice of Methods of Comparison of Crushing and Grinding Operations.

If it is desired to compare a particular size reduction carried out in different machines and the size of feed and product is approximately the same, it does not matter which of the two laws is used. When, however, there is a considerable difference in the character of the material entering and leaving the competing machines, the comparative efficiency of the finer crusher will be relatively higher by the Rittinger method. This will lead to the conclusion that economy will be gained in a crushing operation by putting more and more work on the fine crushing machines, a conclusion which in practice is open to most serious question. (See Table 55.)

Cost Comparison.—This method is an essentially practical system whereby competitive machines can be tested out under working conditions. It necessitates close records of tonnages crushed to the desired screen analysis, power absorbed, repairs and maintenance, and capital charges. This method is usually only applicable to the largest organisations.

Tons Crushed per Horse Power Hour.—This is the simplest way in

which to compare competitive appliances, as it necessitates only measurement of power consumption, screen analysis of the product and tonnage handled.

Crushing Machines are of four general types, namely (*a*) Jaw Crushers, (*b*) Gyratory Crushers, (*c*) Disc Crushers and (*d*) Rolls.

Jaw Crushers.—The best-known type are the Blake, with movable jaw pivoted at the top, and the Dodge, with movable jaw pivoted at the bottom.

A typical Jaw Crusher by Hadfields, Ltd., is seen in Fig. 286. It consists of a rectangular frame of steel with two fixed jaws (13) and swinging jaws 12 and 12A. Both the fixed and swinging jaws are lined with manganese steel, and are corrugated to concentrate the crushing pressure on relatively small areas. The motion of the swinging jaws is derived from the eccentric shaft A, which gives a rising and falling motion to the cast steel pitman 9, leading to vibration of the toggles 14, and consequent reciprocating motion of the movable jaw 12 12A, swinging about the shaft 6A. The motion parts are sprung together by the draw-back springs F.

TABLE 56.

OUTPUT AND POWER REQUIREMENTS OF JAW CRUSHERS.

Size of Receiving Opening.	Output per hr. based on Hard Limestone to 2½ ins. Ring.	Extreme Dimensions (including Shafts).						Size of Driving Pulley.	Width of Belt Recommended.	Revolutions per Minute.	Effective h.p. Recommended.
		Length.		Breadth.		Height.					
ins.	tons.	ft.	ins.	ft.	ins.	ft.	ins.	Dia. face ins.	ins.		
10 × 6	3 to 5	5	5½	3	4	3	7	24 × 4½	4	250	6
12 × 8	5 ,, 6	5	10	3	11	4	0½	24 × 4½	4	250	9
16 × 9½	7 ,, 9	6	3	4	9⅛	4	7	30 × 6	5	250	18
20 × 6	10 ,, 12	6	4	5	5 3/16	4	10½	36 × 7	6	250	22
20 × 10	10 ,, 12	7	4½	5	5 3/16	5	3	36 × 7	6	250	25
24 × 13	20 ,, 22	8	5	6	11	6	1	42 × 10	9	250	40
24 × 19	15 ,, 17	9	0	7	5⅞	7	2	42 × 12	10	250	50
30 × 12	20 ,, 22	9	0	7	11	6	6	42 × 12	10	250	55
30 × 18	20 ,, 22	9	5	7	11	7	5	42 × 12	10	250	60
36 × 24	60 ,, 80	10	6	9	2⅜	7	10	48 × 12½	11	250	75 to 100
42 × 30	100 ,, 140	13	7	10	11¼	9	6	54 × 16	14	200	100 ,, 125

As illustration of the power requirements and hourly output of these jaw crushers, Table 56 gives particulars of these data in respect of the machines made by Hadfields, Ltd.

Gyratory Crushers.—The gyratory crusher consists of a fixed crushing surface in the form of a frustum of an inverted cone, around the axis of which gyrates a crushing surface which has the form of a conical frustrum in an erect position. The material to be broken is fed into the downwardly converging annular space between these crushing surfaces. It is crushed when these surfaces approach and the crushed material

falls through when they recede. The machine is built in two principal types, known as the suspended spindle type and the fixed spindle type. The former is the best known and most widely used, though the latter is steadily increasing in popularity.

A typical gyratory crusher, as made by Hadfields, Ltd., is seen in Fig. 287.

It is to be noted that the crushing cone does not revolve but gyrates; in other words, the main shaft (no. 5) is so supported by the central spindle no. 8, that the bottom is free to move in a circular course, much in the same way as a pendulum when suspended in the usual manner. The pinion (no. 31) is, of course, driven by means of the countershaft no. 32, to which is keyed the pulley no. 35, the motion being transmitted to the bevel wheel no. 18, the latter being fitted with an eccentric boss revolving outside the hollow shaft no. 5.

The crushing cone is securely attached to the hollow shaft, and therefore the two partake of the same motion, the effect being that the crushing cone is constantly approaching and receding from the outside shell liners nos. 27 and 28, so that any stone coming between them is at once cracked, and then released to settle lower down for another blow at the next gyration, or to be discharged if already fine enough. As will readily be observed, the cone is always crushing stone at some part of its circumference, hence the action is continuous, and a large output results.

The gyrating motion imparted to the hollow shaft by the eccentric is naturally greatest at the bottom, and becomes less as the top is approached. It will therefore be apparent that the motion of the cone is comparatively slight, and this fact, combined with the concave form of the surface, against which the stone is broken, and the instant release after cracking, tends to prevent the shattering of the stone.

The crushing cone and mantle and the concave liners are the parts which require most frequent renewal. In the "Heclon" Breaker, these are made of Hadfields Patent "Era" Manganese Steel.

The table on page 519 gives particulars of the throughput and power requirements of Hadfields Gyratory Crushers.

Disc Crushers.—Disc crushers are made in both horizontal and vertical types, and consist essentially of two opposed conical crushing surfaces of large apex angle rotating in the same direction at about the same speed. A typical disc crusher is seen in Figs. 288–9. The discs are supported at an angle to each other and this provides a wider opening between the edges of the discs at one part of their circumference than at the opposite end. When rock is fed through the central feed spout it is thrown by centrifugal force into the opening where the discs are widest apart. It is carried round with the discs to where they are closer together and is crushed in the process. The smaller particles fly out from between the discs into the encircling shoot, whereas the

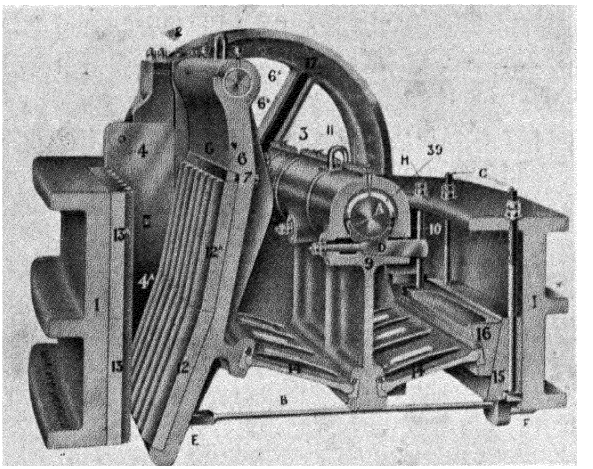


FIG. 286.—Jaw crusher by Hadfields Ltd.

[*See page* 517.

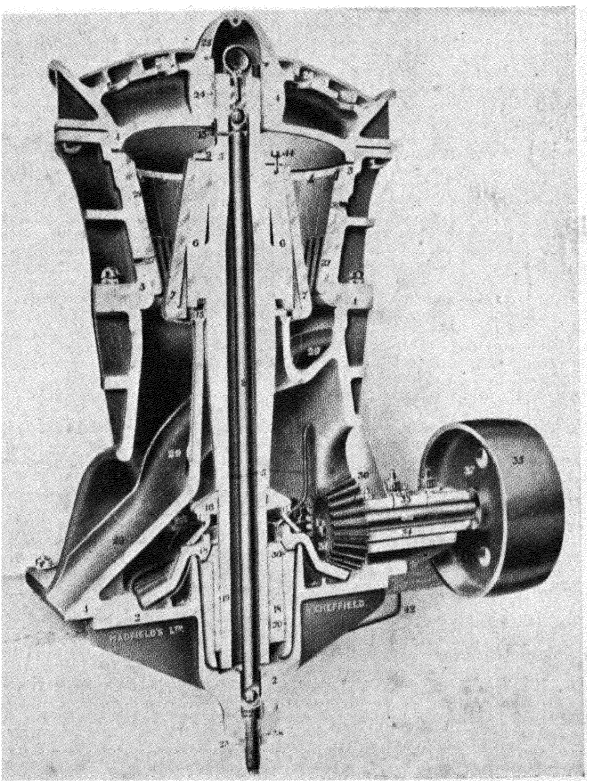


FIG. 287.—Sectional view of style A "Heclon" breaker.

[*To face page* 518.

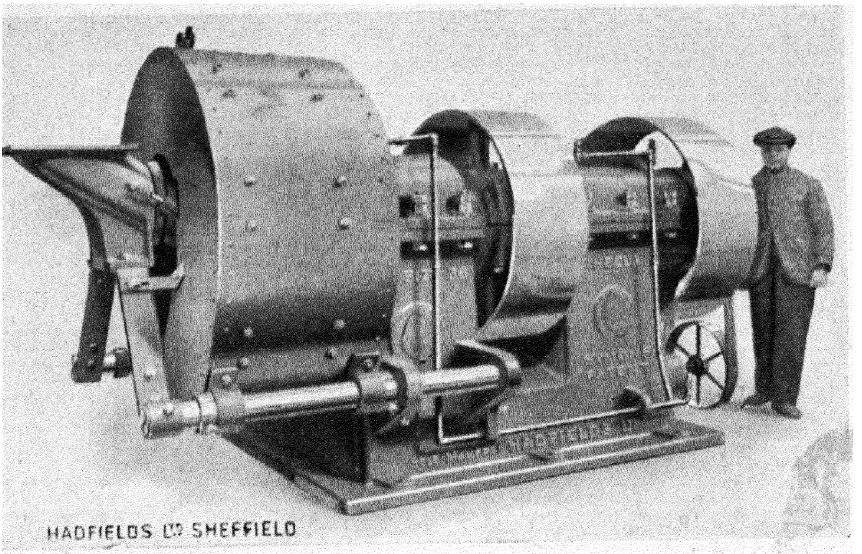


FIG. 288.—"Hecla" disc crusher.

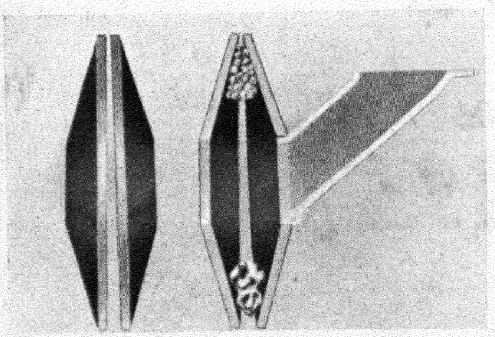


FIG. 289.—View of discs of disc crusher.

[*To face page* 519.

Particulars of Gyratory Crushers by Hadfields, Ltd.

Size.	Approx. Total Shipping Weight (in cwts.).	Approximate Capacity (in tons per hr.) according to character of material. To pass a Ring of :—							Greatest Fineness Recommended.	Speed of Driving Pulley (r.p.m.).	Effective h.p. required according to Size and Nature of Material.
		1½ in.	2 ins.	2½ ins.	3 ins.	3½ ins.	4 ins.	4½ ins.			
No. 3	80	4 to 6	6 to 8	8 to 10	—	—	—	—	1¼-in. Ring	475	12 to 15
„ 4	160	8 „ 12	10 „ 15	15 „ 20	20 to 25	—	—	—	1½ „ „	425	18 „ 25
„ 5	300	—	20 „ 30	25 „ 35	35 „ 40	40 to 50	—	—	2 „ „	375	25 „ 45
„ 6	435	—	—	40 „ 55	55 „ 65	65 „ 80	80 to 100	—	2¼ „ „	375	45 „ 60
„ 7½	710	—	—	—	70 „ 90	90 „ 110	100 „ 130	—	3 „ „	350	75 „ 100
„ 9	1400	—	—	—	—	—	—	150 to 200	4½ „ „	300	100 „ 150

large particles are caught and crushed in the next revolution. The capacity and power requirements of Hadfields Disc Crushers are given in the table below.

TABLE OF WEIGHTS AND CAPACITIES OF "HECLA" DISC CRUSHERS.

Size of Crusher :	48 ins.	36 ins.	24 ins.	18 ins.
	tons. cwts.	tons. cwts.	tons. cwts.	tons. cwts.
Shipping weights . .	15 0	9 10	4 5	2 16
Opening in elliptical feed spout	11¾ × 17	9¼ × 14½	7 × 10⅜	4¾ × 7
Approx. opening between the discs at feed spout	8 ins.	5 ins.	3¼ ins.	2¼ ins.
Largest initial pieces should not exceed (ins.)	15 × 10 × 6½	6 × 5 × 3¾	5 × 4 × 2½	4 × 3 × 1¾
	Size of Ring. | Tons per Hr.	Size of Ring. | Tons per Hr.	Size of Ring. | Tons per Hr.	Size of Ring. | Tons per Hr.
Capacities in tons per hr.	1½ — 50–60 2 — 60–70 2½ — 70–90	1 — 25 35 1½ — 35 10 2 — 40 50	¾ — 15–17 1 — 17 20 1½ — 20–25	½ — 6–8 ¾ — 8 10 1 — 10–12
R.p.m. main pulley . .	100	133	150	200
R.p.m. eccentric pulley .	200	266	400	450
Size of pulleys . . .	54 × 16	44 × 14	34 × 10	28 × 8
Effective h.p. required .	50 65	30–40	18–25	12–18

Rolls.—Crushing rolls are of two general types known respectively as rigid and spring rolls, but the former type is rarely used at present.

Spring rolls consist of two cylinders mounted on horizontal shafts driven in opposite directions. The requirements of well-designed rolls include rugged simple construction ; the springs should exert a pressure sufficient to crush the hardest ore or rock likely to be encountered in service, yet sufficiently flexible to pass unbreakable substances without damage to the machine.

The angle of "nip" of plain rolls is about 17½°. In practice this angle varies with the diameter of the rolls, the size of the feed and product desired, and the set of the rolls. In order to nip large particles, rolls of large diameter are necessary or the reduction ratio of *feed* must be small. When a given-size feed product is not being nipped the usual alternative is to increase the distances between the roll faces, and hence the size of product. Grooving of the rolls or drilling at irregular intervals will assist nip.

Plain- or smooth-faced rolls are limited in practice to a feed of 3½–4 ins., and with a 25° angle of nip and 6 ft. as the largest diameter of roll manufactured the reduction ratio is about 2 : 1 on a 3½–4 ins. feed size.

The following notes on Roll Crushers are taken from a recent paper by Miller and Badger (*Inst. Mech. Eng.* Advance Proof, 1939) :—

Factors Influencing Production from Rolls.—Rolls are used for such a variety of purposes, crushing materials varying so widely in character and within so comprehensive a range of sizes, that it is impossible to lay down arbitrary rules which may be applied without exception to all problems relating to the performance, output, and power consumption of these machines.

One salient feature emerges from a study of the literature on this subject, and that is the universal adoption of the " ribbon theory " as the basis for calculating the output which it should be possible to obtain under given conditions. Although the basic formula is generally accepted, the qualifying coefficient remains indefinite, so that there is still room for some difference of opinion.

The " ribbon theory " is based on the hypothesis that the surfaces of the rolls travel at a known peripheral speed and, assuming the material to be fed in uniform density for the full width of the rolls, and that the faces grip the stream immediately without any slip, the cubical contents of the ribbon which is drawn through the space may be calculated from the width of the gap between the rolls.

The weight should be computed on the basis of crushed material as the feed will normally take this form, and a liberal allowance must be made for voids and irregularity of supply. It should be borne in mind that theoretically the ribbon is supposed to travel at a rate equal to the circumferential speed of the rolls, whereas, in practice, some margin must be allowed for delays due to lack of gripping power. Given rolls with correctly shaped teeth for coarse crushing or, if plain, of sufficient diameter and strength to crush the material without hesitation, and assuming a regular and even feed across the full width of their faces, the actual output would be from 25 to 30 per cent. of the theoretical.

For rolls with smooth faces the theoretical capacity may be calculated by using the following formula :—

$$\text{Cubic feet per minute} = \frac{T \times W \times S}{1728}$$

where T is the distance in inches at which rolls are set apart, W the width of roll face in inches, and S the peripheral speed in inches per minute.

The setting should usually be finer than the maximum size of material required, as the rolls in most cases are only capable of controlling one dimension, and the product will nearly always contain a proportion of pieces having two dimensions greater than that determined by the width of the space at the sizing point. This condition does not hold when a friable material is being treated under a process of choke crushing, as in this case the particles are fractured by packing one on the other.

