SELECTION OF OILS FOR INDUSTRIAL HYDRAULIC SYSTEMS

BY

A. C. SMITH, ESQ., B.Sc.
The Shell Petroleum Co., Ltd.

This article is reproduced by permission of the Editor, 'Scientific Lubrication', and the illustrations by permission of Messrs. The Wellman Smith Owen Engineering Corporation Limited, and Fielding & Platt Limited.

Development of hydraulic systems for the transmission of motion, force or power may be considered to have begun with the introduction of the hydraulic press, one of the great inventions that marked the Industrial Revolution during the latter half of the 18th Century. (It was patented in 1795 by the Yorkshireman, Joseph Bramah, renowned in his day for many innovations, including the beer-engine.) For many years after its introduction the hydraulic press represented industrial hydraulics.

Primarily, the hydraulic press is an instrument of force multiplication. That being so, it is naturally massive, and requires a large fluid charge. An essential requirement of the fluid medium is, therefore, that it should be available in large quantities and at low cost. This is generally true of hydraulic equipment in a very wide field of industry. Apart from the press, hydraulic machines and installations are now built in great numbers and variety.

Hydro-kinetic and Hydrostatic Systems

Hydraulic systems nowadays form two general classes : the hydro-kinetic and the hydrostatic. In the former the working fluid is used primarily as a vehicle of kinetic energy, power being transmitted essentially by acceleration of the fluid in one part of the circuit and deceleration in another. This system, which in its practical form includes traction couplings (' fluid flywheels '), scoop-control couplings and torque converters, is characterized by very large changes in fluid velocity, large changes in pressure being generally avoided. In the hydrostatic system, on the other hand, the working fluid is used essentially as a medium for the continuous application of pressure, power being transmitted to the driven unit by advance of oil against load. Large changes in pressure therefore occur, with corresponding variation in the conditions to which the oil is subjected. The following notes are to be read primarily in relation to hydrostatic systems—for example, steering telemotors, hydraulic brakes, hydraulic presses, reciprocating machine tools and so on.

Suitable Hydraulic Media

The minimum requirements of a hydraulic medium are that it should be virtually incompressible and sufficiently fluid to permit efficient transmission of power. These requirements are, of course, met by many liquids, including many that are chemically inert towards the materials used in hydraulic engineering. Very few, however, meet the over-riding requirement of availability in large amounts at low cost. For practical purposes the only fluids suitable on these grounds for general use in industry are aqueous fluids and mineral oils.

Despite its shortcomings as a hydraulic medium, water is the only practicable fluid for certain applications where very great volumes are required. In particular, water is used in so-called ' open ' systems, which discharge to waste. (Typical open systems are those working bascule bridges, lock gates and caissons.) However, water has obvious disadvantages : it promotes rusting, its lubricating powers are negligible, and it can only be used in a relatively restricted range of temperatures. Rusting can be countered by the use of aqueous emulsions or slurries of ' soluble ' oil, but water remains, in general, unsuitable for circulating systems. Mineral oil, on the other hand, is capable of acting as a lubricant, sealing medium and rust preventive, apart from doing duty as the hydraulic medium.

Compressibility of Mineral Hydraulic Oils

Low compressibility is, of course, a common property of liquids. It is possessed by all mineral lubricating oils, so long as they are free from undissolved air or other gas, and has no direct influence on selection of mineral oil for industrial hydraulic systems. The compressibility to be expected of mineral oils is, however, of interest to the hydraulic engineer, and a few notes on the subject are therefore given.

Oils of different hydrocarbon types show measurable differences in compressibility, paraffinic oils showing slightly less compressibility than naphthenic oils. Such differences between mineral base hydraulic oils are, however, recognized as being of negligibly small order. The following figures, obtained

WELLMAN SMITH OWEN MOBILE FORGE MANIPULATOR WITH "V.S.G." EQUIPMENT

on compression of three typical mineral oils, may be cited to illustrate this. The oils, of aromatic, naphthenic and paraffinic type, were all of approximately the same viscosity (33.5 cs.) at room temperature (65°F.), at which the determinations were carried out. At 50,000 lb/sq. in., the compressibilities of the oils, expressed as percentage reduction in volume, were : aromatic oil—12.0 ; paraffinic—12.4 ; naphthenic—12.6.

