FIRE HAZARDS WITH HYDRAULIC EQUIPMENT

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Introduction

Because of its high power density, flexibility of application and arrangement, and ability to respond quickly and accurately to mechanical, electrical or manual signals, hydraulic power is widely employed for marine application. It is not surprising therefore that the design of a modern warship may involve several miles of hydraulic pipework. Intricate networks of rigid and flexible pipes interconnect power units, control devices and actuators in machinery compartments; ring mains provide hydraulic power to winches, davits, and lifts; and the transfer and handling of shells and missiles involve numerous control valves and actuators with extensive interconnecting pipework. Ships' steering, stabilization, and many other systems also rely for their operation upon hydraulic power. FIG. 1 shows the arrangement of the deck hydraulic equipment in a Type 42 destroyer.

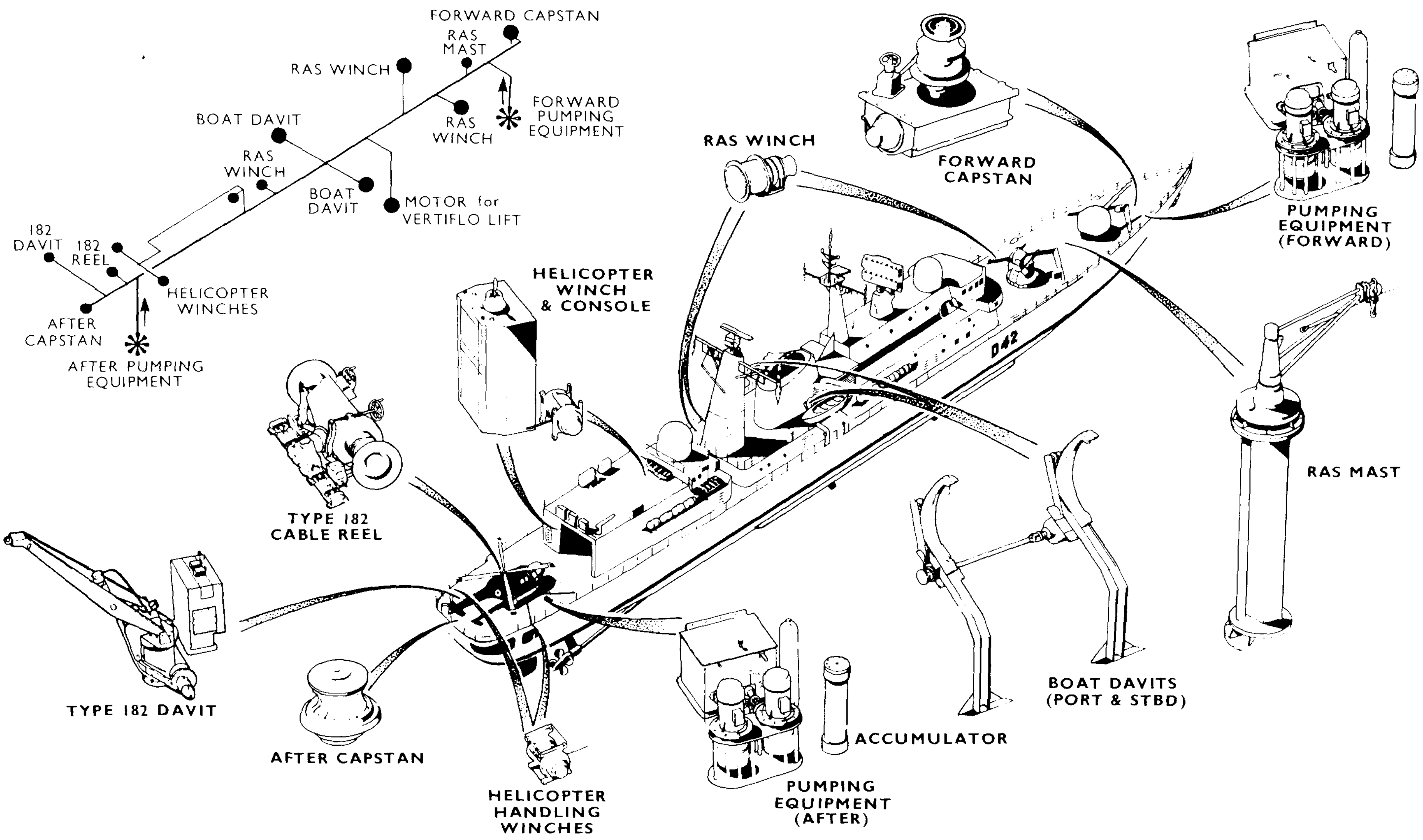

FIG. 1—TYPE 42 DECK HYDRAULICS

At the present time mineral oil fluids are used almost exclusively as the power transfer media for hydraulic systems in the fleet, the more common hydraulic oils being OM-33 in surface ships, OX-30—a mineral oil with an emulsifying additive—in submarines, and OM-15 (DTD585) in aircraft hydraulic systems. Provided these fluids are retained within their pipe systems and component envelopes they do not constitute a significant fire risk. However, because hydraulic systems operate at pressures of anything from 10 to 300 bar, and considerable numbers of pipe and component junctions are involved, which require mechanical joints to connect them together, leakage alone is an all too frequent problem, and is a considerable fire hazard. When hydraulic components or pipes are sited close to the heated surfaces of other equipments the hazard is greatly increased; fires have for example resulted from the auto-ignition of oil-soaked thermal lagging situated below leaking hydraulic fittings. Rubber hoses are also high on the list of fire hazards. In one incident an eyewitness reported seeing a fine mistlike spray escaping from little more than a pinhole in a wire braided rubber hose, which was almost instantaneously ignited upon contact with a heated surface, the resulting fire causing considerable damage.

Rubber joints, seals and hoses are likely to be the first components of a hydraulic system to fail in the event of fire. Simple laboratory tests carried out using a gas burner to raise the surface temperature of a pressurized pipe and coupling arrangement to between 400 and 500°C indicate that the endurance of a coupling employing a circumferential rubber 'O'-ring seal is likely to be of the order of 10 minutes and that, when the seal eventually fails, fluid will be ejected as a jet or spray from around the peripheral clearance between pipe and union nut. Similar fire tests, on the types of hoses commonly used, indicate that failure is likely to occur even more rapidly than with pipe couplings.