Rolls with smooth surfaces, particularly when operated at high

peripheral velocities, are not capable of gripping pieces of large size, and the question of feed size and circumferential speed should therefore be considered together. It is usual, with smooth rolls, to calculate the maximum size of the feed from the coefficient of friction between the roll surface and the material being crushed. The friction angle will vary with the condition of the roll surfaces and the nature of the material, but on hard stone or ore the average will lie between 16 and 18°. For very tough ores and for substances such as serpentine and some of the asbestos rocks 11 or 12° is nearer the mark.

The following table gives the maximum amount which may be added to the setting or space between plain rolls when determining the maximum feed size for materials having three different friction angles :—

Diameter of Rolls (ins.).	Amount to be Added (ins.) for friction angle of		
	11½°.	16°.	18°.
20	0·40	0·77	0·97
24	0·48	0·93	1·17
30	0·60	1·16	1·46
36	0·72	1·39	1·76
42	0·84	1·62	2·05
48	0·96	1·85	2·35
54	1·08	2·09	2·64
60	1·20	2·32	2·93
72	1·44	2·79	3·52

Since the roll shells reduce by wear, due allowance should be made for the change in diameter which may ultimately occur, if the rolls are to operate successfully during the full life of the shells.

Rolls with toothed or longitudinally corrugated surfaces will grip much larger pieces than those with smooth peripheries, and the advantage to be gained by such means depends in large measure on the shape and projection of the chequered or toothed surfaces. When the teeth are carried to extremes it is obvious that the rolls may operate outside the scope of the angle of nip and the " ribbon theory."

Circumferential speed has considerable influence on the gripping power of smooth rolls as is evidenced by the fact that, when the power is disconnected and the rolls slow down to the stopping point, many oversize pieces that have been dancing about at the normal operating speed are seized and crushed and so bring the rolls to a standstill. Rolls of large diameter will crush satisfactorily at higher peripheral speeds than can be used for the smaller sizes, and this would appear to be due to two causes. In the first place, with the larger rolls the nipping point is usually well below the critical zone and the reduction

of the angle of nip ensures a positive grip which may be accomplished more rapidly. Secondly, for an equal extent of reduction the larger rolls have greater arcs of contact on the ribbon and, at equal circumferential speeds, the crushing operation extends over a longer period, which allows the material more time to spread to compensate for the reduction in thickness of the ribbon.

The composite diagram, Fig. 290, has been prepared to illustrate the foregoing remarks. Four sizes of rolls are shown in which the diameters vary in direct proportion, and the heavily shaded areas represent the contact zone in each case when taking a feed of equal size. In the smallest rolls the feed size corresponds to the maximum acceptable at this diameter, and the lighter shaded areas in the other diagrams indicate the reserve spaces within the limiting angle of nip. Calculations show that the contact surfaces increase in proportion to

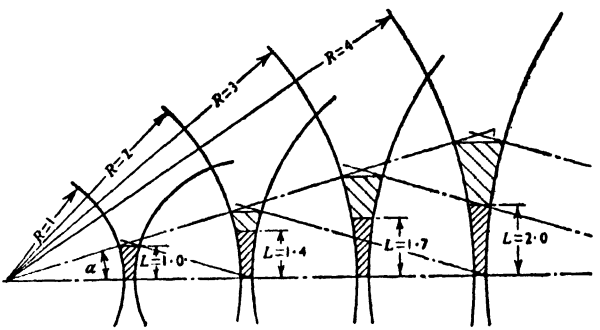


FIG. 290.—Composite roll diagram.

the square root of the diameter ratio, or, in other words, the rolls must be increased in diameter by four times to double the arc of contact. These figures prove that the time factor is of considerable importance, including both the time occupied in taking hold of the material, and the time spent in making the necessary reduction to enable the large feed to pass through a small aperture.

Authorities differ considerably on the question of the best speed for rolls; deeply toothed or corrugated rolls must naturally run slowly. But the trend of modern practice in the use of smooth rolls for ore dressing is to increase the speed to the highest possible limit, which means that the rolls must be designed with massive framework, shafts of large diameter, and extra powerful springs.

For rolls of heavy construction and moderate diameter, varying from 36 ins. to 54 ins., and fitted with shells having medium corrugations or shallow indented teeth, the peripheral speed should not exceed 600–800 ft. per min. when crushing hard rock. Smooth rolls, working well within the angle of nip, may run as fast as 1,200–1,500 ft.

per min. in exceptional cases, but on tough ore 800–1,000 ft. per min. is likely to give the best results except on rolls of very large diameter.

The nature of the material to be crushed must be taken very carefully into account when deciding the peripheral speed of rolls. A friable granular substance with sharp edges and rough surfaces is much more easy to grip and may be crushed at a higher speed with a greater angle of nip than rounded pebbles of a smooth and tough character, or any resistant material.

Circumstances may arise in which the feed consists of a mixture of particles having sharp angular faces with a few rounded pebbles. In such cases the rolls may crush the former with ease while the latter accumulate at the gripping point and impede the flow of material through the rolls. It will be found, however, that pebbles embedded in a stream of granular material are less liable to slip about than those which are free or surrounded by others of a similar character.

Except in the very largest rolls the reduction attempted in a single stage on any tough material should not exceed 4/1, or in other words the maximum size of the feed should not be greater than four times that of the larger pieces in the finished product. This rule does not hold good for friable materials which disintegrate under shock.

Power consumption will be governed by the nature of the material, the extent of reduction, and the output obtained in tons per hour. The modern high-speed belt-driven rolls absorb a very small amount of energy in overcoming frictional losses; there are no unbalanced parts to rotate and the kinetic energy from the masses of the rolls and belt pulleys helps to flatten out any irregularities. The power required is therefore directly proportionate to the amount of work done on the material. When making a reduction of 4/1 on tough rock the average power consumption may reach as much as $1\frac{1}{2}$ h.p. per ton per hour, whilst on soft stone the figure might be as low as $\frac{1}{2}$ h.p. per ton per hour.

As an illustration of the large size in which roll crushers are now made, Fig. 291 shows a set of high-speed rolls for breaking ironstone. The machine will take any size feed that can be handled by steam shovel and will reduce it to a product of 6–8 ins. The output is about 400 tons/hr. and the power requirements 200–300 h.p.

Intermediate Crushers may be classified into the following types: (*a*) stamps, (*b*) swing hammers or impact mills, (*c*) disintegrators.

Stamps are a mechanical form of the ancient mortar and pestle. There are two forms, namely the steam stamp and the gravity stamp. The latter form is in more general use and is widely used in preparing precious metal ores for amalgamation. The feed to stamps is between 1 and $1\frac{3}{4}$ ins., and the weight of the stamps is between 900 and 2000 lbs., and the height of drop 5–8 ins. with about 100 drops per min.

Swing Hammer Mills.—A typical swing hammer mill as made by

Edgar Allen is seen in Fig. 291. It is designed to give a granulated product for road-making purposes, and the action is clear from the illustration. The liners and hammers are of manganese steel, and normally no screens are required, as the adjustment of the breaking plate by the handwheel shown provides for variation in product size. Particulars of the output of such machines are given in the table below.

EDGAR ALLEN ROTARY GRANULATOR CAPACITIES. S.11. TYPE.

Tons per hr. (dry materials).

Material.	Size of Product 85 per cent. passing Square Mesh (ins.).	No. 1 Approx. Power 12–15 h.p. Mouth Opening 8 ins. × 13 ins.	No. 2 Approx. Power 25–30 h.p. Mouth Opening 12 ins. × 17½ ins.	No. 3 Approx. Power 40–60 h.p. Mouth Opening 16 ins. × 19½ ins.	No. 4 Approx. Power 100–120 h.p. Mouth Opening 20 ins. × 44 ins.
Limestone, slag, etc.	¾	6–10	15–20	35–45	60–70
Gravel	¾	5–8	12–15	25–35	50–55
Granite, whinstone, etc.	¾	4–7	10–12	20–25	30–50
Max. size of feed	—	2½ ins.	3½ ins.	4½ ins.	6½ ins.

The speed and the number of hammers depends on the material and the grading required.

Disintegrators.—These may be regarded as a light type of swing hammer mill and are used for fine grinding of friable materials such as

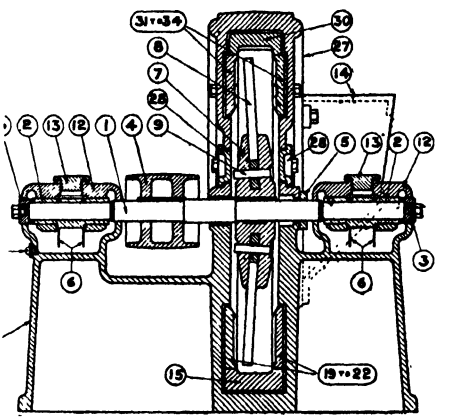


FIG. 292.

borax, dry chalk, cork, maize, resin, soya beans and the like. The lower part of the chamber of the machine is fitted with screens, the mesh of which is arranged in accordance with the fineness of grinding desired.

In the Christy & Norris Disintegrator the beaters are made of high-carbon steel, and the screens are of cast iron or of steel for heavy work such as the grinding of bones. The particulars of the range of machines made by this company are as follows :—

Size No.	Revs. per min.	Dia. of Pulley.	Width of Belt.	Dia. of Beater Chamber.		Approx. Brake Horse Power.
		ins.	ins.	ft.	ins.	
12 ins.	5000	3¼	3	1	0	4 to 8
17 ins.	4100	4	4	1	5	6 ,, 12
22 ins.	3300	5	4½	1	10	10 ,, 16
30 ins.	2500	7	6	2	6	16 ,, 25
3½	1800	9	8	3	3	25 ,, 40
4½	1300	15	10	4	6	40 ,, 70

A section of a Christy & Norris Disintegrator is seen in Fig. 292.

Fine Grinding Machines.

The classification of these machines is as follows :—(*a*) centrifugal

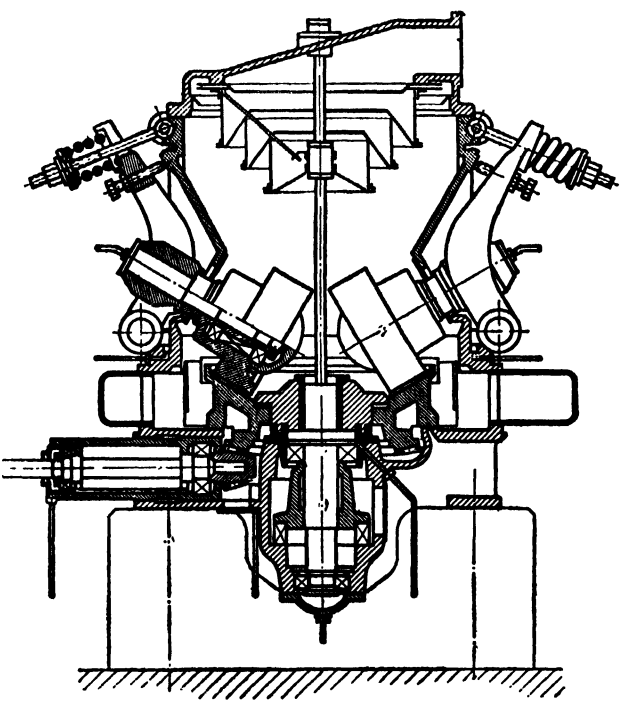


FIG. 294.

machines of the ring roller type ; (*b*) burrstones ; (*c*) roller mills, ball and tube mills.

Centrifugal-Ring-Roller Grinders.—The principle of nearly all such machines is the grinding action between revolving rollers and a revolving hand grinding ring.

A "Lopulco" ring roller mill is seen in Figs. 293–4. A small number of rollers rotating on stationary shafts are spring supported against a revolving grinding ring driven in a horizontal plane resulting in reduction of the raw material between the ring and rollers. The machine may be made with two, three or four rollers, depending upon the size. The grinding pressure is adjustable by means of the external springs shown.

The ring roller mills are always used in conjunction with some form of air separator device, often fitted with a supply of hot air for use with wet raw materials which may be dried during the grinding operation.

Ball and Tube Mills.

This is an important class of fine grinding machines. The distinction between the two types is largely one of ratio of length to diameter and purpose. Both consist essentially of a rotating horizontal cylinder containing balls of steel, iron, flint, etc., the feed to which is introduced into one end through a hollow trunnion, and the impact of the balls cascading over each other results in fine grinding. Ball mills are used for coarser grinding than tube mills, have larger ratio of diameter to length, contain larger grinding media, and often, as in the cement industry, are used to prepare material for final grinding in tube mills.

Practical Grinding in Ball and Tube Mills.

Grinding in ball and tube mills may be either wet or dry, depending upon the type of process. For wet grinding sufficient fluid must be introduced to produce a mixture of the consistency of thick cream. In dry grinding the material may contain a small percentage of moisture, but it must not be sufficient to cause the material to become sticky. An excess of free and in some cases chemically combined moisture has a cushioning effect which reduces the capacity of the mill. Bone dry materials grind with the highest efficiency.

Ball and tube mills for non-corrosive grinding are lined with white cast iron, manganese steel, or special alloy steel plates, and the grinding balls may be forged steel or alloy steel. The pebble mill is used for grinding where corrosion may be important, or where iron in the product is undesirable. The grinding media may be flint pebbles, and the lining of silex or other suitable ceramic non-corrosive material.

Grinding in ball and tube mills may be either in open or closed circuit, and both methods of grinding may be wet or dry.

Open circuit grinding is that method where the material is fed at one end of the mill, and is discharged at the other end in a finished state.

It is the most simple system and is generally employed for relatively coarse products, although it is also used where a reasonably fine product is desired at a sacrifice of power consumption and general overall efficiency, with the sole advantage of simplicity.

Closed circuit grinding is so termed when the product of the mill is sent to a sizing device and the oversize is returned to the mill for regrinding. When so operated, the mill has a greater capacity and the product contains little or no oversize, depending upon the adjustments made to the classifier. When grinding to a fineness in excess of 35 mesh, it is almost essential to use closed circuit grinding, if the mill is to be operated economically, since otherwise the cushioning effect of the fine particles greatly retards the rate of reduction of the larger particles.

A ball mill made by Edgar Allen of Sheffield is seen in Fig. 295. These mills are made for both wet and dry grinding, with and without sieves.

The periphery of the mill is formed of hard steel grinding-plates, stepped as shown ; the plates, being perforated, allow the material to leave the inner chamber of the mill as it is reduced to powder ; that portion passing from the inner chamber falls on to a second perforated plate or check sieve, which allows only the finer portion to enter the outer chamber, on which is fixed a final series of sieves, so arranged as to produce the necessary fineness. In each case the rejected portions are returned automatically to the inner chamber for further reduction ; consequently the process of grinding becomes continuous and automatic. The ground material is delivered from the bottom or hopper portion of the chamber into bags by operating a slide, or the bottom may be left open for the finished material to be carried away by a conveyor, or in tubs. Material up to 6 ins. cube can be fed to the largest mill. The usual size of feed is about 2 ins. cube.

Details of Construction.

The side plates, which are of rolled steel in the larger sizes, and of cast iron in the smaller sizes, are mounted on cast-iron centres keyed on to the main shaft. The feed hopper is of very substantial build, is bolted to the inner edge of the main sole plate, and remains steady in working under all conditions. In addition to the renewable steel grinding-plates, the sides of the mill are fitted with hard steel renewable plates, secured to the wrought steel plate sides by bolts. The outer dust-casing consists of two parts, and is constructed of steel plates in sections, with angle iron joints. There is also a large inspection-door extending the whole width of the casing, so that screens may be easily removed for renewal when necessary.

Dust-collecting.

The top of the dust-casing is fitted with an outer nozzle, from which

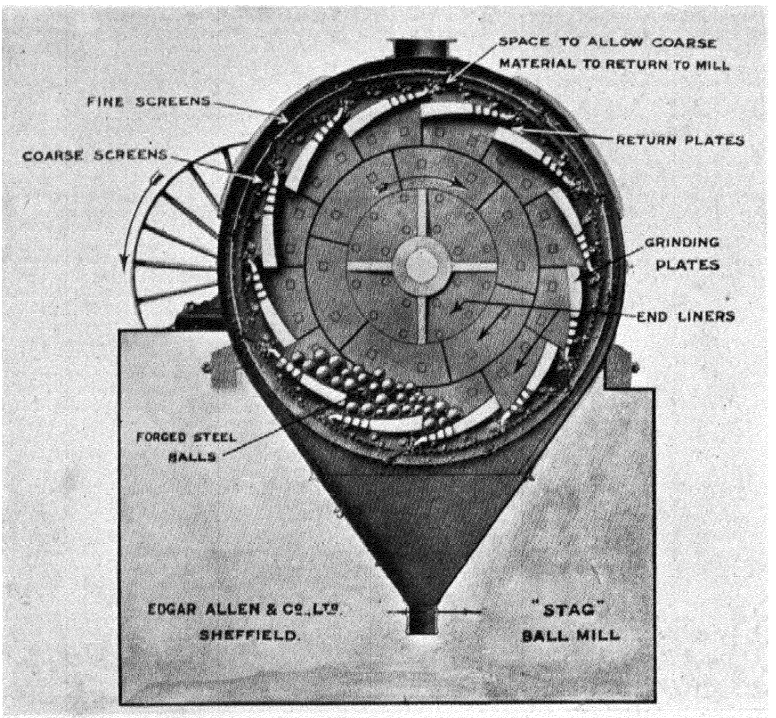


FIG. 295.—Ball mill by Edgar Allen & Co., Ltd.