Variation in compressibility exists also between oils of different viscosities, those of higher viscosity tending to show lower compressibilities, but again the differences in compressibility are only slight, at least over the range of viscosities of mineral oil base hydraulic media. An illustration of this is that a paraffinic oil of viscosity of the order of 320 cs. at 65°F. showed compressibility of 11.95% at 50,000 lb/sq. in. and room temperature by comparison with 12.4% shown by a similar oil of 33.5 cs. viscosity at 65°F.

For practical purposes all mineral oils are thus substantially the same in respect of compressibility. Again expressed as percentage reduction in volume of the oil under pressure, compressibility may be taken to be of the order of 0.5%/1,000 lb/sq. in. pressure up to 4,000 lb/sq. in., increasing to a total value of about 5.2% at 14,200 lb/sq. in. These are approximate mean values over a temperature range of 50 to 210°F.

Oils show increase in compressibility with increase in temperature. The temperature/compressibility effect appears to be similar to that of viscosity/compressibility and is, at least to a large extent, attributable to the effect of temperature on viscosity. Over the more usual working temperature range of power-operated industrial hydrostatic systems of 50 to 150°F. mean compressibility is somewhat lower than that given above, being up to about 4.9% at 14,200 lb/sq. in.

Operating temperature of oil in power-operated industrial hydrostatic systems is usually of the order of 80 to 130°F. but may sometimes be up to 180°F.

Solution and Entrainment of Air

Hydrostatic systems are especially liable to develop trouble if excessive amounts of air gain entry into the circuit. Aeration of the oil greatly increases its compressibility, the results being manifest as chattering, noise, vibration, and generally erratic behaviour of the system. Similar effects occur, of course, where other gases (e.g. nitrogen) are present in the oil in undissolved form.

So far as selection of the oil is concerned, distinction must be made between solution and entrainment of air. Mineral oils of all hydrocarbon types will dissolve a certain amount of air, and for practical purposes all may be taken to absorb substantially the same quantity under given conditions. Differences exist between oils of different viscosities, solubility tending to decrease with increase of viscosity, but such differences are of comparatively small order over the range of viscosities of mineral oils used as hydraulic media. The quantity of air dissolved depends in some degree on the temperature of the oil but is mainly governed by the equilibrium pressure.