Smoke and fumes from oil fires are further serious hazards. In the hose incident outlined, the fire was accompanied by a considerable amount of smoke and several naval personnel in the area were overcome by fumes and required medical attention. Besides their combustible nature, rubber hoses pose other potentially serious problems. Unlike rigid metal pipework, rubber hoses age, the quality and performance deteriorate significantly with time, and in most naval hydraulic applications hoses need to be replaced after a life of 5 years.

An Assessment of the Fire Hazard

Perhaps understandably in peacetime fires occur more frequently in ships building or undergoing refit than in operational warships. The initiating causes are various but usually stem from tasks and activities that would not normally be carried out on an operational ship, such as welding, temporary wiring, disconnection of equipment, bulk handling of oil and other flammable liquids, the presence of spilt oil and flammable debris, etc.

Under more hostile conditions, shock and explosions may displace pipework and components, leading to the discharge of hydraulic fluid and, because many systems store fluid in gas-pressurized accumulators, ejection is likely to be the form of a sustained jet or spray. With this combination of circumstances, a minor and relatively easily contained fire resulting from enemy attack could therefore rapidly escalate into something far more serious and difficult to control.

Fires and fumes are not the only hazards likely to arise from the use of mineral oil. Should oil escape into the gas side of an air-charged accumulator, detonation due to compression of the mixture can and has occurred. Most systems are changing over to nitrogen as the gas, but this does involve finding additional space for nitrogen storage.

The relative significance of the fire hazard associated with a particular hydraulic system is dependent upon a great many factors, including equipment location in the ship, fluid capacity (particularly the pressurized reserve fluid), the amount of rigid and flexible pipework, state of maintenance, adjacent equipments, etc. It is possible therefore that any of the following occurrences could give rise to appreciable fire hazards, particularly under action conditions when the chances of such events occurring simultaneously and at numerous locataions are likely to be high:

(*a*) The fracture or displacement of couplings and metal pipework due to shock or direct damage.
(*b*) Rupture or perforation of rubber hoses and end fittings.
(*c*) The presence of 'leakage' hydraulic oil from couplings and other components.
(*d*) Failure of elastomeric seals and rubber hoses due to heat or fire from secondary sources.
(*e*) Damage to the structure or sealing of other hydraulic components, particularly hydraulic accumulators and reservoirs.