[*See page* 528.

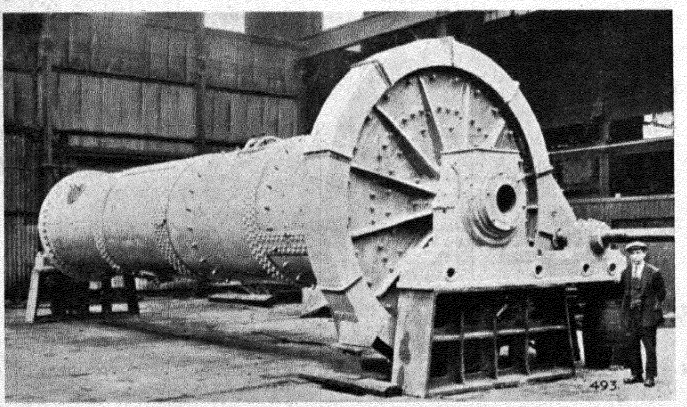


FIG. 296.—Combination tube mill by Edgar Allen & Co., Ltd.

[*To face page* **529.**

the dust (generated by the rotary action of the mill) may be arrested in a balloon, or carried away by a pipe.

Starting.

In many cases it is advisable to have fitted to the mill a friction-clutch instead of fast and loose pulleys, the clutch enabling the mill to be started with less shock to gearing. It also greatly facilitates starting where the reserve of power in engines is a little above that required to drive the mill when in motion.

TABLE OF PARTICULARS OF "STAG" BALL MILLS.

Sizes: . . . —	0	1	2	4	6	8	10
Diameter of drum (ins.)	26	42	54	72	90	108	122
Width of mill-drum (ins.)	15½	28½	36	42	54	55	55
Revolutions of mill-drum per min.	45	35	33	27	25	21	20
Approximate B.H.P. required	1	3	6	15	32	40	50–65
Revolutions of belt-pulley per min.	45	35	175	148	95	85	84
Width of belt-pulley (ins.)	3	5	5	8	9	10	13
Diameter of belt-pulley (ins.)	24	42	30	48	60	78	84
Approximate charge of steel balls, cwts.	¾	3	6	16	30 to 35	40 to 50	55 to 60
Maximum size of feed, ins. cubes	¾	1½	2	2½	3½	4½	6

Tube Mill Grinding.

Tube mill grinding may be divided into four classes :—

(1) For fine grinding either wet or dry material which has previously been roughly ground, or pulverised, in a preparatory mill, such as a ball mill.

(2) For the preliminary treatment of either wet or dry material which has been reduced to a size equal to about 2 ins. cube.

(3) For the preliminary and final treatment of either wet or dry material which has been reduced to a size equal to about 2 ins. cube.

(4) For the treatment of dry material, in conjunction with air-separation, the material having been reduced to a size equal to about 2 ins. cube.

Combination Tube Mill by Edgar Allen & Co., Ltd.

The Combination Tube Mill is divided into two or more sections by diaphragms of special design fixed in the interior of the mill. The first sections are charged with large steel balls and the second or finishing sections with smaller steel balls or other grinding media (Fig. 296).

This type of mill is eminently suitable for grinding cement clinker, raw materials, coal and various types of ore.

The following is a brief description of a tube mill of the above type made by Edgar Allen of Sheffield :—

The shell is built up in several sections, varying in number according to the size of the mill. Each section is formed of a heavy mild steel plate.

Longitudinal and circumferential mild steel butt straps of ample width and of a thickness slightly greater than the shell are utilised to form the joints. All joints are multiple riveted, rivets are all machine driven and countersunk inside so as to give a smooth interior for the lining. Manhole openings are provided in shell, elliptical in shape and are reinforced by heavy mild steel plates and riveted to shell.

A heavy cast steel angle ring, accurately bored to fit the shell, is attached to it at each end by double riveting.

The feed end is extended at the periphery to allow for attachment of the gear ring and is also arranged for the attachment of the end liners. The delivery end is suitably arranged for the fitting of the discharge diaphragm.

Shell Lining.

The preliminary compartments are lined with heavy chrome steel plates, the stepped type being supplied as standard. These plates are attached to the shell by means of lowmoor or grade " A " iron bolts of large diameter.

The finishing compartments are lined, as standard, with hard cast-iron bars fitted round the shell and held in place by a suitable number of key bars arranged at equal distances round the shell and secured thereto by suitable bolts.

Other types of liners can be supplied in addition to the standard types mentioned above, either to suit customers' own requirements or to provide for special conditions.

The feed end is lined with chrome steel liner plates arranged in a convenient number of segments which are bolted to the mill end.

The trunnions are provided with cast-iron liners suitably tapered for inlet to, or discharge from, the mill.

All bolts securing the liners to the shell are of lowmoor or grade " A " iron, are of ample proportions and are countersunk inside. Each bolt is fitted with two nuts and washer, also a special felt washer placed next to the shell, to make it dust- or watertight.

Diaphragms.

The mill is divided by means of diaphragms into several compartments, the actual number depending on the size and requirements

of the mill. The diaphragms are of the single or compound type according to requirements.

Each diaphragm consists of a number of cast-chrome steel grid plates having suitably dimensioned slots, and secured at the centre to a mild steel plate. At the periphery the grid plates are provided with a suitable flange by means of which the diaphragm is secured to the mill shell by lowmoor or grade " A " iron bolts of large diameter, countersunk inside.

Discharge Diaphragm.

This diaphragm is formed by a number of cast-chrome steel grid plates, each provided with properly spaced slots. Ribs are cast on the back of the grid plates which act as lifters, to transfer the ground material from the periphery of the mill to the centre, for discharge through the trunnion. The complete diaphragm, which also acts as the discharge end lining, is attached to the mill end by suitable bolts countersunk inside.

A cast-iron centre-piece is provided on the discharge diaphragm for extending it into the trunnion liner.

Dry Feeder.

A table feeder is supplied as standard. This consists of a cast-iron horizontal, revolving table, surrounded by a cast-iron tray. Material is fed on to the table from a hopper above, through an adjustable sleeve, and is removed from the table by means of an adjustable plough, these adjustments providing a means of regulation of the feed. The feeder is driven by belt from the mill countershaft, through one set of bevel gears. A cast-iron feed pipe is fitted between the feeder and the mill trunnion.

This type of feeder gives a simple and efficient means of providing an adjustable and regular feed to the mill.

Twin feed tables can be supplied where it is necessary to feed two dissimilar materials to the mill. In this case the drives to the tables can be coupled so that, within limits, the tables can be made to deliver correct relative proportions of each material to the mill.

The Hardinge Ball Tube Mill.

The Hardinge Mill operates on the principle of a number of grinding bodies rotated in a conical drum, mounted on hollow trunnions through which the material passes to and from the grinding zone. The grinding elements, in dropping, grind the material passing through the mill, first by impact and then by attrition.

The conical shape of the mill causes a natural automatic segregation both of the grinding media and of the material being ground. The parabolic circulating effect keeps the mass active and promotes a

quick discharge of the fines and a violent agitation of the grinding media.

The classification of material, as well as of the balls or pebbles, is illustrated in Fig. 297, which shows that in the largest diameter of the mill the incoming feed is crushed by the largest balls or pebbles with the greatest superincumbent weight, with the greatest height of fall and with the highest peripheral speed. As the material travels towards the discharge, the crushing force is gradually diminished, because the grinding media are smaller and drop from a lesser height, thus reducing power consumption. The reduction by attrition, however, is increased on account of the greater surface exposed.

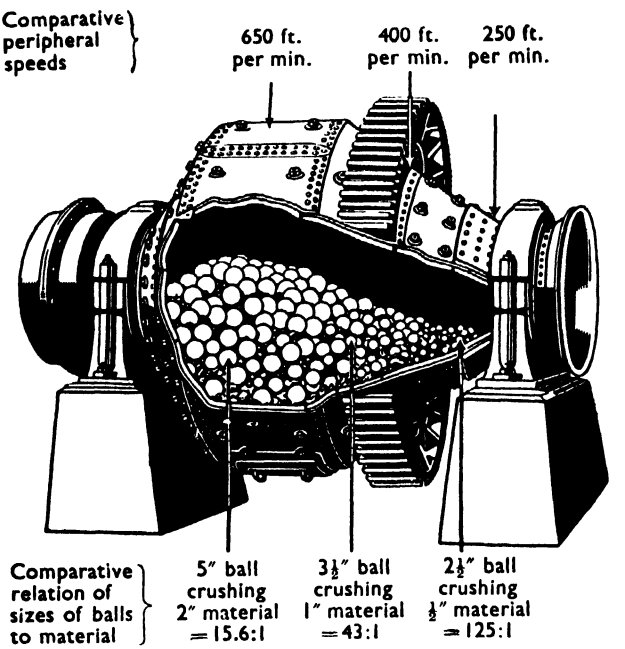


FIG. 297.—Hardinge ball-tube mill.

Dry Grinding in Tube Mill in Closed Circuit with Air Classification.

The principle of dry fine grinding in closed circuit is well illustrated in Fig. 298, which shows a Hardinge mill with attached Raymond air classifier.

The Raymond air classifier fitted to this plant operates on the principle of reversed air currents, which gives control of the fineness under all conditions. The air is injected into the mill at the discharge end. The current reverses itself at the feed end of the grinding zone of the mill and is drawn back to the discharge end, carrying the product with it.

The oversize drops out in the rotary classifier outside the mill and is picked up by the incoming current of air and blown back to the grinding zone.

A product of any commercial degree of fineness can be secured by the use of this classifier. Material does not pass through the fan, so that the wear is reduced on the blades and casing and operation is simplified by eliminating the necessity for shutting down the mill to renew fan parts. Materials having greater than normal moisture content can be ground successfully in this system, as the moisture liberated is discharged as a vapour through a vent-pipe. Pre-heated air can be supplied as a drying medium if desired.

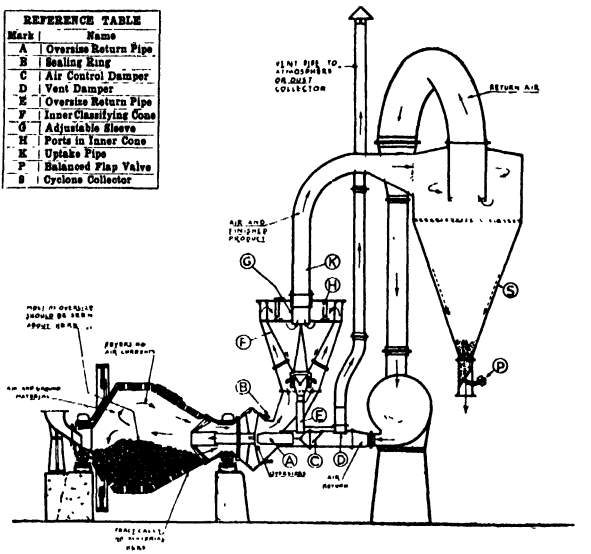


FIG. 298.—Hardinge ball-tube mill in closed circuit with air classifier.

Operation of Raymond Air Classifier.

This classifier is capable of delivering a product as fine as 99·9 per cent. through 325 mesh under normal conditions.

The fan blows the air into the mill through the central pipe. The air is withdrawn round the pipe and the oversize is dropped into the rotary classifier revolving with the mill. The oversize is lifted by buckets and dropped into an opening in the return pipe and blown into the mill. The product is classified again in the Raymond classifier, passing between the two cones within the classifier.

At the top, canes in the inner cone deflect the air in such a way that the fine oversize is thrown to the outside of the inner cone, where it drops through the flap valve into the return pipe and is returned to the mill for regrinding.

A vent pipe is fitted on the pressure side of the fan to discharge moisture or any air which has leaked into the system on the vacuum side.

Power requirements of Hardinge mills are as follows :—

HARDINGE MILL IN CLOSED CIRCUIT WITH AIR CLASSIFICATION GRINDING VARIOUS MATERIALS.

	Bituminous Coal.	Anthracite Coal.
Mill	10 ft. × 66 ins.	10 ft. × 66 ins.
Feed	1¼ ins.	4 mesh
Product	70 per cent. minus 200 mesh	82 per cent. minus 200 mesh
Capacity per hr.	24½ tons	11 tons
Power for mill	370 h.p.	370 h.p.
Power for auxiliary equipment	95 h.p.	70 h.p.
Ball load	57,000 lbs.	57,000 lbs.
Ball consumption per hr.	0·1 lbs.	0·3 lbs.
Liner consumption	10 to 15 yrs.	8 to 10 yrs.
Speed of mill	19 r.p.m.	19 r.p.m.

LIMESTONE.

Mill.	Feed.	Product.	Cap. per Hour.	Mill Power.	Aux. Power.	Moisture.
10 ft. × 66 ins.	½ in.	88 per cent. minus 200 mesh	22½ tons	390 h.p.	120 h.p.	1 per cent.

CEMENT.

	Fineness 82 per cent. through 200 mesh.	Fineness 88 per cent. through 200 mesh.	Fineness 94 per cent. through 200 mesh.
Mill	10 ft. × 66 ins.	10 ft. × 66 ins.	10 ft. × 72 ins.
Feed	½-in. clinker (crushed)	½-in. clinker (crushed)	¼-in. clinker (crushed)
Capacity per hr.	17 long tons	14·5 long tons	13·25 long tons
Power for mill	414 h.p.	404 h.p.	425 h.p.
Power for fan	95 h.p.	95 h.p.	130 h.p.
Ball load	60,000 lbs.	60,000 lbs.	66,000 lbs.
Speed of mill	18 r.p.m.	18 r.p.m.	17·8 r.p.m.
H.p. hrs. per ton	29·7	33·9	41·4

Description of Andrews' Classifier in Closed Circuit with a Hardinge Mill.

An Andrews' classifier in closed circuit with a Hardinge mill is shown in Fig. 299. In Fig. 300 the latest type of Andrews' classifier in closed circuit with a Hardinge mill is shown diagrammatically.

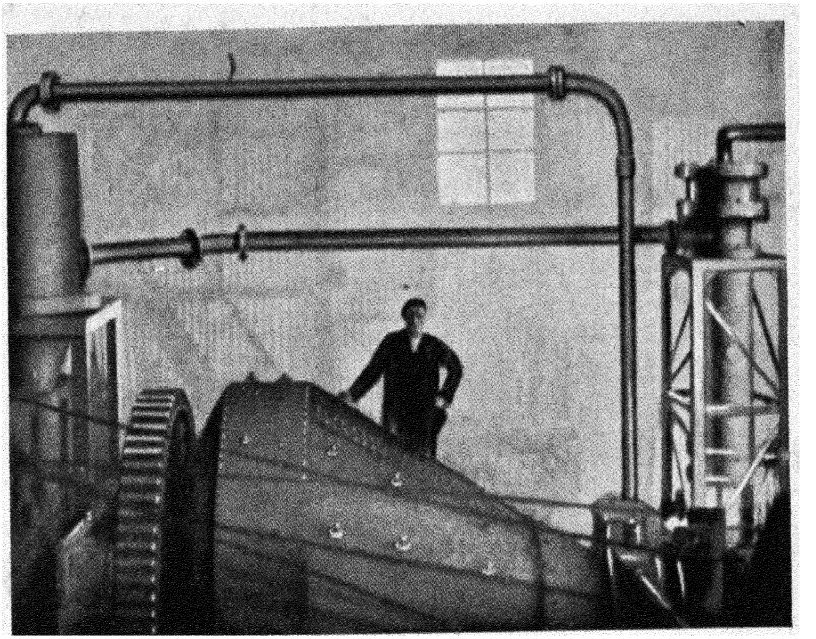


FIG. 299.—Andrews' classifier in closed circuit with a Hardinge mill grinding copper ore.

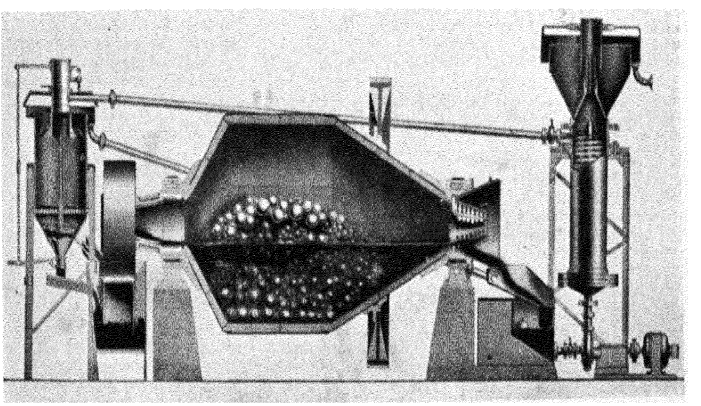


FIG. 300.—Hardinge tube mill with Andrews' classifier.