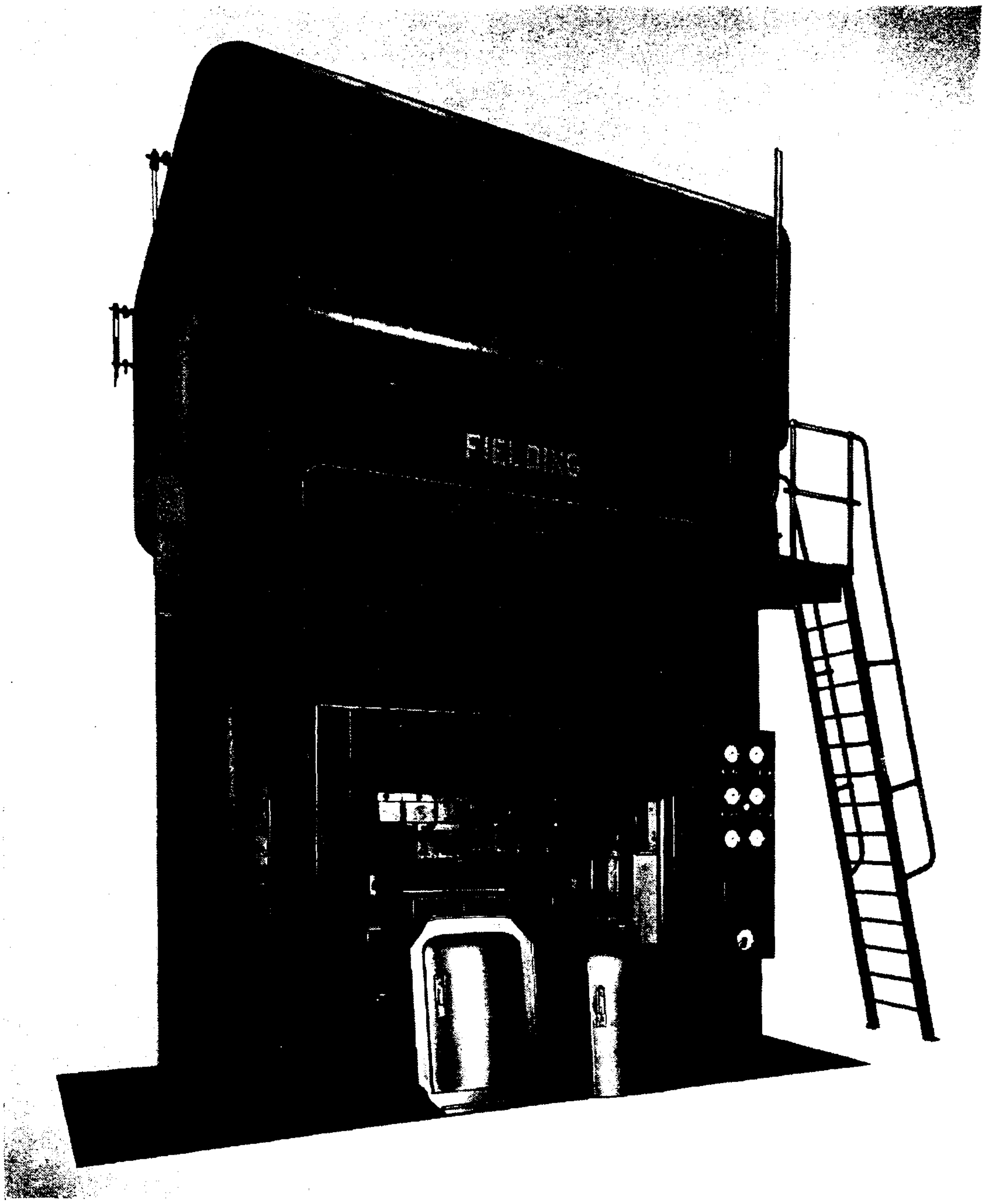
Between 30° and 210°F. the effect of temperature on the solubility of air in oils is not pronounced, and there is no general agreement between different workers as to the general effect, some reporting increases in solubility with temperature and others reporting decreases. However, work carried out by the author's company on mineral oils typical of those used as hydraulic media has shown only very small change in solubility of air (Bunsen Absorption Coefficient) over the range of operating temperatures obtaining in practice.

The effect of change of pressure is, of course, very marked. At normal temperature and pressure the solubility of air in mineral oil is of the order of 8 to 9% by volume, i.e. 80 to 90 c.c/litre. At pressures up to about 200 atmospheres Henry's law may, for practical purposes, be taken to be approximately valid for solution of air in mineral oil, and the volume of air dissolved, measured at the pressure prevailing, will remain about the same if the temperature is unaltered. (Henry's law states that at constant temperature the mass of gas dissolved in a given volume of liquid is proportional to the partial pressure of the gas. So long as the gas obeys Boyle's law the specific volume of the air varies inversely as the weight in solution in a given volume of oil, and the volume of air in solution, measured at the pressure prevailing, consequently remains constant.) At pressures exceeding about 200 atmospheres the quantity of air in solution in the oil will no longer vary linearly with pressure, and it is to be expected that deviation from the linear relationship will increase as the state of the air becomes far removed from that prescribed for a perfect gas.