Reducing Risks by Better Design and Maintenance

It is possible to reduce many of the fire hazards associated with existing mineral oil hydraulic systems, without materially altering the design. Examples of how this can be achieved are:

(*a*) Greater care and attention to the assembly of couplings, seals, joints etc. Damage to pipe surfaces or 'O'-rings, or coupling malassembly is usually not apparent until a system has been assembled and pressurized, and is therefore difficult and costly to rectify.
(*b*) Replacement of rubber hoses at recommended intervals of time, ensuring that new hoses are correctly fitted, free from torsional and linear stresses, without sharp bends, sited well clear of heat sources and other potential hazards, and regularly inspected for signs of damage or failure.
(*c*) Tightening up of maintenance procedures to minimize oil spillage.
(*d*) Fitting of muffs, shrouds, deflectors, traps, etc. to prevent fluid from coming into contact with heated surfaces, lagging materials etc.

Attention to the above will certainly prevent excess fluid leakage, with its consequential fire hazard. Recommendations (*a*), (*b*), and (*c*) can be extremely cost-effective, reducing not only the fire risk but improving reliability and performance generally. Effectiveness is however dependent upon good documentation and inspection procedures, together with the education and co-operation of the personnel involved. Recommendation (*d*) can be very effective in reducing fire hazards in older design systems, but involves considerable cost and installation time, and makes further demands upon maintenance staff.

If, however, some redesign is permitted, the integrity of the mineral oil system can be much further improved, for example by:

(*a*) Employing small self-contained hydraulic package units rather than ring main systems in surface ships.
(*b*) Reducing the number of breakable couplings by butt or sleeve welding, or by the use of pipe couplings which are cryogenically expanded before fitting.
(*c*) Employing welded-in cartridge type valve bodies.
(*d*) Limiting the use of rubber hoses to essential applications only, viz isolation of movement, shock, and noise.

(*e*) Fitting flow-fuses in the branches of ring main systems to shut off the flow of fluid in the event of pipe rupture.

(*f*) Making the maximum use of ship's structure to shield and protect pipework and fluid reservoirs.

(*g*) Routeing pipework clear of hazardous areas, e.g. running pipework as far as possible within frames, on the inboard side of upper deck bulkheads and on the underside of upperdecks, and keeping hydraulic pipework well clear of steam and other 'hot' equipments, etc.

(*h*) Fitting fluid level gauges with heat-resisting glass and push button spring-loaded valves to prevent excape of fluid in the event of glass failure.

Extensive system redesign is usually costly; however it is often possible to introduce many of the above proposals into later build of an existing design without greatly increasing costs.

It is of course impossible to guarantee completely effective hydraulic fluid containment, particularly in a warship under hostile conditions, with the ever-present possibility of structural damage and fire through enemy action. Nevertheless, attention to the above will undoubtedly reduce the spread of fires in areas where structural damage is less serious.

The Use of Fire-Resistant Hydraulic Fluids

Having accepted that it will be impossible to prevent excapes of hydraulic fluid under certain circumstances, it is apparent that the resulting hazard could be reduced if a fluid less flammable than a mineral oil were used. Water is one of the very few non-flammable fluids but, unfortunately, disadvantages such as its poor lubricating properties and high freezing point make it unacceptable for R.N. use. A number of so-called 'fire-resistant' hydraulic fluids are available commercially. They will all burn under certain conditions, but are less flammable that mineral oils. They are normally classified in four main groups:

(*a*) *Dilute emulsions* contain about 95% water with 5% soluble oil/additives to assist lubrication, corrosion protection, etc. They offer very good fire resistance but are poor lubricants, only suitable for lightly loaded, low-pressure hydraulic systems. They cannot be used below 0°C.

(*b*) *Invert emulsions* contain about 40% water dispersed in 60% oil. They offer the best lubricating properties of the water-containing fluids (but are significantly poorer than mineral oils). Their fire resistance is marginal and they cannot be used below about −10°C.

(*c*) *Aqueous polyglycols* contain some 40% water, the remainder being a mixture of glycols and polyglycols to give the required viscosity. Their lubricating ability is generally slightly poorer than the invert emulsions, but they can offer better fire resistance (particularly in the spray ignition hazard) and have good low temperature performance.

(*d*) *Synthetic fluids* (e.g. phosphate esters) have lubricating properties which are similar to mineral oils. The degree of fire resistance depends on chemical composition but many fluids will burn and some can produce toxic products of combustion. Generally, they are not compatible with standard elastomers, paints, plastics, etc.