[*To face page* 534.

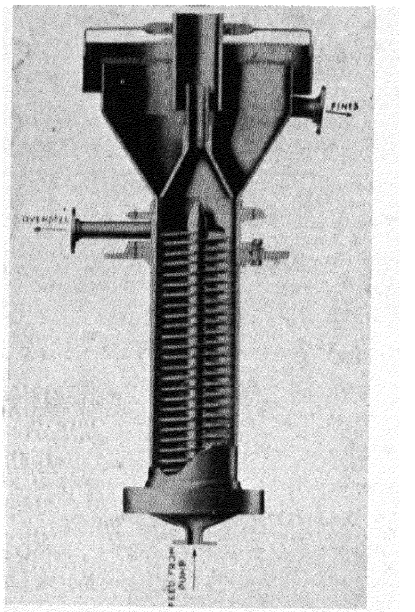


FIG. 301.—Andrews' classifier.

[*To face page* 535.

The mill discharge, diluted and thoroughly intermixed with the circulating water returned from the oversize tank, and with make-up water, is pumped through the spiral vortex classifier, a section of which is shown in Fig. 301.

Under the combined influences of centrifugal force, gravity and eddy currents, the oversize particles collect in the inside lower corner of the channel and are discharged through the tangential outlet at the top of the spiral. The velocity in the spiral, which is about 6 or 7 ft. per sec., is well above turbulent velocity and is sufficiently high to prevent any particles settling out.

For many purposes, where classification is required at 60 or 80 mesh, this preliminary grading is sufficient.

Fine Classification.

In cases, however, where a finer product is required, a conical discharge head is attached directly to the top of the spiral vortex (see Fig. 301). The fine and intermediate particles at first rise through both the inner and outer annular channels. The decreased velocity, due to the increased area above the outer channel, causes the intermediate particles, which are too large to be carried by the final overflow velocity, to accumulate above this outer passage. The resistance due

HARDINGE MILL IN ENCLOSED CIRCUIT WET GRINDING WITH HYDRAULIC CLASSIFIER.

IRON OXIDE.

Mill.	Feed.	Product.	Cap. per 24 hrs.	Power (h.p.).	Ball Load.	Speed Mill.	Moisture by Weight.
4 ft. 6 ins. × 16 ins.	50 mesh	99·99 per cent. through 200	24 tons	20	4000 lbs.	30 r.p.m.	33 per cent.

METAL RECLAMATION.

Mill.	Feed.	Product.	Capacity per hr.	H.p.
4·6 ins. × 16 ins.	1½ ins.	Minus 20 mesh	2½ tons	20

POTTERY SLIP.

Mill.	Feed.	Product.	Capacity per hr.	H.p.
6 ft. × 48 ins.	Minus ¼ in.	99·9 per cent. through 200 mesh	470 lbs.	14–15

to the increased density thus caused in the outer channel forces the whole stream to rise through the inner passage. This passage terminates in a circular central tube, carried above the overflow level, which permits air bubbles to escape without disturbing the overflow. This circular central tube also has the effect of projecting all the particles downwards in the opposite direction to the overflow. Thus the large and intermediate particles are flung down with considerable velocity on to the top of the outer annular passage, leaving the fine particles free to rise upwards without having to pass through a dense eddying mass of material.

As there is now no rising velocity through the outer annular channel, these intermediate and oversize particles are discharged downwards on to the top of the main oversize stream. An adjustable serrated band around the top of the head ensures uniform overflow at all points.

The table on page 535 gives approximate data of the capacity and power requirements of Hardinge mill with hydraulic classifier.

Mechanical screens are frequently used in connection with grinding plant. Interesting designs are seen in Figs. 302 and 303.

The Edgar Allen Imperial Vibrating Screens (Fig. 302) work on the principle of a patented eccentric motion, incorporating two main duplex bearings each fitted with two roller races in the same housing, the inner races being arranged eccentrically and transmitting a " throw " to the body of the machine, thus giving a positive vibrating motion to the screens.

The mechanism is completely housed, free from dust, and dampproof, and incorporates a drive shaft passing right through the machine and thus keeping the main bearings in line. This drive shaft is protected by a substantial hollow shaft connecting the sides of the screen body and extended at each end into the main bearings.

The bearings are carried in heavy brackets in which are housed the two roller races as separate units rotating one inside the other, and in the same plane of rotation, the outer race being concentric with the bearing brackets and the inner race eccentric to it and to the drive shaft.

The screen is driven by flywheel pulleys with suitable adjustment for balancing. One pulley is grooved for a V-rope drive, the other having a plain face so that it can be used as a belt pulley if required. The bearing brackets are attached to the supporting frame of the screen, the body of the screen being supported from the frame by suitable springs and in such a way that the weight of the body is taken by the springs, thus relieving the bearings of this weight.

The frame carrying the screen can be supported in several ways as best suited for each particular problem ; it can either be slung from above by means of cables and springs, or hinged at one end and slung by cable at the other, or carried on brackets at both ends.

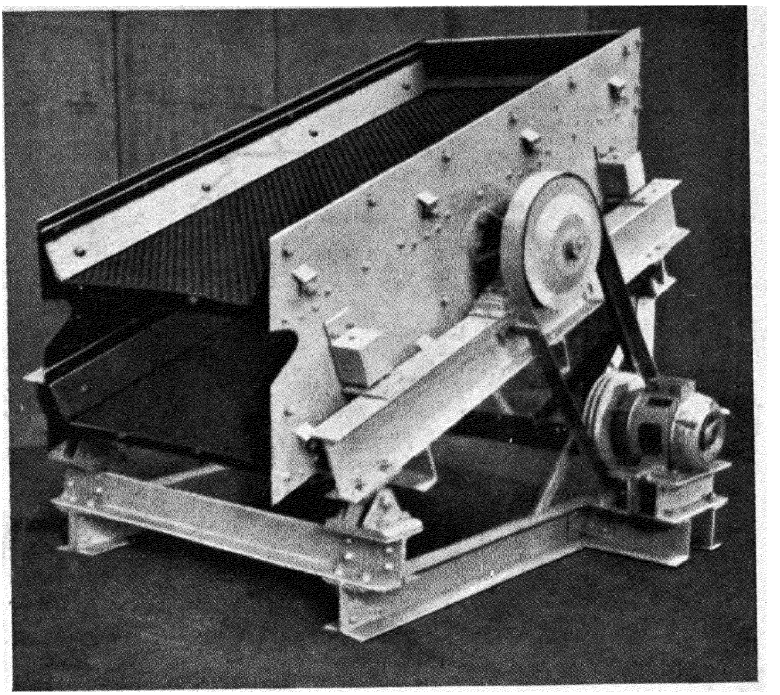


FIG. 302.—" Imperial " vibrating screen by Edgar Allen & Co., Ltd.

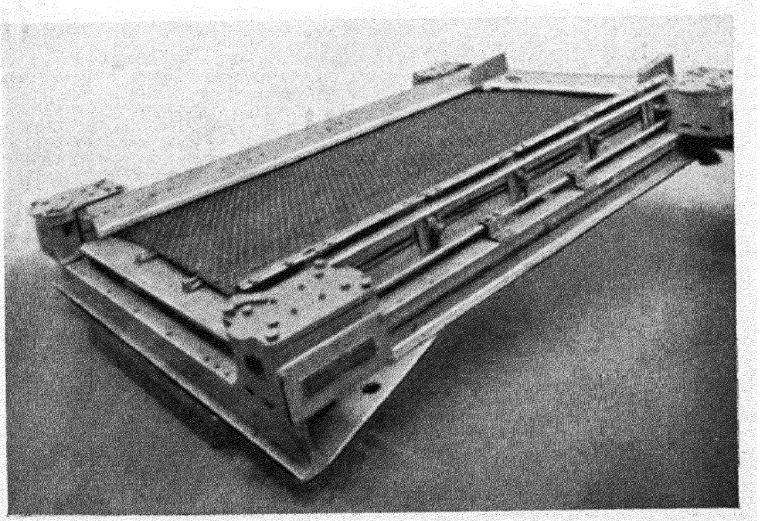


FIG. 303.—Hum-mer " patent vibrating screen, type 400.

[*To face page* 536.

The screen meshes are held in frames and are secured to the screen body through suitable clamp bolts and plates which give to the screen mesh the desired tension.

The Type 400 Hum-mer Screen (Fig. 303) represents a recent development in screening by electric vibration.

There are four electric vibrators, one at each corner. The two vibrators at the feed end are yoked together by a cross armature beam, as also are the vibrators at the discharge end.

These armature beams are intensely vibrated and transmit the vibration to the screen cloth stretching and supporting structure, which provides a rigid, taut screening surface. This method of power distribution provides active vibration over the entire screen area.

The rubber-covered supporting bars will carry any load and the hook bolts keep the screen surface in constant tension. The wire cloth is not subject to a racking or bending motion but is kept smooth and taut. If wear is unusually heavy on upper end of screen, due to abrasive nature of material, the cloth can be supplied in two sections.

The Type 400 Vibrator provides 1800 short, powerful strokes per minute combined with a sharp impact. This vibration allows the material to hug the screen cloth, each particle twisting and turning, the fines working down to the screen cloth and through the openings. Each vibration is terminated with a sharp impact which prevents " blinding " of the screen openings.

The Type 400 Hum-mer can be furnished with an enclosed body if desired.

CHAPTER XVI

CHEMICAL WORKS PUMPING

THE transfer of fluids from one point to another in chemical process work necessitates special considerations chiefly because of the corrosive nature of many of the liquors handled.

Centrifugal pumps are often used, but made in special materials such as ebonite, stoneware, silicon iron, stainless steel, etc. Special arrangements are often made in regard to stuffing boxes. For example, the "Lennox" pump in silicon iron, which is used principally for handling sulphuric acid, is fitted with a special stuffing box which has a sealed chamber behind it connected by holes through the impeller to the suction side of the pump. This arrangement keeps the box under slight suction and so prevents leakage. The spindle of such pumps can be supplied in stainless steel, and the pumps are manufactured to handle up to 60,000 galls. per hour, and heads up to 150 ft.

Many designs of what are known as "unchokable" centrifugal pumps are very useful for handling slurries and suspensions. Such pumps differ from the ordinary centrifugal pump only in the design of the impeller and casing, in that such parts are so constructed that there is ample clearance to prevent choking. The mechanical efficiency of such pumps is naturally low, but this aspect is often relatively unimportant.

Multi-stage centrifugal pumps are often used for the high pressures required in filtration through filter presses. For example, Messrs. Haughton Metallic Packing Co. manufactured a range of two-stage pumps with contact parts in regulus metal and stainless steel spindles suitable for feeding towers of the Glover and Gay Lussac type. The design provides for one gland on the suction side, subject only to atmospheric pressure. A 2-in. pump of this type gives heads up to 100 ft. at 1440 r.p.m., and under these conditions will handle 60 galls. per min. A three-stage pump by the same maker gives heads up to 150 ft., and four-stage to 200 ft. Vertical centrifugal pumps for chemical work are often employed, the reason for such construction being considerations of space and ease of erection over tanks and the like.

Messrs. Kestner make an interesting glandless centrifugal pump for handling strong sulphuric acid, which, if strong, possesses good

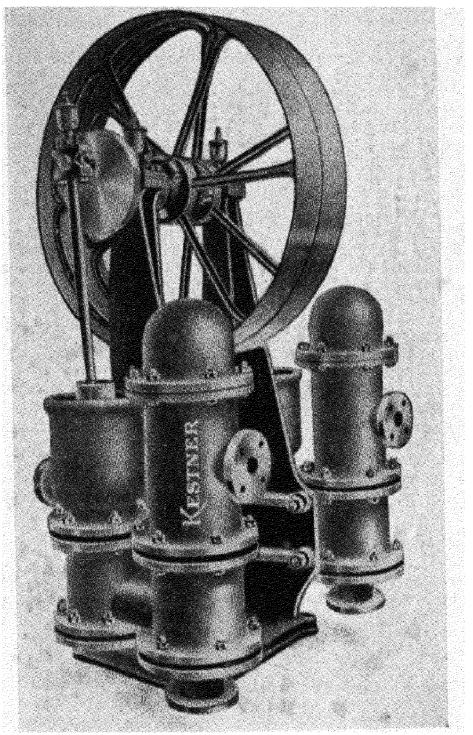


FIG. 304.—Kestner patent plunger type pump.

[*To face page* 538.

lubricating properties. The impeller shaft is fitted with a silicon iron sleeve, revolving in a silicon iron liner in the pump casing. The clearance between shaft and sleeve is adjusted to give an intentional flow of acid through it, thus ensuring lubrication by the strong acid. The overflow is taken to a catch pot and returns by a drain pipe to the supply tank. The pump may be made in various metals such as regulus, cast iron, etc. Reavell (*Proc. Chemical Engineering Group Soc. Chem. Ind.*, 1936, **18**, 25) states that the wear on the sleeve of

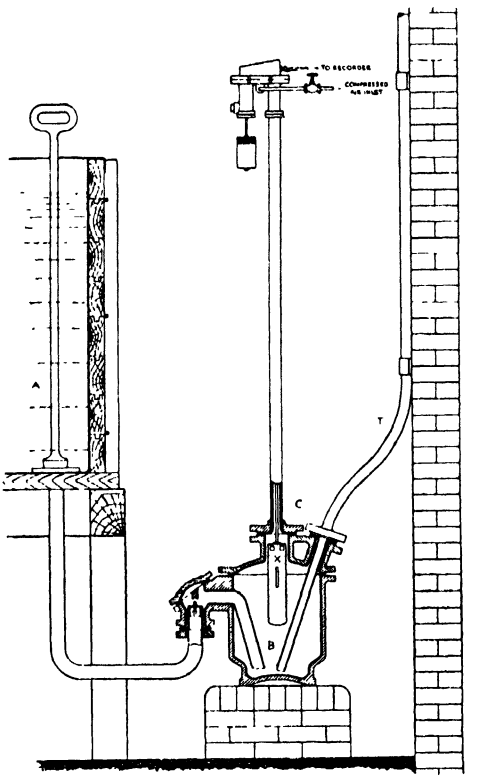


FIG. 305.—Diagram of Kestner acid elevator.

such glandless pumps is very slight, and that many pumps run for years without appreciable wear.

Vertical glandless centrifugal pumps are also used and have some advantages in construction over the horizontal type. For example, a vertical pump can be suspended in a tank within the liquor to be pumped, so that the necessity for a stuffing box is entirely avoided. The Lee Howl patent pump is of this type.

Plunger pumps are also much used in chemical works, and again design is influenced by the necessity to combat corrosive conditions. A glandless vertical plunger pump by Kestner, Ltd., is again based on

the lubricating qualities of strong sulphuric acid. The plunger is made in silicon iron and works in a silicon iron barrel. As before the clearance between the two is carefully adjusted to give a predetermined seep of acid which is collected and returned to the supply tank. Such pumps are made in various capacities up to 2600 galls. per hour, and the mechanical efficiency is given as 80 per cent. The limit of strength of acid below which the pump is not normally used depends on the temperature and the exact nature of the acid, but usually these pumps are not used for acid below 1·4 sp. gr. Fig. 304 shows such a plunger pump by the Kestner Evaporator & Engineering Co., Ltd.

Compressed-Air Displacement Pumps such as the acid egg are often used for handling corrosive liquors. One type in stoneware has already been described (see Fig. 50). An automatic acid egg by Kestner is seen in Fig. 305. The body is fitted with a non-return valve for the inlet of acid, and an internal dip pipe connecting to the discharge branch, the cover carrying a standpipe to the top of which is fitted the operating head. A float follows the up-and-down movement of the acid in the body, and this motion is transmitted by the float rod to the elevator head which incorporates an inlet valve for the compressed air and an outlet valve for the exhaust air. These two valves are automatically actuated by the float gear in such a way that the elevator alternately fills by gravity from the feed tank and discharges acid up the delivery pipe.

Such acid elevators are available in a wide range of materials such as cast iron, regulus metal, rubber lined and lead lined.

The steam or compressed air ejector is often used for small lifts and where contamination is unimportant. For example, a 2-in. ejector can deal with 2000 galls. per hour against a head of 50 ft. when supplied with steam at 65 lbs. per sq. in. The steam consumption is about 500 lbs. per hour. (Reavell, loc. cit.)

APPENDIX

THE DESIGN AND OPERATION OF CHEMICAL PLANT FROM THE SAFETY ASPECT

THE operations carried out in the chemical industry are in general much more hazardous than the majority of other industries, and because of this peculiarity, most countries have passed legislation to safeguard the health of the workers in chemical processes.