Whilst the air in a charge of hydraulic oil is in solution it has little effect on operation of the system, but if the pressure is reduced some of the air comes out of solution and the possibility then exists that considerable quantities of undissolved air may be entrained in the oil. Air so freed from solution is likely to be finely dispersed in the form of minute bubbles.

With a completely closed hydraulic system the quantity of air in the oil is, of course, limited to that present when the system is first charged. During operation of such a system, therefore, a cyclic effect is likely to take place whereby the same air is alternately partially liberated from solution at low pressures and dissolved again at high pressures. Although this involves limited entrainment of undissolved air, experience shows that trouble is not to be expected on this account if the system is well vented when the oil is first put into it.

Systems including an oil reservoir are usually open to the atmosphere, in that the reservoir is usually fitted with a breather. (A breather is essential where considerable differences in oil level occur.) Here again, however, adequate venting when the system is first charged should normally suffice to prevent excessive aeration of the oil, provided that : (1) the system is properly maintained and, in addition to having been provided with adequate means of initial venting, has been designed with care ; (2) the oil is able to separate readily from air, particularly to yield air from solution without excessive foaming.



550-TON TREBLE ACTION DEEP-DRAWING OIL-HYDRAULIC PRESS BUILT BY FIELDING AND PLATT LTD., GLOUCESTER

Proviso (1) refers mainly to the oil reservoir. If the oil in the reservoir is turbulent, considerable amounts of air may be drawn into the circuit by the pump. Turbulence is most likely to be caused by unsuitable arrangement of oil return leads, which should always be carried to a point well below oil level. This applies to all such leads, including those from relief valves.

The mechanism of foaming, referred to in proviso (2), resembles in some respects that of emulsification. Emulsions and foams both consist of one phase dispersed within another, and both are capable of being stabilized by the presence of substances that tend towards the interface between the one phase and the other. In foam, air is the dispersed and oil the continuous phase.

Mineral oils vary considerably in their ability to separate from air. This property is identified with ability to resist the formation of foam. Good anti-foaming properties are therefore required of hydraulic oils, and to obtain enhanced performance in this respect foam-suppressant additives are widely used.

Oxidation Stability

Resistance to chemical change is a self-evident requirement of a hydraulic medium. As applied to mineral oil this means that the oil must be of high oxidation stability.

By comparison with, say, cylinder lubrication in I.C. engines, the conditions to which hydraulic oils are subjected are not severe. Nevertheless, the oil is subjected to heating and agitation in the presence of air, which cannot be excluded completely, and metallic catalysts provided by copper and other metals of which the systems are made. Under such conditions unsuitable oils are capable of breaking down comparatively rapidly, forming soluble and insoluble degradation products. If this is allowed to happen the results may be increase in viscosity of the oil, deposition of sludge in the system, and inability of the oil to separate from water and air. Corrosive attack on the system itself by acidic products of oxidation may also occur if badly deteriorated oil is allowed to remain in use.

Suitably formulated oxidation-inhibited oils show prolonged induction periods far outlasting the service life of conventional oils.

Ability to Prevent Corrosion

Experience has shown that oils of high oxidation stability remain free from corrosive acidity for long periods. However, some quantities of moisture and air are inevitably present in the system, and rusting is liable to occur, irrespective of the condition of the oil, if ferrous surfaces of the system are exposed to moisture in the presence of air. This applies to surfaces flooded by oil, as well as those above oil level, since air is dissolved in the oil. The results of rusting are most unwelcome : apart from damage to the system through corrosive pitting and the direct action of rust as an abrasive, rust is a catalyst of oxidation of the oil. The oil, therefore, should have good metal-wetting properties, so that it can maintain a protective film over the surfaces of the system.

Incorporation of a suitable rust inhibitor in the oil can provide a reliable safeguard against rusting without detracting from other desirable properties. The value of this lies in that a high degree of refining impairs the metal-wetting ability of lubricating oil. (At one time this presented a serious problem, especially with naval turbine systems in the early stages of the Second World War.) The anti-rust additive is a chemical, added in very small quantity, which is composed of strongly polar molecules having the property of attaching themselves firmly to metal. The additive is adsorbed on the surfaces of the system and confers on the oil strong resistance to displacement by water.