In so far as Great Britain is concerned the following legislation affects the work of the chemical engineer :—

1. The Factories Act, 1937.
2. The Explosives Act of 1875.
3. The Boiler Explosions Acts of 1882–1890.
4. Lead Paint (Protection against Poisoning) Act, 1926.
5. Petroleum Consolidation Act.
6. S.R.O. 1922, No. 731. Chemical Works Regulations.
7. S.R.O. 1908, No. 1312. Regulations for generation, transformation, distribution and use of electrical energy.
8. S.R.O. 1907, No. 17. Regulations for the manufacture of paint and colours.
9. S.R.O. 1911, No. 752. Regulations for the smelting of materials containing lead, the manufacture of red or orange lead and the manufacture of flaked litharge.
10. S.R.O. 1921, No. 1443. Regulations for the manufacture of certain lead compounds.
11. S.R.O. 1908, No. 1258. Regulations for vitreous enamelling of metal or glass-compounds.

The legal requirements in respect of chemical process work in Great Britain have been recently admirably summarized and discussed by Pratt and Marlow (*Proc. Inst. Chem. Eng.*, 1934, **12**, 21). This paper has since been published in booklet form by The Institution of Chemical Engineers, and a copy should be in the hands of every chemical engineer engaged in process work in this country.

The point of view of Imperial Chemical Industries, Ltd., in regard to safety, has recently been fully described by Hiscock, " Works Hygiene and Accident Prevention " (*Jour. Soc. Chem. Ind.*, 1936, **14**, 222), in which he states :—" The policy of I.C.I. is based funda-

mentally on the principle that the people in charge of manufacturing operations are just as responsible for carrying through these operations without accident or ailment as they are for carrying them out with good yield, on time schedule, and at an economic cost. *Safe working* is placed *higher* in connection with the carrying out of an operation than any other consideration. Yields and output are sometimes sacrificed at the altar of safe and hygienic working. Manufacture has been shut down completely when the possibility of danger has been found."

Other interesting points from Dr. Hiscock's article are as follows :—

(*a*) *Handling of Chemicals.*—Plant and process layout should be designed to cut down handling of chemicals to the minimum possible. Corrosive liquors and solvents should be stored in closed and vented vessels and conveyed in closed pipe lines. Acid handling, if not properly organized, is always liable to cause minor accidents, and bucketing is to be avoided.

(*b*) *Plant Design.*—Systematic inspection of processes and plant by full-time inspectors often reveals weaknesses in safety precautions. Atmosphere in places where any nitrobenzene is used as solvent must be well ventilated, even to the extent of working practically in the open-air. A meeting of a committee on design is always called if major alterations are desired, with the aspect of the safety of the worker as the first thought.

(*c*) *Protective Clothing and Appliances.* — A complete change of clothing, including underwear, is provided for certain processes, overalls for others, and rubber boots for most process workers. Goggles are scheduled for many operations such as those involving the use of acid and caustic reagents. *Gloves* (cotton stockinet) are provided for handling phthalic anhydride, but rubber gloves alone are not permitted since they induce sweating and often contain chemicals of doubtful action on the skin. *Gas Masks* and *Respirators* are always available and all staff fully conversant with their use.

(*d*) *Cleanliness.*—Housekeeping—baths—lavatories and the like. Special care must be taken in chemical works in regard to sanitary arrangements.

(*e*) *Propaganda and Instructions.*—Every opportunity is taken of impressing workers with the necessity for their co-operation in regard to safety measures, and all staff fully and regularly instructed in accident preventive methods.

The Association of British Chemical Manufacturers has drawn up two publications dealing with safety which are—Part I, "Model Rules—Safety Rules for use in Chemical Works," and Part II, "Detailed Instructions—Safety Rules for use in Chemical Works." Both booklets are worthy of the closest perusal since they represent

a standard of safety drawn up as the result of the many years' experience of the constituent members of the Association.

In addition, the Home Office have published a large number of leaflets dealing with accident prevention, with special reference to the guarding of dangerous parts of machinery. Particulars of these publications can be obtained from H.M. Stationery Office.

Often the size of a chemical plant will justify the appointment of a "safety officer," not necessarily a whole-time appointment, but a member of the senior operating staff. His functions would not interfere with the normal routine management, but his duties would be to inspect regularly all safety arrangements, including fire precautions.

Records should be kept of all accidents, and the occurrence of fires, so that remedial measures may be arranged on the result of periodical analysis thereof.

INDEX OF AUTHORS

ACCLES & Pollock, 266, 272.
Aiton, J. A., 243, 247, 254.
Aiton & Co. Ltd., 247.
Allen, Edgar, & Co. Ltd., 525, 528, 530, 536.
Allen, W. H., & Co. Ltd., 304.
Alliott, E. A., 419, 481, 508.
Aluminium Co. of America, 430.
American Brass Company, 25, 26, 30, 32.
American Enka Corporation, 152.
American Hard Rubber Co., 161, 413.
American Petroleum Institute, 223.
Amer. Soc. of Mech. Eng., 91, 189, 190, 193, 209, 210, 211, 217, 219, 220, 221, 222, 223, 231, 242.
American Soc. for Testing Materials, 101, 117.
Andrews, 124.
Atkinson, 70.
Attwooll, 169.

BABCOCK & Wilcox Ltd., 205, 210, 265.
Bach, 231, 233.
Backus, 471.
Badger, W. L., 331, 347, 358, 400, 440, 520.
Bailey, 120.
Baker, 459.
Bansall, 264.
Barbet, 469.
Barrs C. E., 62.
Bartlett & Snow Co. Ltd., C.O., 410, 411, 412.
Baumann, 118.
Bayard, 270, 330.
Bell, 516.
Belliss & Morcom, 298, 323, 327.
Bewsher, 461, 466.
Blair Campbell & McLean, Ltd., 393, 396, 398.
Blairs Ltd., Glasgow, 20.
Blaw Knox, 210, 211.
Board of Trade, 91, 178, 192, 193, 195, 199, 231, 238, 243, 244.
Boelter, 335, 336, 345, 346, 369.
Boltzmann, 287.
Borg-Warner Corporation, 114.
Bradley, 136.
Brauer, 72.
British Carbo Union, 427.
British Cast Iron Research Assoc., 82.
British Chemical Manufacturers, Assoc. of, 542.
British Electrical and Allied Research Assoc., 119.
British Non-Ferrous Metals Research Assoc., 82.
British Standards Institution, 4, 5, 62, 91, 169, 195, 246.
Broadbent & Sons, T., 509.
Brown-Firth Research Laboratories, 126.
Buffalo Foundry and Machine Co. Ltd., 421.
Buist, 264.
Burch, 476, 478.
Burton, H. H., 122.

CALIFORNIAN Redwood Assoc., 174.
Carey Co., The Philip, 285.
Caro, 72.
Cenco Hyvac, 479.
Chance, Bros., Ltd., 284.
Chapman & Hall, Ltd., 349.
Chase Brass and Copper Co., 25, 26, 30, 32, 40.
Chemical and Insulating Co., Ltd., 285.
Chemical Engineers, The, Institution, 541.
Chemical Research Laboratory, 181, 479.
Chemical Works Regulations, 179, 541.
Christy & Norris Ltd., 526.
Clark, 471.
Claude, 121.
Clenshaw, 120.
Coates, W. M., 184.
Cochran & Co., Ltd., 334.
Colbeck, 141, 146.
Combined Metals Reduction Company. 502.

Commentry-Fourchambault et Decazeville, 121.
Cook, 183, 184.
Copper Development Assoc., 1.
Corning, Glass Works, 155.
Cournot, 136.
Cox, J. L., 120, 125, 141.
Cronite Foundry Co., Ltd., 46.
Cullen, Dr. W., 71.

DAVIS, 279.
Davy, C. H., 205.
Davy, H., 71.
Debray, 70.
Deutsches Kupfer Institut, 1.
Deville, 70.
Dickenson, 120, 122.
Dittus, 335, 336, 345, 346, 369.
Donald, M. B., 161, 165.
Dorey, S. F., 212.
Dow Chemical Co., 400.
Dufton, 279.
Dühring, 459, 460, 461.
Dulong, 277.
Du Pont de Nemours, 265.
Duriron Co., Dayton, Ohio, 88.
Durrans, Dr. T. H., 71.
Duzer, Van, 249.

EASTMAN, 339.
Edgar Allen & Co., Ltd., 524, 528, 529, 530, 536.
Edwards, 167.
Engineering (Bureau of U.S. Navy), 223.
Escher Wyss, 356, 387, 398.

FAIRLIE, A.M., 71.
Fansteel Metallurgical Corp., Chicago, 56.
Felix, A., 463.
Firth, Thos., & John Brown, Ltd., 241.
Firth Vickers, Ltd., 114.
Fishendon, 279.
Fox, Samuel & Co., 102.
Frank, 72.
Fraser & Co., Ltd., W. J., 420, 431, 463.
Freundlich, 424.
Fry, H. L., 349.

GALPERIN, 387.
Gard, 274.
Gas Light & Coke Co., 427.
Gay Lussac, 538.
Gayley, 402.
Geber, 150.
General Ceramics, Co., 152.
Genève, 266.
German Steam Boiler Committee, 217.
Gilliland, 437.
Gilson, J., 235.
Glover, 538.
Goodrich, B. F., & Co., 161.
Griffiths, E., 279.
Griffiths, H., 422.
Grimm, 469.
Guinot, 471.
Gwynnes Pumps, Ltd., 90.

HABER, F., 72.
Hadfield, Sir R. A., 133.
Hadfields, Ltd., 121, 133, 258, 517, 518, 524.
Handforth, S. L., 72.
Harding, 349.
Harding, 531, 532.
Hare, Robert., 70.
Hatfield, W. H., 104, 122, 123, 130, 133.
Haughton's Metallic Manufacturing Co., London, 88, 538.
Hausbrand, 343.
Haynes Stellite Co., 37.
Hebbard, 358.
Henry, 435, 438.
Hiscock, 541, 542.
H.M. Stationery Office, 543.
Hodson, G. N., 152.
Hoehn, 184, 185, 186, 187, 193, 203, 231.
Holler, Dr. Ing H.., 1.
Hudson, F., 138.
Humphrey, 264.
Huntington, Heberlein & Co., Ltd., 414, 415, 416.

I.G. Farbenindustrie, 177.
Imperial Chemical Industries, 264, 294, 541.
Ingersoll Steel and Disc Co., 114.
Inglis, 122, 124.
International Nickel Co., 40.
Iron and Steel Industrial Research Council, 101.
Iron and Steel Inst., 102.

JELINEK, Hugo, 354.
Johns, Manville Corp., The, 287.
Johnson, A. E., 120.
Johnson, C., 70,
Johnson Matthey & Co., Ltd., 69.
Jones, D. W., 61.

KAHLBAUM, 471.
Kaiser, 72.
Kanter, 117.
Kaye, 479.
Keasbey & Mattison, The, Co., 285.
Kendall, 101.
Kerr, R., 21.
Kestner Evaporator and Engineering Co., Ltd., 171, 390, 391, 392, 399, 417, 538, 539, 540.
Keyes, 471.
Kick, F., 512, 516,
Kingsbury, 149, 150.
Knietsch, 71.
Knight, C., 70.
Korber, 193.
Korn, E. und, 514.
Kowalke, 86.
Krauss, 71.
Krupp, Fried, 141, 210, 241.
Kuhlmann, F., 72.

LANGMUIR, 287.
Lamé, 179, 181.
Lecat, 471.
Lee Howl, 539.
Lennox, 538.
Lessing, 431, 466.
Lewis, K. G., 102.
Lewis, K. L., 270, 437, 438, 447.
Lloyds, Register of Shipping, 91, 219, 222.
Lunge, 70.
Lutz, 270.

McADAMS, 270, 339, 341, 344, 349, 437.
McCabe, 370, 406, 438, 440, 441, 449, 457.
McCready, 406.
Macdonald, 68, 169, 170.
McGillivray, 141, 146.
McGraw Hill Book Co., Inc., 339, 341, 437, 440.
Manlove, Alliott & Co., Ltd., 411, 481, 485, 493, 494, 496.
Manning, 141, 146.
Marlow, 541.
Maschinen Fabrik Sangerhausen, A. G., 90.
Mather & Platt, Ltd., 80, 81.
Merrill, 417.
Metropolitan Vickers Co., Ltd., 323.
Meslier, M. R., 219.
Messel, 71.
Michigan, University of, 331.
Miller, 520.
Mirrless Watson & Co., Ltd., 394–6.
Mitchell, Ltd., L. A., 410.
Mollier, 311, 313, 315, 316, 321.
Monell, Ambrose, 40.
Monsanto Chemical Co., 400.
Morgan, Sir G. T., 479.
Morris, 335.

NAGLE, 349.
National Boiler and Gen. Insurance Co., Ltd., 190, 196, 231, 284.
National Physical Laboratory, 138, 284.
National Radiator Co., 349.
Navigation and Steamboat Inspection (Bureau of, U.S. Dept. of Commerce), 223.
Norsk Hydro Electric Works, 430.
Nusselt, 344, 358.

O'MARA, R. F., 408.
Ostwald, 72.

PAGES, 136.
Partington, 65.
Patart, 469.
Pearson, 122.
Peclet, 278.
Pedersen, 48.
Peters, 438, 441.
Petit, 277.
Pettibone, 459.
Phillips, 71.
Pickering, 167.
Pittsburgh Lectrodryer Corporation, 430.
Pittsburgh Piping and Equipment Co., 254.
Poiseuille, 329.
Ponchon, 452.
Porritt, 157.
Potter, H. V. 171.
Prache & Bouillon, 388, 389.
Pratt, 541.
Pridgeon, 347.
Prodorite, Ltd., 177.

RAOULT, 435, 438.
Raschig, 431.
Raymond Company, 408, 532.
Reavell, 539.
Reece, 294.
Reiher, 341.
Revere Copper and Brass Co., 25, 26, 30, 32.
Reynolds, Osborne, 329, 371.

Rillieux, Norbert, 354, 386.
Rittinger, 512, 514, 515, 516.
Robert, 350.
Robertson, 183, 184.
Robey & Co., Lincoln, 90.
Rosenblum, 469.
Rubber Growers Assoc., 161, 163, 165.

SAMUELS, 294.
Säureschutz Gesellschaft, 171.
Savarit, 452.
Schuster, 203, 225.
Service, T. M., 122.
Sherwood, T. K., 404.
Siebel, 193.
Sorel, 438, 457.
Spring, 117.
Square, 71.
Stadler, 512, 513, 516.
Stefan, 277, 287.
Stevens, 471.
Stevens, H. P., 161, 165.
Stewarts & Lloyd, Ltd., 248, 255.
Sulzer Bros. Ltd., 304, 307.
Sunier, 469.
Swenson Evaporator Co., 331, 395, 396.
Swiss Assoc. of Steam Boiler Prop., 184, 218, 219, 224.

TAPSELL, 120, 136.
Taylerson, 101.
Tentelow, 71.
Thermal Syndicate, Ltd., 155.
Thiele, 438, 441, 449, 457.
Thompson, 249.
Thompson Bros., Bilston, 114.
Thompson John & Co., Ltd., 205, 210.
Thyssen, 203, 204.
Tilley, J. N., 72.
Trouton, 441.
Tungay, 87.

ULSAMER, 341.
Underwood, 54, 453.

VALENTINAS, 150.
Vulcan Boiler & General Insurance Co., Ltd., 239.
Vulcan Copper & Supply Company, 454.

WALKER, W. H., 270, 437.
Walker, J. O., 176.
Watson, Laidlaw & Co., Ltd., 510.
Webre, 386.
Wellner, F., 354.
Westinghouse Elec. & Mfg. Co., Ltd., 323.
Whitman, 335.
Wilkins, R. A., 28.
Willans, 298, 323.
Willard, 349.
Wollaston, 70.

YOUNG, Prof. S., 471, 472.

SUBJECT INDEX

ABRASION, resistance to, of cast iron, 76, 81.
— — — — stainless steels, 109.
Absorption as a method of drying, 403.
Acetanilide, use of aluminium for, 54.
Acetate—rayon silk—use of silver for, 69.
Acetates, use of copper for handling, 3.
Acetic acid, materials for use with, 3, 23, 38, 39, 54, 69, 80, 88, 105, 107.
— anhydride, use of aluminium for, 54.
Acetone, use of aluminium for, 54, 80.
Acid chromate solutions, use of copper for, 3.
— elevators (*see also* Air lifts), 152, 539–40.
Admiralty brass, properties of, 24, 25, 31.
— gunmetal properties of, 26.
Adsorption, 402, 422–30.
activated alumina, 430.
— — carbon, 422–30.
— plants using activated carbon, 426, 427.
— capillary condensation theory, 422–24.
— gas phase, 428, 429.
— liquid phase, 427.
— " Lectrodryer " plant for, 430.
— mechanism of adsorption, 424
— silica gel, 427–29.
Air bottles for diesel engines, 43, 178.
— lifts, materials for (*see also* Acid elevators), 28.
Alcohol, materials of construction for, 28, 54.
— manufacture of absolute, 471–74.
Alkalis (materials of construction for), 3, 29, 34, 38, 48, 90, 108, 109.
Alpha iron, 92.
Alum, materials of construction for, 28, 36, 54.
Alumina, 48, 430.
Aluminium, properties and particulars of, 23, 24, 39, 42, 47–55, 87, 89, 133, 430.
— brass, 24, 25, 31.
— bronze, 26, 28.
Aluminium casting alloys, 52.
— chloride, 3.
— foil, 53.
— hydrate, 48.
— joining methods, 48.
— mechanical properties, 47.
— minimum purity, 51.
— oxide, 26.
— paint, 53.
— physical properties, 47.
— pressure vessels, 231, 235.
properties at low temperature, 146, 147.
— protection coating, 53.
— silicon alloy, 50.
— soldering, 50.
— sulphate, materials for handling of, 3, 28, 54, 80.
— uses in chemical engineering, 51.
— welding, 48, 49, 50, 53.
Amino-hydrocarbons, aluminium for use with, 54.
Ammonia, materials for handling of, 3, 54, 89, 103, 108.
Ammonium, compounds.
— materials of construction for—
bicarbonate, 54.
bromide, 50.
carbonate, 54.
chloride, 58, 80.
hydroxide, 54.
nitrate, 54, 80.
sulphate, 3, 28, 54, 80, 108.
Aniline, aluminium for use with, 54.
Antimonial lead alloys, 63.
Antimony as a constituent of non-ferrous alloys, 4, 5, 52, 63.
Armco iron, 141.
Arsenic as a constituent of commercial copper, 2.
Artificial silk industry, materials for, 34, 63, 109.
Asbestos, 13, 273–85.
Asphalt, 169, 170.
Austenitic,
— cast iron, 77, 79, 80, 81, 90.
— — — corrosion resistance, 78, 80.
— — — electrical properties of, 83.
— — — heat resistance, 82.

Austenitic cast iron, high expansion, 83.
— — — non-magnetic properties of, 83.
— nickel silicon cast iron, 82.
— steels, 81, 103–105, 109, 112, 113, 120, 130, 132.
Autoclaves, 20, 26, 42.
Azeotropic distillation, 471.

BAUXITE, for manufacture of aluminium, 48.
Beer, materials of construction for, 36, 111.
Benzoic acid, 54.
"Birmasil Special," aluminium alloy, 52.
Binary mixtures, distillation of, 433.
Bismuth, 62.
Bleaching Kiers, 36.
Board of Trade Regulations, 178.
Boiler, 294–302.
baffle plates, 46.
— cost of raising steam in, 296, 297.
— drums, 122, 123.
— tubes, 29, 118.
Boiling pans, 20, 88, 231–35.
Bolts for covers of pressure vessels, 190, 191, 192.
— — flanges of H.P. piping, 247, 249–53.
Boracic acid, materials for, 80.
Boric acid, materials for, 54.
Brass, 23, 24, 25, 26, 31, 49, 50, 51, 83.
— Admiralty, 24, 25, 31.
— aluminium brass, 25, 31.
— commercial bronze, 25.
— high, 25.
— physical properties of, 25.
— properties of, at low temperatures, 146, 147.
— — — — elevated temperatures, 138, 140.
— Muntz metal, 25.
— naval, 24, 28.
— red, 25.
— Roman bronze, 25.
— Tobin bronze, 25.
Bromine, materials for handling of, 54, 58, 88.
Bronze, 24, 49, 52, 83.
— aluminium, 26, 28.
— leaded, 28.
— phosphor, 26, 28.
— physical properties of, 26, 28.
— properties of, at elevated tempeartures, 140.
— silicon, 28, 32.
— welding of copper, 20.
Brick, thermal conductivity of, 288.
Brine, materials for handling of, 43.

CALCIUM chloride, materials for, 3, 54.
Carbon, 40, 41, 76, 83, 84, 89, 119, 124, 125.
— activated (*see* Adsorption).
— cast steel, 117, 122, 123.
— dioxide, aluminium for use with, 55.
— disulphide, aluminium for use with, 55.
— steels, 91, 97, 119, 120.
— tetrachloride, materials for use with, 34, 55, 80.
Carbolic acid, materials for, 3.
Carburising boxes, materials for, 46.
Case hardening of steels, 94.
Cast iron and alloys, 74–90.
— — austenitic, 77.
— — copper additions to, 78.
— — corrosion, resistance of various, 75, 77, 78–80.
— — electrical and magnetic properties of, 83.
Emmel iron, 75.
— erosion resistance of, 81.
— — heat resisting, 77, 82.
— — high silicon acid resisting, 83.
— — Lantz iron, 75.
— low alloy, 75.
— mechanite, 75.
— special structural, 75.
Celluloid, etc., explosives, materials for, 110.
Cellulose, 34.
— extraction processes, materials, 109.
Cements, acid resisting, 177.
Centrifugal dryers, baskets for machines, 108, 505.
Chile nitrates, materials for, 109.
Chilled rolls, 77, 520.
Chlorine, materials for handling, 38, 39, 55.
Chromium as a constituent of ferrous and non-ferrous alloys, 45, 46, 52, 76, 78, 79, 82, 83, 84, 89, 96, 97, 98, 99, 102, 119, 120, 124, 125, 130, 133.
— molybdenum steels, 124–28, 137.
— non-ferrous materials, 136.
— nickel ferrous alloys, 121
— — molybedenum, 106.
— nickel steel, 104–109.
— — — (resistance to nitric acid), 105.
— silicon steel, 122.
— stainless steel, 137.
— steel, 137.
— vanadium steel, 100, 122, 124.

Cider, materials for handling, 111.
Citric acid, materials for, 3, 54, 80, 108.
Clock pendulums, low expansion metals for, 45.
Coal-hydrogenation plant, 123.
Coatings, metallic, 21.
— nickel chromium, 23.
— silver, 22.
— tin, 21.
Coke, crusher segments, 90.
Colloid mills, materials for, 42.
Condensers, 23, 28, 51.
— tubes, 24, 31.
" Constantan," 29.
Copper, 1–23, 41, 45, 52, 68, 78, 100, 102, 104, 105, 107.
— alloys of, 23, 24, 27, 28, 31, 39, 40, 62, 78, 87, 100–102.
— aluminium additions of to, 4, 26.
— annealing of, 2.
— arsenical, 2.
— best select, 2.
— brazing of, 5.
— bronze welding of, 20.
— chloride, materials for use with, 80.
— corrosion resistance of, 3.
— deoxidised, 2.
— electric arc welding, 6.
— — spot welding, 6.
— fluxes for soldering, etc., 12.
— high conductivity, 1.
— hydrogen attack of, 141.
— mechanical properties of, 1.
— metallic coatings on, 21.
— nickel alloys, 4, 28, 30.
— nickel, chromium coatings, 23.
— nitrate, materials for use with, 28.
— oxy-acetylene, welding of, 6–20.
— physical properties of, 1.
— pressure vessels in, 231–35.
— properties at elevated temperatures, 3, 138.
— — — low temperatures, 146–47.
— ordinary temperatures, 1.
— resistance to corrosion, 3.
— steam pipes, 244.
— steels, 100, 101, 102.
— silicon alloys, 31, 32.
— silver coatings, 22.
— soldering of, 4, 5.
— sulphate, materials for, 3, 28.
— tin alloys (bronzes), 24.
— tin coatings, 21.
— tough pitch, 2.
— tubes, 17.
— welding of, 5–20
— zinc alloys (brasses), 23, 24.
Corrosion, resistance of materials (*see* particular materials).
Creep, 117–41.
— of copper, 136.
— steels and alloys, 117–37.
— non-ferrous materials, 136–41.
— steam pipes at high temp., 243, 251.
Creosotes, materials for, 55.
Crushing and grinding equipment, 76, 512–37.
— Andrews' wet classifier, 534.
— ball and tube mills, 527, 528, 529.
— centrifugal machines, 527.
— choice of methods, 516.
— combination tube mills, 529.
— crushing rolls, 520, 521, 522.
— disc crushers, 518, 519.
— disintegrators, 525, 526.
— dry feeder, 531.
— dust collecting in, 528.
— gyratory crushers, 517, 518.
— Hardinge ball tube mill, 531, 532, 534, 535.
— Hum-mer screens, 537.
— impact mills, 524, 525.
— jaw crushers, 517.
— Kick's law, 512, 513.
— mechanical screens, 536.
— Raymond air classifier, 532, 533.
— Rittinger's Law, 512, 514.
— Stadler's development of Kick's law, 514.
— stamps, 524.
— swing hammer mills, 524, 525.
— vibrating screens, 536.
Cryolite, 48.
Cuprammonium process, materials for, 109, 110.
Cupric salts, materials for, 39.
— oxide, 4.
Cupronickels, 29, 30, 31.
Cuprous oxide, 3, 4.

DAIRY products, materials for, 111.
Deoxidised copper, 2.
" Dezincification," 24.
Distillation, 431–80.
— absolute alcohol, manufacture of, 471–74.
— azeotropic, 471.
— barbotage of column, 468.
— batch, 456, 457.
— binary mixtures, 433.
— boiling point diagrams, 433.
— bubble cap, column, 432, 433, 463.
— constant boiling mixtures, 469.
— " Duhring lines," 459, 460.
— efficiencies in practice, 453.
— enrichment lines, 444–48.
— ethyl acetate, manufacture of, 475.
— evaporation, 476.

Distillation, experimental unit and description, 454–56.
— fractionating columns, 431, 438, 466.
— Henry's Law, 438.
— ideal plate, 440.
— Lessing's contact rings, 431.
— material and heat balances for, 440.
— McCabe and Thiele's method, 449.
— mechanism of fractionation, 439.
— mixture of benzene and toluene, 435, 436, 437.
— practical example of plant, 461.
— Raoult's Law, 435.
— Raschig rings, 431.
— sieve plate columns, 432.
— steam, 457.
— sublimation, 479, 480.
theoretical number of plates in fractionating column, 441.
— Trouton's rule, 441.
— vacuum fractionation, 476, 477.
— vapour pressure relationships, 433, 434.
Drying, 402–21.
absorption, 403.
adsorption, 402.
— batch dryers, 418, 419, 420.
— chemical precipitation, 403.
— classification of dryers, 410.
— continuous band dryer, 410.
— decomposition of water, 403.
— deposition of the moisture as ice or water, 402.
— drum dryers, 420, 421.
— equilibrium moisture content, 404.
— evaporation method, 409.
— "Flash dryer," 408.
— humidity, influence of, 406.
— pressing out of water by mechanical pressure, 402.
— principles of drying, 403, 404, 407.
— rate of drying, 404, 405.
— rotary driers, 410–14.
— sprayer, 416–18.
— vacuum shelf dryers, 421.
— vaporisation by vertical continuous dryers, 414, 415.
Duralumin, 51.
"Durichlor" acid resisting irons, 88.
"Duriron" acid resisting irons, 88.
— mechanical properties of, 88.
— physical properties of, 88.
"Duroprene," 165, 168.
Dyestuffs, materials for, 36, 42.

EDIBLE oil and fats, materials for, 55.
Electric arc welding, 6, 49.
— furnace, 48.
Electric heating elements, 46.
— lamps, 45.
— resistance, butt welding, 5.
— spot welding, 6.
— welding, 37, 39, 41, 203.
Electro deposition of coatings, 21.
"Embrittlement" of steels, 127, 128.
"Emmel Iron," 75.
Engines (back pressure), W. H. Allen, 304.
— — — Belliss and Morcom, 298, 323.
— — — combined power and process steam, 295–305.
— — — steam requirements of, 299–304.
— — — Sulzer, 304.
— Willans Line, 298.
Engines (pass out), Belliss and Morcom, 298.
— — — characteristics of, 305–9.
— — — Sulzer, 307.
Ethyl Acetate, materials for, 55, 475.
Ethylene, Dichloride, materials for, 55.
"Eureka," 29.
Evaporators, 24, 28, 108, 328 401.
— air vents in, 359.
— apparent coefficients, 362, 363.
— basket, 351.
— boiling point and temperature drop, effect of, 364.
— capacity of multiple effect, 375, 376.
— comparison of various types, 372, 373.
— condensers for, 396.
— double effect (Blair, Campbell & McLean), 396, 397.
— Escher Wyss, 356.
— forced circulation, 355, 356, 357.
— horizontal tube, 354.
— inclined tube, 353.
— liquor level, effect of, 360, 361.
— long tube, 352, 390.
— multiple effect, boiling point elevation, 378, 379.
— — — calculations involved, 381–386.
— — — method of feeding, 380, 381.
— — — temperature distribution, 376, 377.
— principles of multiple effect, 373, 374.
— salting type, 392.
— single effect (Mirrlees, Watson), 394.
— triple effect (Blair, Campbell & McLean), 393.
— — — (Swenson Evap. Co.), 394, 395.
— vacuum pumps, 396, 398, 399.
— vapour recompression method, 387–390.

Evaporators, vertical tube, 350, 351.
" Everdur " copper silicon alloy, 32.
Expansion bends and joints, 253–56.

FANS, materials for, 28.
Fatty acids, materials for, 3, 28, 55.
Ferric salts, use of " Hastelloy " for, 39.
— chloride, materials for, 3, 58, 80.
— sulphate, materials for, 3, 28, 69.
Ferrous sulphate materials for, 3, 28.
" Ferry, " 29.
Fertilisers, constructional materials for, 108.
Film coefficient in heat transfer, 331–35.
— apparent coefficients, 362, 363.
— — effect of boiling points and temperature drop, 364–67.
— — — — liquor level, 360, 361.
— — — — scale in evaporators, 369–72.
— — forced circulation evaporators, 367, 368.
— — liquid film in evaporator, 357, 358, 360.
— — steam film in evaporator, 357, 358.
Filtration, 28, 481–511.
— Berkefeld filter, 499.
— Burt filters, 503.
— centrifugals, 505, 509, 510, 511.
— chamber presses, 481, 482, 483.
— cloth for, 42.
— Dorrco filter, 503.
— enclosed pressure filter, 499.
— " Eimco " disc filter, 502.
— filter presses, 481–89.
— filtering appliances, 481.
— frame presses, 484.
— hydro extractors, 505.
— — — (balancing), 506, 507.
— Kiefer filter, 503.
— leaf, 494, 495.
— Manlove, Alliott & Co. Ltd., 485, 493, 494.
— " Metafilter," strip type, 492, 493.
— — filter bed, 494.
— multi-leaf auto filter, 498.
— plate presses, 484.
— pressure filters, 152, 491.
— pulp filters, 503.
— rotary continuous filter, 499–502.
— " Rovac " rotary filter, 499, 500.
— Seitz Hercules filter, 504.
— Sweetland filter, 495, 496, 497.
— vacuum filter, 152, 491.
— — filters, continuous, 499.
— Vallez filter, 497.
Filtration, washing in the filter press, 486–91.
Fireboxes (locomotive), copper for, 4, 29.
Firebrick, thermal conductivity of, 288.
Fish manures, materials for, 109.
Flame welding, 8.
Flange joint, 7, 17.
— — for high pressure piping, 247, 249–53.
Flow of fluids in tubes, 328–49.
— — — — — Reynold's number, 329.
— — — — — turbulent, 329, 331.
— — — — streamline, 329, 331.
Fluorine, materials for, 58.
Fluxes, for joining of various materials, 4, 5, 12, 37, 39, 49, 50.
Food processing equipment, 23, 31, 34, 36, 47, 49, 54, 55, 69, 108, 111.
Forge welding, 5, 203.
Formaldehyde, materials for, 55.
Formic acid, materials for, 3, 38, 39, 55, 80, 107.
Fractionating columns, 155, 431, 436, 466.
Fruit juices, materials for, 36.
Fuel oil, materials for, 80.
— production, materials for, 109.
Furnaces, castings, 82.
— conveyor chains, 46.
— gratings, 46.
— heat loss through, 290.
— insulation for, 290–93.
— rails, 46.
Fused silica (vitreosil), 155.
— chemical plant in, 156.
— — resistance of, 156.
— laboratory operations, 157.
— properties of, 155.

GALLIC acids, materials for, 28.
Gamma iron, 92.
Gas welding, 37.
Gases, thermal conductivity of, 338.
Gelatine, 55.
Glassware (Industrial, Chemical), 153–157.
— — — chemical plant in, 153.
— — — fractionating column, 155.
— — — properties of, 153.
Glue, materials for, 55.
Glycerol, materials for, 55.
Gold, 68, 69.
Grinding machinery (*see* Crushing and Grinding machinery).
Gunmetal, Admiralty, 24.