Effects on Flexible Materials

Natural rubber swells and deteriorates in contact with mineral oils, and is therefore unsuitable for use in sealing units of systems with such hydraulic media, although it may be used as a compounding agent in the preparation of synthetic rubbers.

The behaviour of natural rubber at extremely low temperatures is superior to that of synthetic rubbers, but for most industrial purposes it is questionable whether natural rubber is preferable (except perhaps on grounds of availability). Sealing elements of natural rubber are nevertheless widely used in some hydraulic systems such as automotive brakes, for which it is consequently necessary to use hydraulic media other than mineral oil. Castor oil base fluids are best known for such purposes. For industrial hydraulic systems, however, the advantages of mineral oil outweight those that may attach to natural rubber, and oil-resistant synthetic rubber should be used. Suitable synthetic rubbers give excellent service in such applications.

Separation from Water

Good demulsibility, or ability to separate readily from water, is a further important requirement of a hydraulic oil. Conditions of operation of a hydraulic system are frequently conducive to condensation of moisture and accumulation of water in the oil, and sometimes the system is exposed to contamination by water present in its environment.

Unless a charge of hydraulic oil can be freed of water there is a danger of formation of a stable water-in-oil emulsion. Such an emulsion may consist almost entirely of water and good oil, stabilized by a small amount of contaminants of the system. Finely dispersed oxides and hydroxides of iron, also oil-soluble metal soaps formed through deterioration of the oil, are capable of promoting very persistent emulsions ; to maintain good demulsibility over long periods of service the oil therefore requires good chemical stability and must be able to prevent corrosion of the system.

General Viscosity Requirements

Provided the requirements considered in the foregoing notes are satisfied, industrial hydraulic oils are chosen by viscosity. A full series of oils for the purpose has to include a considerable number of grades of different viscosities.

For industrial hydrostatic systems the oils normally used cover a viscosity range from about 11.0 to 135 cs. at 100°F. Hydraulic oils of lower viscosity are generally used only for hydro-kinetic systems. Oils of higher viscosity, up to 280 cs. at 100°F., are sometimes required where operating temperatures are high.

For any specific application the viscosity chosen should represent a balance between the requirements of power transmission and those of lubrication and sealing. Efficient transmission of power is most readily obtained with light oils. Internal friction increases with the viscosity of the oil, and use of too heavy an oil is capable of resulting in severe over-heating and loss of power. On the other hand, lubrication and sealing require that hydraulic oil should be of comparatively high viscosity. In practice, choice of the oil is usually a matter of deciding on the lowest viscosity necessary for these two purposes.

Maintenance of a fluid film between surfaces moving over each other depends primarily on the viscosity of the oil, which can be regarded as a measure of its resistance to extrusion from the working clearance. Sealing also depends on the viscosity of the oil. Even with a very small clearance space, oil of too low viscosity will leak at an excessive rate. This gives rise to increased pump and motor slip, accompanied by generation of heat. Thus for both lubrication and sealing the oil requires a certain resistance to displacement under pressure. The oil must not, of course, be of too high viscosity, not only because thick oil is inferior to thin oil for power transmission, but also because oil of too high viscosity may fail as a lubricant. The danger is that heavy oil may be unable to penetrate narrow channels and spread through the working clearances quickly enough to maintain the lubricating film. Breakdown of the oil film causes severe overheating, and once the film is broken it cannot readily re-form. Ruinous wear is then liable to occur.

Viscosity and Pressure

Lubricating oils increase in viscosity as the pressure increases. The table indicates this effect in the case of four typical hydraulic oils, predominantly paraffinic in type. It will not be noted that small differences in viscosity between oils at atmospheric pressure may correspond with large differences in viscosity at high pressures.

Oils that show the greatest change in viscosity with temperature also show the greatest change in viscosity with pressure. For example, R. B. Dow (N.Y. Meeting of the Society of Rheology, 1936) showed that three oils, of Viscosity Index 103, 74 and —20 and all of kinematic viscosity of 45 cs. at 130°F. showed increase of viscosity by factors of X25, X35 and X100 respectively at 26,000 lb/sq. in. and the same temperature.

The increase in viscosity with pressure is relatively small at high temperatures but increases markedly as the temperature is reduced. The proportion by which the increase of viscosity with pressure in low V.I. oils exceeds that in oils of higher V.I. also increases as the temperature is reduced.

In most applications where oils are subjected to very high pressures between working surfaces the increase in viscosity with pressure will be counterbalanced by the opposite effect due to the development of high local temperature in the oil film. With relatively low temperatures, however, the increase in viscosity with pressure may be relatively large. As mentioned, the increase will be less in oils of higher V.I., but high V.I. oils have been found to show a sudden increase in viscosity to immeasurable magnitude when a certain pressure is reached. This critical pressure falls very rapidly with reduction in temperature and may be well below 1,000 atmospheres at temperatures under 70°F. It is possible that increase in viscosity caused by increase in pressure plays some part in the phenomenon known as ‘ hydraulic lock ’, whereby pistons, rams and so on tend to remain, after relief of high pressure, in the position at which load was last applied to them.

ABSOLUTE DYNAMIC VISCOSITY (Centipoises) at 50°C. and 100°C.

Pressure Kg/sq.cm. gauge	0		200		400		600		800	
Temperature Centigrade	50°	100°	50°	100°	50°	100°	50°	100°	50°	100°
Oil A.	7.3	2.4	10.3	3.1	14.0	4.0	18.7	5.0	25.0	6.2
Oil B.	10.4	3.0	15.1	4.1	21.0	5.5	28.9	7.1	39.0	9.4
Oil C.	17.8	4.3	28.0	5.3	40.5	7.5	58.0	10.0	80.0	13.0
Oil D.	35.8	6.7	51.4	9.0	79.0	12.4	122.0	16.3	179.0	22.0

Oil A — Absolute Kinematic Viscosity 12.5 cs. at 100°F.
Oil B — „ „ „ 19.0 cs. „ „
Oil C — „ „ „ 34.0 cs. „ „
Oil D — „ „ „ 75.0 cs. „ „

Viscosity Index and Pour Point

Mineral oils for service as hydraulic media must be of adequate viscosity at the highest temperatures of operation, and of sufficient fluidity at the lowest. If the viscosity falls too far at high temperature, the oil may fail to maintain efficient sealing of working clearances, the results being reduction of pump capacity and discharge pressure, and may fail also as a lubricant, with the result that excessive wear takes place. If the oil does not flow sufficiently freely when cold the result is liable to be cavitation, causing erratic operation of the system and overloading of the pump. Generally speaking, therefore, the oil should be of high Viscosity Index. In oils of viscosity up to about 70 cs. at 100°F., however, high Viscosity Index may be of less importance than low pour point, which in these lighter oils may have to be below —20°F.

Selection of Viscosity

The following notes refer to orthodox power-driven closed circulating systems of constant-delivery or variable-delivery type.

The requirements of the pump, which is the heart of the hydrostatic circuit, largely determine the viscosity of oil most suitable for a hydrostatic system, although the requirements of the receiver or motor, and of certain valves, must also be considered and are occasionally preponderant.

From the point of view of their viscosity requirements, hydraulic pumps in general can be classified according to the magnitude of the working clearances occupied by oil under high pressure.

Relatively large clearances are common to all reciprocating pumps with discharge valves formed by surfaces moving over each other, as in the Williams-Janney and similar pumps, which have sliding (face) valves and in pumps of the Hele-Shaw type, which have rotary (pintle) valves. Such pumps owe their special characteristics to the incorporation of sliding or rotary valves, in that they not only permit infinite variation of delivery, but are reversible and regenerative, i.e. they will deliver oil in either direction, without reversal of drive, and are capable of being driven as motors.