HARDENING, 93.
" Hastelloy," A., C. and D., 37, 38.
— physical properties of, 38, 39, 40.
" Haveg " (plastic for chemical plant), 171, 172, 173.
Heat exchangers, 105.
— insulation, 273–93.
— loss from heated surfaces, 287–93.
— — of ovens, kilns and the like, 287.
— — from pipes and flat surfaces, 274, 282.
— — by radiation from ovens, etc., 287.
— — Stefan and Boltzman's Law, 287.
— — through furnace walls, 290.
Heat-resisting steels, 130–36.
— — heat treatment of, 132.
— — resistance to corrosive gases, 133.
— — — — scaling, wear and impact, 133, 135, 136.
— — stability at high temperature, 133.
— — strength at high temperature, 136.
Heat transfer, air heaters, 349.
— — coefficients of "Dowtherm," 400, 401.
— — coils immersed in tank, 343.
— — condensers, 350.
— — condensing vapours, 343.
— — " Dowtherm," 400, 401.
— — evaporators, 357–72.
— — film coefficient, 333.
— — fluids in natural convection, 342, 343.
— — — outside of pipes. 341, 342.
— — general principles of, 330–44.
— — heated fluids, 399–401.
— — — oils, 399.
— — hot-water pipes immersed in water, 349.
— — steam pipes immersed in water, 349.
— — smoke tubes of boilers, 349.
— — through jacketed pans, 343.
— — — pipes, 334, 335.
Heat transmission through insulation, 274–76.
' Hecla," A. T. V., 133.
Henry's Law, 438.
' Herculoy " copper silicon alloy, 32.
High brass, 25.
— conductivity copper, 1.
— temperature, properties of metals at, 117–48.
Homogenising tanks, 35.
Hot dipping, tinning of copper, 22.
— rolling, of nickel clad steel, 35.
Humidity of air, effect on drying, 406.
Hydro-extractors, design and details of, 505–507.
Hydrobromic acid, materials for, 58, 69.
Hydrochloric acid, 28, 29, 37, 38, 39, 80, 87, 88, 105, 113.
— — plant, for storage of, 150.
Hydrocyanic acid, materials for, 55.
Hydrofluoric acid, materials for, 69.
Hydrogen, 58, 124, 125.
— attack on copper, 141.
— — — steel, 124.
— — — non-ferrous metals, 141.
— peroxide, materials for, 69, 80.
— sulphide, materials for, 55.
Hydroiodic acid, materials for, 69.
" Hypernik," 44.

INCONEL, 46.
— physical and mechanical properties 46, 47.
IngAclad, 114, 115.
— — manufacture, 115.
Insulation (heat), 273–93.
— — asbestos magnesia, 281–84.
— — calculation of, for furnaces, 290–93.
— — cork, 280.
— — " Dextramite," 285.
— — economy in use of, 274.
— — general considerations of, 274–280.
— — glass silk, 284, 285.
— — heat loss from bare pipes and flat surfaces, 282.
— — heat transmission of, materials for, 274.
— — high temperature ovens, 285–93.
— — " Hytemp," 285.
— — low temperature, 280–81.
— — moderate temperature, 281–85.
— — optimum thickness of, 276, 283, 289.
— — pipes, high temperature insulation for, 286.
— — practical data for various temperature ranges, 280–93.
— — properties of magnesia for, 275.
— — requirements of a good non-conductor, 273.
— — Sil-O-Cel, 289–93, 337.
— — stoves, ovens, etc., 286–93.
— — thermal conductivity, 274.
— — — — of refractories, 288–93.
— — various temperature ranges, 273, 274.

Invar, 45.
Iodine, materials for handling, 55.
Iridium, 69.
Iron (*see* Cast iron), 23, 26, 40, 44, 46, 48, 52, 101.
— Armco, 141.
Ironac, 88.
— corrosion test, 89.

JOINTING material, high pressure flanges, 249, 253.
Juices, fruit and vegetable, materials for, 36.

KETTLES, size mixing, 36.
— varnish, 36.
Kick's Law, 512, 513.
Kiers, bleaching, 36.
" Killed spirits," 4.
" K " Monel metal, 40, 42.
— — — heat treatment of, 43.
— — — mechanical properties of, 42.
— — — physical properties of, 42.
— — — uses of, 43.
" Koroseal," 169.

LACQUERS, materials for, 110.
Lactic acid, materials for, 28, 54, 108.
Lantz iron, 75.
Lead, 4, 23, 26, 58, 61–65.
— antimonial lead alloys, 63.
— burning, 65, 66, 67.
— copper additions to, 62.
— density, 58.
— homogeneously lead-lined plant, 63.
— mechanical properties, 60.
— repairs to tanks and vats, 66, 67.
— sheet, 60.
— tellurium, 63.
— ternary alloys, 62.
— thermal properties, 60.
— weight, 60.
Leaded bronze, 28.
Leather industry, " IngAclad " for, 36.
Lessing's contact rings, 431.
Liquids, thermal conductivities of, 338.
Locomotive fireboxes, 4, 29.
— staybolts, 103.
Low expansion cast iron, 84.
— temperature, properties of metals at, 117–48.

MAGNESIUM, 52.
— chloride, cast iron for use with, 80.
— sulphate, cast iron for use with, 80.
Magnet steel, 136.
Magnetic properties of nickel iron alloys, 44.
Manganese, 23, 26, 32, 40, 52, 76, 78, 79, 83, 84, 87, 89, 96, 125.
— steels, 81, 95, 137.
Martensitic iron, 84.
— steels, 103, 104, 113.
Measuring tapes, 45.
Meehanite iron, 75.
Mercury, 51, 55.
— salts, materials for, 3, 55.
" Metafilter," filter, 494.
— strip type, 492, 493.
Metal polishes, materials for handling, 36.
Metals, properties at low temperature, 141.
— thermal conductivities, 337.
Metallic coatings on copper, 21.
Mild steel, 31, 41, 49, 100, 101.
— — corrosion of, 100.
Milk and milk products, materials for, 47.
Mills (*see* Crushing and Grinding equipment).
Mining industry, materials for, 76.
Molybdenum, 96, 99, 100, 101, 104, 105, 107, 108, 109, 119, 120, 124, 125, 128.
Monel metal, 40, 41, 78.
— — corrosion resistance, 41.
— — hydrogen attack, 141.
— — steam valves, 141.
Monel metal " K," 40, 42.
— — — heat treatment of, 43.
— — — mechanical properties, 42.
— — — physical properties, 42.
— — — uses of, 43.
Monel, silicon in, 40.
" Munmetal," 44.
Muntz metal, 25.
Muriatic acid, plant for storage of, 150.

NAVAL brass, 24, 28.
Nickel, 2, 23, 26–29, 33–46, 62, 76–87, 96–99, 109, 120, 124, 128.
— alloys, 37–47.
— aluminium, 56.
— cast iron, 76, 84, 90.
— chromium, 45, 46, 97–100.
— — (creep properties), 136.
— — iron, 45, 46, 84.
— — molybdenum, 100, 122, 124, 125, 128.
— — steel (temper brittleness), 99.
— clad steel, 34–37.
— copper, 29.
— — (creep properties), 136.
— dilitation properties of, 44.

Nickel, hardness, 34.
— iron, 44.
— lead, 62.
— magnetic properties of, 44.
mechanical properties of, 33.
— molybdenum iron alloys, 37.
— physical properties of, 33.
— properties of, at low temperature, 146, 147.
— rivets, 37.
— silver, 30, 31.
steel, 97, 120, 130, 136, 137.
— (low carbon), 102.
— white iron, 84.
"Nicrosilal," 82, 84.
"Ni-hard," 84, 90.
"Ni-Resist," 79, 80, 84.
— corrosion test, 80.
"Ni-Tensyl," 84, 90.
Nitralloy, 103.
Nitrates, materials for, 108.
— fertilisers, materials for, 108.
Nitric acid, 3, 29, 39, 54, 55, 69, 80, 86–89, 105.
— plant for storage of, 150.
"Nitricastiron," 89, 90.
— tests, 90.
Nitriding process, 103.
Nitro-cellulose explosives, 110.
— process, 110.
Nitrogen, 89, 103.
— hardened cast iron, 89.
— — steel, 103.
Nitrous gases, 55.
Nomag, 78, 83, 84.
Non-ferrous materials, 1–73.
— — comparative coeficient of expansion at elevated temperature, 138.
— — creep properties, 136.
— — high nickel tin bronzes at elevated temperature, 138.
— — hydrogen attack of, 141.
— — metals at elevated temperature (chart showing particulars of), 139.
— — nickel, to improve properties at elevated temperature, 138.
— — properties at elevated temperatures, 136, 138.
— — properties at low temperatures, 146.
— — steam valves at elevated temperatures, 138.
— — tensile strength of various, at elevated temperature, 138.
Non-metallic materials of construction, 149–177.
— thermal conductivities, 337.
Normalising of steels and alloys, 93.

OIL, 43.
— distillation process, 123.
— industry, 31.
Oleic Acid, materials for handling, 55, 107.
Oleo-margarine, materials for handling, 36.
Organic acids, material for handling, 36.
Orthophosphoric acid, materials for handling, 113.
Osmium, 69.
Oxalic acid, materials for handling, 3, 55, 80.
Oxidiser coolers, 105.
Oxy-acetylene welding, 6, 37–41, 48, 88, 102, 203, 211, 226.
— hydrogen welding, 48.
Oxygen, 28, 57, 58.

PAINTS, plant for, 110.
— rubber, 162.
Palladium, 69.
Palmitic acid, aluminium for use with, 55.
Pans, copper steam jacketed, 233.
Paper industry, materials for, 36, 43, 109.
Perchlorates, copper not advised for, 3.
"Permalloys," 44.
Persulphates, copper not advised for, 3.
Petrol storage tanks, materials for, 53.
Pharmaceutical products, materials for, 34.
Phenol, materials for, 55.
Phosphor bronze, 26, 28, 80, 109.
— — corrosion test, 80.
— — properties at elevated temperature, 138.
Phosphorus, 2, 83, 89.
Phosphoric acid, materials for, 39, 55, 80, 105, 106.
Photographic emulsions, materials for, 34, 36.
Pickles, materials for, 111.
Pickling tank plant, 28, 42.
Picric acid, materials for, 55, 87.
Pig iron, 48.
Piping and Pipework, 28, 51, 88, 105, 242–272.
— — — alloy steels for, with analysis and properties, 267–270.
— — — bolts for flanges of, 247, 249–253.
— — — capillary, 266.
— — — copper, 244.
— — — "Corwel" joint, 247.
— — — creep at high temperature, 243, 251.
— — — "Dawson" joint, 248.

Piping and Pipework, design of, 242, 243, 244, 248.
— — — drainage, 259.
— — — expansion bends and joints for, 253–256.
— — — fitting branches to, 257.
— — — flanges for, 244–253.
— — — flow of steam in, 261–264.
— — — graphical method of obtaining heat transfer in, 270–272.
— — — heat transfer in, for various fluids, 270–272.
— — — high pressure steam, 249–53.
— — — — — at Trenton and Delray power stations, 249–253.
— — — hydrogenation of coal, 266.
— — — insulation of, 265.
— — — joint material for H.P. flanges, 249–53.
— — — large installations, 264–66
— — — material for, 242, 249–53.
— — — non-ferrous metals, 266.
— — — non-metallic materials, 266.
— — — plastic materials, 266.
— — — pressure drop in, for various fluids, 270–72.
— — — reducing valves, 261.
— — — Sarlun joint, 246.
— — — standard expansion bends, 255.
— — — "Staybrite" steel for, 266.
— — — steam, 242.
— — — — receivers, 258.
— — — — separators, 258.
— — — — traps, 260.
— — — superheaters, 249.
— — — supports, 259.
— — — synthesis of ammonia, 266.
— — — tubes, 266.
— — — valves for steam pipes, 249–252.
— — — weldless construction of, 244–253.
Plastics, chemical plant, 171–73.
— — corr. resistance of, 172, 173.
— definition of, 171.
— "Haveg," 172.
— manufacture of, 171.
— properties of, 171–73.
Platinum, use in chemical industry, 69–70.
Potassium chlorate, materials for, 55.
— chloride, materials for, 28.
— hydroxide, materials for, 3, 28.
Preserves, materials for handling, 111.
Presses (*see* Filtration).
Pressure vessels, for the Chemical Industry, 178–241.
Pressure vessels, acetylene welded, 211–13.
— — bolted covers for, 190.
— — bolts for, 190–92.
— — brazing of, 178, 231.
— — cast, 178, 195.
— — cast iron hot plates, 196–98.
— — chemical works regulations, 179.
— — creep considerations in design of pressure vessels, 203.
— — designed on "thin" cylinder theory, 179, 180.
— — — — "thick" cylinder theory, 179–84.
— — dished ends for, 229–31.
— — end plates, design of dished, 184–87, 190.
— — — — — — flat, 187–92.
— — Factories Act, in relation to, 178, 179.
— — forge and hammer welded, 203, 204.
— — hollow forging, 178, 240.
— — hydraulic test, 226.
— — — — aluminium, 231, 235.
— — — — copper, 231–35.
— — — — thin shells subject to external pressure, 235.
— — investig. of explosions of, 178.
— — material for welded, 216–26.
— — metallic arc welded, 204–6.
— — official regulations for (B.O.T. rules), 178.
— — openings in shell and end plates, 192–94.
— — protection against overpressure, 236–40.
— — regulations for welded—
Great Britain, 216.
U.S.A., 217.
Germany, 217.
Switzerland, 218.
Sweden, 219.
Italy, 219.
France, 219.
Lloyd's, 219, 222.
American Petroleum Inst., 223, 224.
U.S. Navy, 223.
Schuster, 225.
— — rivetted construction of, 178, 198–203.
— — rules for design of welded joint, 222–31.
— — safety valves for, 236–40.
— — shells in compression, 193–95.
— — soldered, 178.
— — spherical shells, 236.
— — welded, 178, 203–31.
— — workmanship, 215–16.

Pressure vessels, X-Ray examination of, 208–10, 216, 223, 224.
Process steam plants, combined power and, 295–327.
— — allocation of fuel costs, 319–323.
Propionic acid, materials for, 54.
Protective clothing and appliances in handling of chemicals, 542.
Pumps and pumping (chemical works), 28, 42, 43, 105, 538–40.
— — — centrifugal pumps, 538.
— — — compressed-air displacement pumps, 540.
Kestner, Messrs., 538 40.
Lennox pump, 538.
— — — multi-stage centrifugal pumps, 538.
— — — plunger pumps, 539.
— — — unchokable pumps, 538.
" Pyrex," physical characteristics, 153.
— — pipework for chemical plant, 153.
Pyrometers, materials for, 29.

RADIATION from heated surfaces, 277, 287.
— — furnace walls, 290.
— Stefan and Boltzman's Law, 287.
" Radio metal," 44.
Raoult's Law, 435.
Reaction soldering, 50.
Red brass, 25.
Refractories, thermal conductivities of, 288–93.
Retorts, materials for, 46.
— calcination, 46.
Reynold's number, 329.
Rhodium, 69.
" Rhometal " 44.
Rightward welding, 6, 14, 15.
Rittinger's Law, 512, 514.
Rivets, aluminum, 51.
— copper, 231.
— duralumin, 51.
— nickel, 37.
Rivetting, 48, 51, 198–203.
— of copper, 231.
Roman bronze, 25.
R. R. Alloy, 56.
Rubber, 110, 157–69.
— belting, 162.
— chemical resistance, 165–69.
— constituents of, 157.
— ebonite, 158.
— for use with acetic acid, 167.
— — — — alkalies, 167.
— — — — gases, 167.
— — — — hydrochloric acid, 165.
Rubber for use with nitric acid, 167.
— — — — phosphoric acid, 167.
— — — — sulphuric acid, 166.
— hard, 158.
— hose, 161.
— latex, 36, 163.
— lining of chemical equipment, 161.
— paints, cements, etc., 162.
— processing of, 157.
— soft vulcanisation, 158.
— synthetic, 169.
— typical, used in chemical work, 158, 159, 160, 161.
— use in chemical engineering, 161–169.
— varnishes, 162.
Ruthenium, 69.

SAFETY aspect in chemical works, 541 43.
Salad creams, materials for, 111.
Salicylate and salicylic acid, materials for, 55.
Salt manufacture, 24, 36.
— spray, materials to resist, 38.
Sauces, materials for, 111.
Screens (*see* crushing and grinding equipment).
Sea water, materials to resist, 80.
Silica gel, 427.
Silicon, 32, 40, 52, 76, 83 9, 133, 137.
— bronze, 28, 32.
— chromium steels, 130, 137.
— irons, 86, 87, 88.
— Monel, 40.
Silver, 25, 68, 69.
— coatings, 22.
— nickel, 30, 31.
— sulphide, 69.
— use in chemical plant, 69.
Singe plates, 4.
Size mixing kettles, 36.
Soap manufacture, 36, 111.
Soda, recovery plant, 36.
— solution, 48.
Sodium, salts, etc.
— carbonate, materials for, 55.
— chloride, materials for, 28, 55, 80.
— fluoride, materials for, 50.
— hydroxide, materials for, 3.
— hypochlorite, materials for, 80.
— silicate, materials for, 36.
— sulphate, materials for, 80.
— sulphide, materials for, 43, 80.
Soldering, 45, 48, 50, 62.
— aluminium, 50.
— properties at low temperature, 146, 147.
— reaction, 50.