A disadvantage of valves of these types is, however, that slip (leakage of oil) across them becomes considerable at high pressures. To minimise valve slip it is general practice to use comparatively heavy hydraulic oils of viscosity about 70 cs. at 100°F. Oils of higher viscosity, up to about 280 cs. at 100°F., may be required for pumps operating at abnormally high temperatures. Oils of 90 to 135 cs. viscosity are frequently used in marine steering gear, with pumps of the types under consideration, where such oils are required for the main engine circulating system and it is desired to minimise the number of different grades carried on board.

Generally speaking, hydraulic oils of high viscosity are not required for pumps other than those first mentioned, except where operating temperatures are high, or the pump is heavily loaded, or where sealing is poor with lighter oils. For example, oils of relatively high viscosity may be required for heavy-duty gear pumps, to seal the clearances at the end faces and over the tips of the teeth.

By contrast with reciprocating pumps incorporating sliding or rotary valves, the high-pressure working clearances are extremely small in reciprocating pumps with seated valves. In these the valves are usually of spring-loaded ball or mushroom type, and the pistons are lapped-in to fit the cylinders without rings or packing. Diametrical clearance between piston and cylinder is normally no more than 40 micro-inches per inch diameter. In such pumps the fluid medium does not require to be of high viscosity to form an efficient seal, and oils in the viscosity range 11 to 33 cs. at 100°F. are widely used. Light-duty pumps of vane, screw and gear type can also normally run with light oils without excessive wear or sacrifice of volumetric efficiency. Oils of viscosity 33 to 70 cs. at 100°F. are commonly suitable for these.

No general rule can be laid down as to the influence of working pressure on the viscosity of oil required. A series of pumps of different types, all delivering at, say 2,000 lb/sq. in., might include units using the highest viscosity hydraulic oils and others using almost the lowest.

Components of the system other than the pump do not often have much effect on the choice of oil viscosity. Hydraulic motors present the same viscosity requirements as those of the pumps they resemble ; usually pump and motor in the same circuit are similar in design. Cylindrical receivers are not ' selective ' with respect to oil viscosity, except that there is a danger of cavitation with heavy oils during the approach stroke of large rams. It is sometimes necessary, if the use of heavy oil is unavoidable, to fit thermostatically-controlled heating and cooling coils in the filling tank, and to arrange for the oil there to be under air pressure. Heavy oils may be unsuitable unless such special provision is made for them. The design of line valves in the circuit may also have some bearing on choice of viscosity.

Larger filling and exhaust valves are generally necessary with heavy oils in large ram systems, again because of the danger of cavitation during fast travel. Another valve that may affect choice of viscosity is the flow control valve used in conjunction with constant delivery pumps. It may be necessary to use lighter oil in a system incorporating one of certain units of this type.

There is liable to be some increase in pressure of oil across a point of constriction where the oil has to increase in velocity to pass through. With a relief valve that is not fully balanced it is usual to make the maximum velocity of oil through the valve several times higher than in the line under pressure, in order to have a relatively small loaded area. In consequence such a valve may permit considerable increase in oil pressure above that at which it first opens. Where this is so, lighter oils may give rise to lower power losses if continuous discharge through the valve takes place.

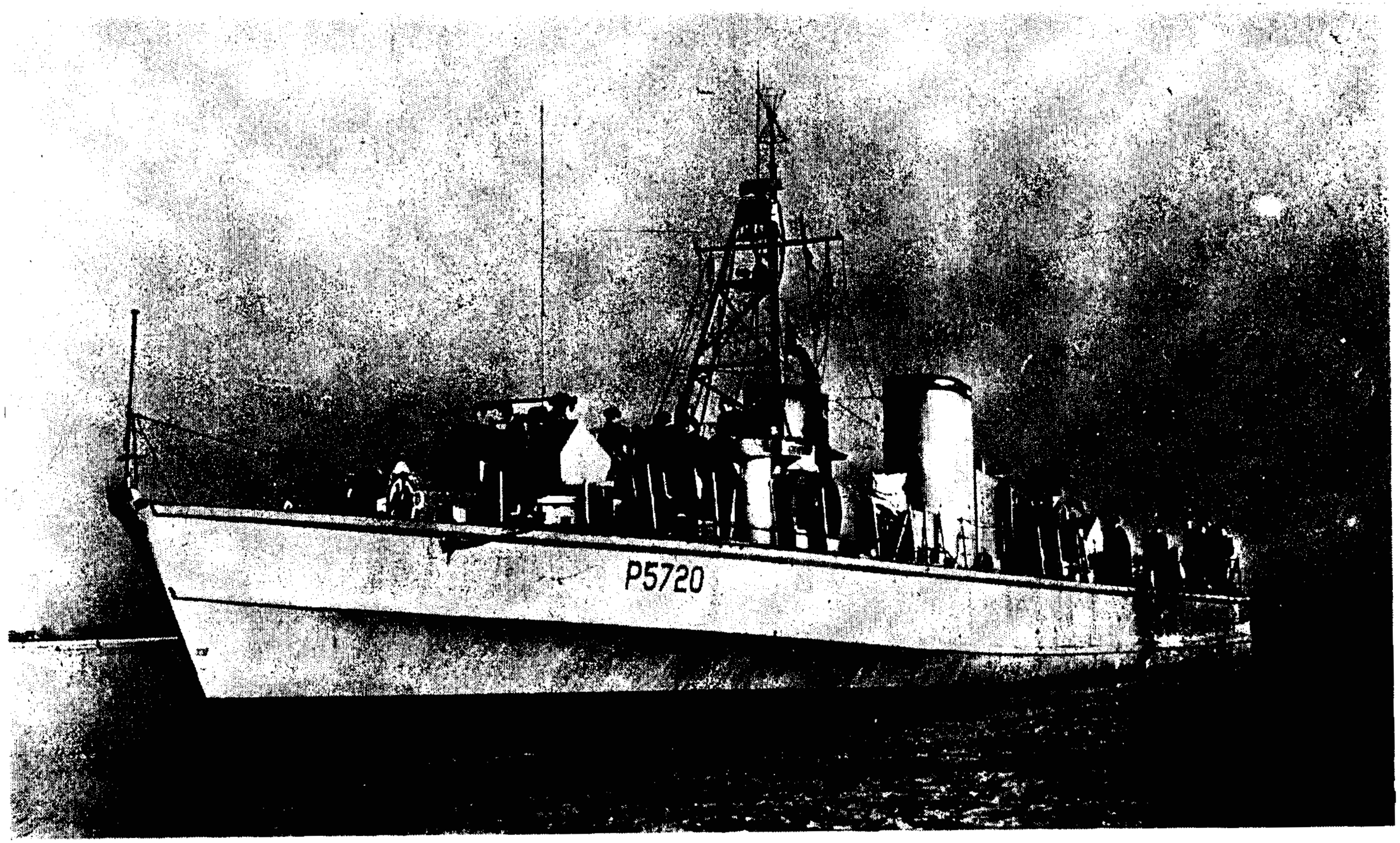
Comments by the Naval Ordnance Department

Foam Suppressant Additives. There is evidence to suggest that these can retard the separation of oil from air.

Hydraulic Lock. There appear to be two other types of this in addition to the one described by Mr. Smith. One is associated with the build-up of very small dirt particles, and may be countered by ' dither ' or by extreme filtration if these can be tolerated ; alternatively, an additional force must be provided to break the lock. The other is attributed to the annular passage between a valve and its bore being tapered in an adverse way related to the oil flow.

Correspondence in *Engineering* during 1951-2 is relevant.

Selection of Viscosity. V.S.G. machinery has operated satisfactorily in shop tests at viscosities equivalent to those which would obtain when using an oil of viscosity about 33cs. at 100°F. over a range of temperatures up to 210°F.



H.M.S. " Bold Pathfinder "