Specific heat of gases, 338, 339.
Spot welding, 49, 50.
Spray drying, 416.
Stadler's ordinal numbers, 514.
Stainless clad steel, 114.
— iron, 120.
— steel, 103, 141.
Stannic chloride, materials for, 58.
Steam, distillation, 457.
— piping, 118.
— plant for chemical work, 294–327.
— process, 295–327.
— valves (Monel metal and stainless steel), 141.
Stearic acid, materials for, 55, 107.
Steels and alloy steels, 35, 91–116.
— annealing, 93.
— case hardening, 94.
— chart of alloys suitable for various temperature ranges, 137.
— chromium in, 137.
— — molybdenum in 137.
— copper in, 100, 104, 105.
— corrosion resisting, 105, 106.
— hardening, 93.
— heat treatment, 92.
— high chrome stainless, 137.
— — nickel, 137.
— impact tests at low temperature, 141–47.
— magnet, 137.
— manganese, 95, 137.
— molybdenum, 137.
— nickel, 96.
— — clad, 34–37.
— normalising, 93.
— properties at low temperatures, 141–147.
— silicon, 137.
— — chromium, 137.
— stainless clad, 114.
— structural (mechanical properties), 94.
— tempering, 93.
— tensile tests at low temperature, 141–47.
— tubes, 17.
Stills, 88.
Stoneware, chemical, 150–52.
— acid elevator, 152.
— analysis of, 150.
— high temperature heating surface, 152.
— manufacture of, 150.
— mechanical properties of, 150.
— method of heating, 152.
— physical properties of, 150.
— plant for storage of various acids, 150.
— pressure filter, 152.
Stoneware, vacuum filter, 152.
Storage tanks, 105.
Sublimation, 479, 480.
Sugar manufacture, 24.
Sulphite liquors, materials for, 109.
— process, materials for, 109.
— solutions, materials for, 3, 28.
Sulphur, 52, 55, 69, 83, 89, 109.
— dioxide, 3, 28, 56.
Sulphuric acid, 3, 26, 28, 29, 38, 39, 56, 61, 62, 63, 69, 80, 86–89, 105, 108.
Sulphurous acid, 28, 29, 39, 56, 80.
Superheaters, etc., 46, 118, 249.
Superphosphates, 108.
Synthesis of ammonia, 123, 124.
Synthetic ammonia, 108, 121, 266.
Syrups, materials for, 36.

TANK waggons, 105.
Tanning, 111.
Tantalite, 57.
Tantalum, 56–58.
— corrosion resistance tests, 59.
— mechanical and physical properties, 56.
Tar products, materials for, 42.
Tartaric acid, materials for, 3, 56, 80.
Tellurium, in lead, 62–65.
— resistance to hydraulic bursting, 64.
Tempering of steels, 93.
Ternary alloys, of lead, 62, 63.
Textile industry, materials for, 35.
Thermal conductivity, heat insulation, 274.
— — gases, 338.
— — liquids, 338.
— — metals, 337.
— — non-metals, 337.
— — refractories, 288–93.
Thermocouple sheaths, materials for, 46.
Thermometers, 51.
Thermostats, 45.
Thiokal, 169.
Tin, 45, 23, 24.
— coatings, in copper, 21.
Tinning of copper—
— electrodeposition, 21.
— hot dipping, 22.
— spraying, 22.
— wiping, 22.
Titanium, 104, 120.
Tobin bronze, 25.
" Tough pitch " copper, 2.
Towers, 105, 170.
Transport drums, 105.
Trinitrotoluene, 56.
Trouton's rule, 441.

Traps, steam, 260.
Tubes (*see* Pipes).
— copper, 17.
— steel, 17.
Tungsten, 104, 120.
— arc, 49.
Turbines, 43.
— blading, 105, 133.
— cylinders, 118.
— discs, 118.
Turbines (back pressure), 304, 305.
— — — W. H. Allen & Co., 304.
Turbines (pass out), 309 23.
— — — Belliss & Morcom Ltd., 323, 326, 327.
— — — principles of, 309 11.
— — — Metropolitan Vickers, 323.
— — — use of Mollier diagram, 311–316.
— — — Westinghouse Electric & Manufacturing Co., 324.
Turpentine, 56.
distillation of, 431.

ULTRAMARINE, material for handling, 56.

VACUUM, concentration pans, 90.
— pumps, 398.
Valves, 28.
— for steam pipes, 249 52.
— — reducing, 261.
Vanadium, 100.
— steel, 100.
Varnish, materials for, 42, 56, 110.
— kettles, materials for, 36.
Vegetable juices, materials for, 36.
Vinegar, materials for, 3, 69, 80, 107, 111.
Viscose process, materials for, 35, 109.
Viscosity, definition of, 328.
— gases, 341.
— liquids, 339.
— water, 328, 340.
Vitreosil (*see* Fused silica).
Vitreous enamelling, 83.
V-joint, for welding, 7, 16, 18.

WATER, metals for use with, 3, 56.
— density, 340.
— properties, 340.
— thermal conductivity, 340.
Water, viscosity, 340.
Welding, 5, 37, 39, 48, 49, 50, 51, 57, 102, 112, 203, 204.
— aluminium, 48, 50, 53.
— arc, 6, 37, 41, 48, 49, 203, 205.
— atomic, 48, 203.
— — hydrogen, 37, 49, 204.
— bell or cup joint, 7.
— bronze, 20.
— butt joint, 7, 17, 57, 213.
copper, 5, 8, 12.
corrosion-resisting steel, 111.
— flange joint, 7.
— flame, for acetylene welding, 8.
— forge, 5, 203.
— gas, 37, 203.
hammer, 53, 203.
leftward and rightward, 6, 211.
— machines, 48, 205.
— metallic arc, 203, 205.
nickel, 57.
— oxy-acetylene, 6, 37, 41, 48, 53, 88, 211.
— oxy-hydrogen, 48, 53.
— of pressure vessels, rules for, 216–231.
— resistance butt, 5, 203, 204.
— roller, 57, 203.
— seam, 49.
— spot, 6, 49, 50, 57.
— V-joint, 7, 213.
— X-joint, 7.
Wines, materials for, 111.
Wiping, tin, 22.
Wood, 174–77.
— chemical resistance of, 174, 176.
— pipework for chemical plant, 176.
— properties of various, 175.
— storage tanks of, 176.
Wrought iron, 102, 103.

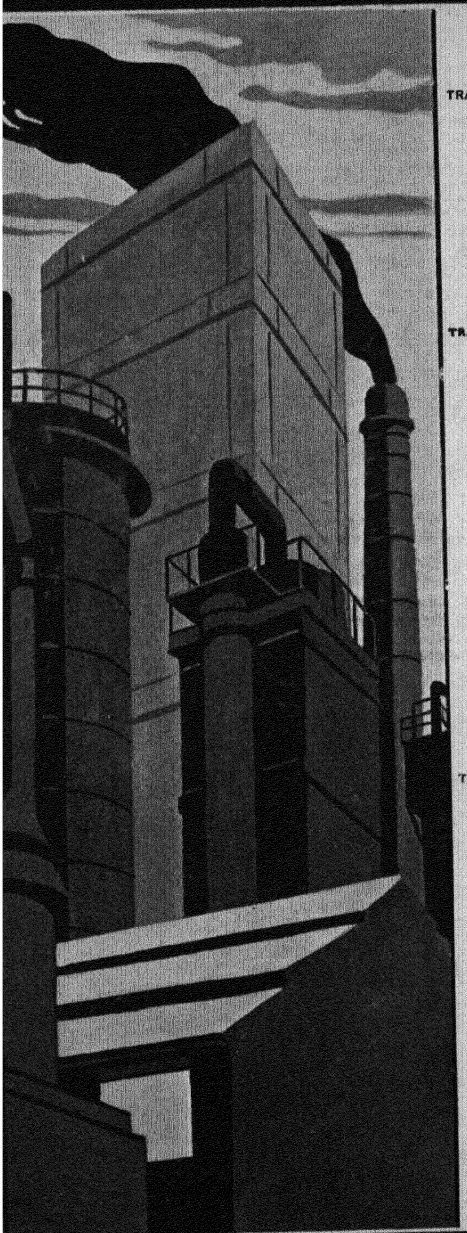
X-JOINT, for welding of copper, 7, 16, 18.

"Y" ALLOY, 56.
Yorkshire Iron, 102.

ZINC, 5, 23, 24, 26, 29, 50, 51.
— chloride, materials for, 3, 4, 28, 50, 113.
— nitrate, materials for, 28.
— sulphate, materials for, 3, 28.

ADVERTISEMENTS
OF
CHEMICAL PLANT
ETC.

Steels FOR THE CHEMICAL INDUSTRIES



TRADE HECLA MARK TRADE ERA MARK

HIGH TENSILE ALLOY STEELS

TRADE ERA MARK TRADE Galahad MARK

C.R.

CORROSION RESISTING STEELS

TRADE ERA MARK

H.R.

HEAT RESISTING STEELS

TRADE ERA 131 MARK TRADE HECLA 153 MARK

CREEP RESISTING STEELS

CASTINGS
FORGINGS
ROLLED PRODUCTS

COMPLETE HIGH PRESSURE AUTOCLAVES

HADFIELDS LTD.

AREA OF WORKS EAST HECLA & HECLA WORKS SHEFFIELD. BUILDINGS, COV 64 ACRES

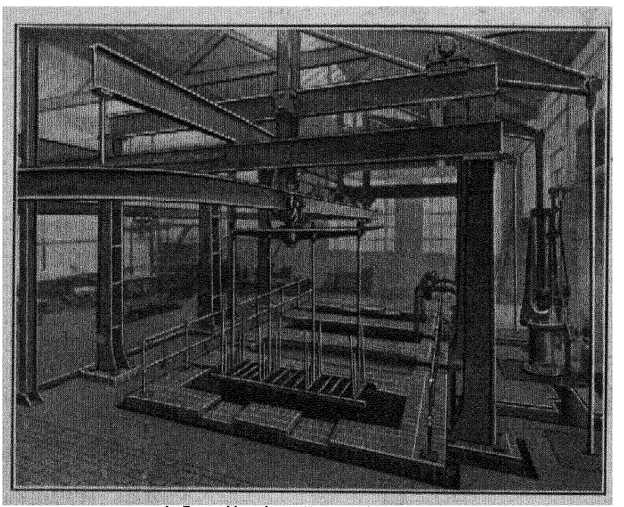
PRODORITE LIMITED

Specialists in

ACID-PROOF FLOORS & TANK LININGS.

INDUSTRIAL FLOORS with hard wearing properties, freedom from dust, resistance to oil and water penetration.

WALL and FLOOR TILES for hard wear and artistic effect.



A Four Vat Installation for Sheet Pickling

LITHCOTE ACID-PROOF LININGS.

SCHORI METAL SPRAYING.

GUNNED BITUMEN.

Write for descriptive literature to :—

London Office :
ARTILLERY HOUSE,
ARTILLERY ROW,
VICTORIA STREET,
LONDON, S.W. 1

PRODORITE LTD.

Head Office :
EAGLE WORKS,
LEABROOK,
WEDNESBURY.



ACIDS

IN ALL STRENGTHS FOR ALL PURPOSES

Supplied in any quantity and scientifically packed for transport anywhere

GLASS BOTTLES and WINCHESTER QUARTS
GLASS and STONE JARS (2-4 galls.)
CARBOYS (10-14 galls.)
STEEL DRUMS (1 cwt.-10 cwt.)

Specially constructed tanks for conveyance by road or rail

Tank Barges

ACIDS

OLEUM
(FUMING SULPHURIC)
SULPHURIC ACID
BATTERY ACID
HYDROCHLORIC ACID
NITRIC ACID
DIPPING ACID

ALSO
DISTILLED WATER (PURE)

SPENCER CHAPMAN AND MESSEL LIMITED

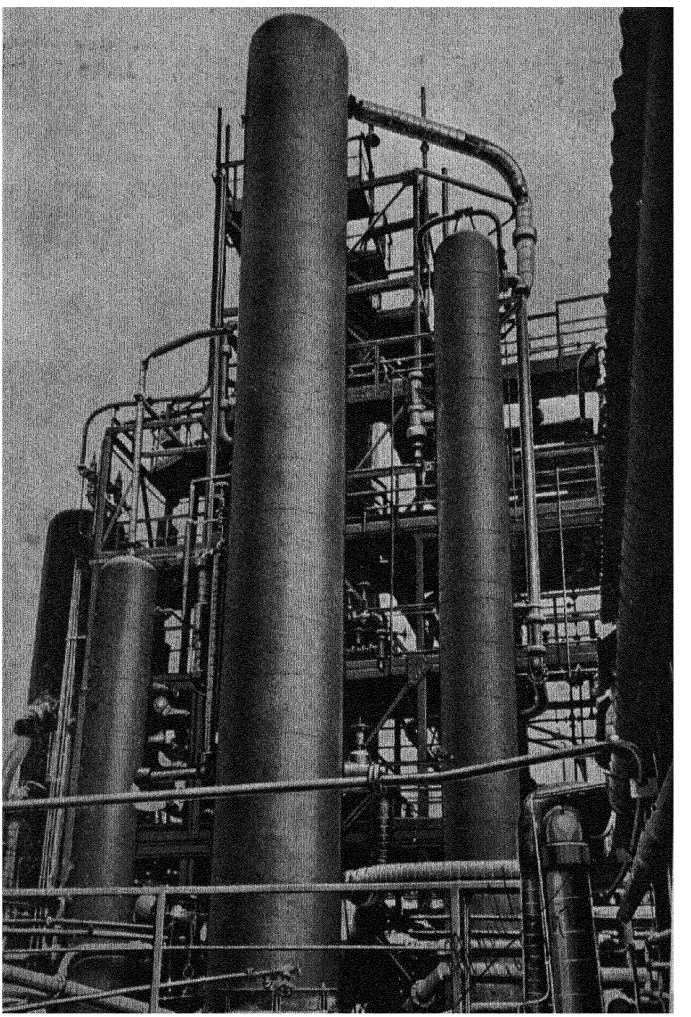
WALSINGHAM HOUSE, SEETHING LANE, LONDON, E.C.3

Telephone: Royal 1166 (3 lines)

Works: Silvertown, E.16

Telegrams: "Hydrochloric Fen—London"

Thompson
"Class I" Fusion Welding



FUSION WELDED STILL. 57 ft. 6 in. long × 6 ft. 4 in. diameter. Constructed for one of the leading Chemical Firms. All Body Seams X-Rayed throughout.

JOHN THOMPSON (Wolverhampton) LTD.

WOLVERHAMPTON, ENGLAND

Approved by Lloyd's Register of Shipping as manufacturers of
"CLASS I" FUSION WELDED VESSELS

MATTHEY PRODUCTS

for the

CHEMICAL INDUSTRIES



PLATINUM LABORATORY APPARATUS. Crucibles, electrodes, dishes, capsules, foil, tongs, spatulas, microapparatus, boats, filter-cones, triangles etc.

PLANT—PURE SILVER AND SILVERED COPPER. For use in the manufacture of acetic acid, vinegar, formic acid, formaldehyde, dyestuffs, foodstuffs, confectionery, essential oils, photographic chemicals, fine chemicals.

"STAYBRITE" STEEL GAUZE. For use in sieving, screening, straining or filtering processes where a tough corrosion-resisting material is required.

CHEMICAL PRODUCTS. Salts of all precious metals, including silver nitrate, gold chloride, and platinum chloride. Salts of rhodium, iridium, palladium, osmium, and ruthenium.

PLATINUM GAUZE CATALYSTS. For use in ammonia oxidation, etc. Gauze units of standard size or to customer's own specification.

BASE METALS. Cadmium, bismuth, selenium, antimony, mercury, molybdenum, etc.

JOHNSON, MATTHEY

& CO., LIMITED.

Head Office :

73/83, HATTON GARDEN
LONDON, E.C. 1

Telephone :
HOLborn 6989

Telegrams :
"MATTHEY, SMITH, LONDON"

MODERN PLAN

Our staff of trained Chemical Engineers is always ready to co-operate with Clients in the design of complete Chemical Process Plants. Development units are available at our works for experimental work involving evaporation, distillation and fractionation. By the use of DOWTHERM Heating, temperatures up to 735°F can be applied, and provision is also made for high vacuum work.

By FRASERS of DAGENHAM

STAINLESS STEEL EQUIPMENT on any SCALE

Rotary, Trommel-type Drier with Stainless Steel Barrel 7′ 3″ diam. × 30′ 0″ long. An example from our General Catalogue. May we send you a copy for your files?