It is immediately evident that none of the fire-resistant fluids currently available is going to offer a significant reduction in fire hazard without introducing several undesirable side effects. For several years the Naval Petroleum and Technology Division of RAE has been evaluating the various fluids available, either as a replacement hydraulic fluid for existing systems or as a fluid to be specified for future ship designs. A full report of the work has been published elsewhere[1]. The dilute emulsions were rapidly eliminated, since they would be completely inadequate for the more compact, high-performance hydraulic equipments required for R.N. service, and because they had inadequate low temperature performance. The synthetic fluids could not be used as a replacement fluid in existing systems because of material compatibility problems; even in new designs, material compatibility would impose design constraints. Furthermore the fluids present a greater health hazard than mineral oils which, in view of the inevitable leaks, would be undesirable. Finally, the fluids when heated or burnt produce copious acrid fumes which in some cases are toxic and would make damage control in the confined spaces of warships extremely difficult. Consequently, this class of fluid was also excluded from further investigations. A number of invert emulsions were examined but all suffered from poor low temperature performance. This, together with their limited fire resistance and some doubts about long-term emulsion stability, eliminated them. Thus the aqueous polyglycols were left. All the commercially available products tested proved incompatible with sea water, forming varying quantities of precipitate. However, one company developed a product which was sea water compatible and met all the other essential requirements. This has been selected for use in future R.N. hydraulic systems and designated 200-X. It will reduce the fire hazard substantially in the spray ignition situation. However, in conditions where the water can evaporate (for example, a leak on to unprotected lagging) it offers no advantage over mineral oils, so it is important to design the hydraulic systems with this limitation in mind.

The Performance of Components and Systems with Fire-Resistant Fluids

A number of different fire-resistant fluids have been evaluated but this paper will concentrate on the aqeous polyglycol (200-X), making comparison with the mineral oil hydraulic fluids OM-33 and OX-30 were appropriate.

Basic Fluid Properties

The viscosity of 200-X varies less with temperature than mineral oils (see TABLE I) so that its low temperature performance is good. Normally it should not be used at temperatures greater than 60°C because of the risk of evaporation of the water. Unfortunately, unlike mineral oils, the viscosity

TABLE I—*Viscosity/Temperature Characteristics*

Fluid Properties	*Mineral oils*		*Polyglycol*
	OM-33	OX-30	200-X
Viscosity (mm^2/sec) at 40°C at 0°C max	26/33 500	26/30 630	35/40 300
Pour Point (°C max)	−30	−30	−50 Typical

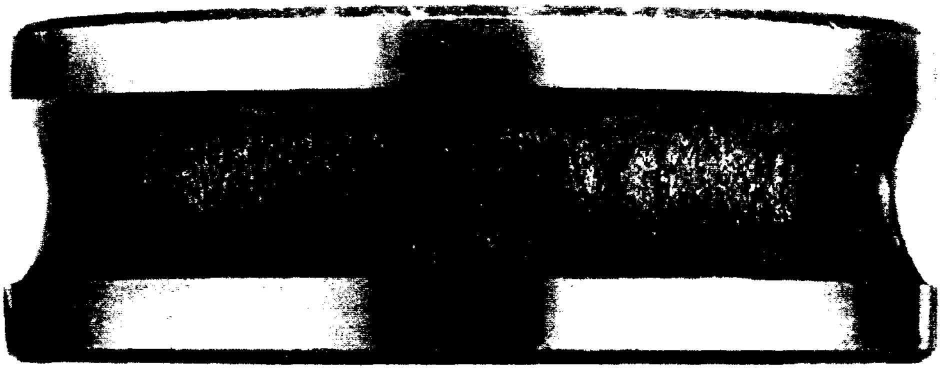

FIG. 2—FAILED ROLLING CONTACT BEARING, SHOWING DAMAGE TO INNER TRACK

of 200-X does not increase rapidly with pressure; consequently components which rely on elastohydrodynamic lubrication to separate the surfaces are likely to present lubrication problems. Rolling contact bearings are an obvious example (FIG. 2) and the problems are exacerbated by the presence of water in 200-X, since this produces a dramatic further reduction in fatigue life. Extensive laboratory testing has demonstrated the difference in performance between 200-X and the mineral oils (FIG. 3). The graph uses the C/P ratio as the indicator of severity, since this figure is available from bearing catalogues; C is the dynamic capacity of the bearing and P the applied load. Sliding contacts operating under boundary lubrication (i.e. with significant metal-to-metal contact) are likely to suffer from increased wear rates with 200-X although its performance with phosphor bronze sliding against En 31 steel appears exceptionally good.[2]

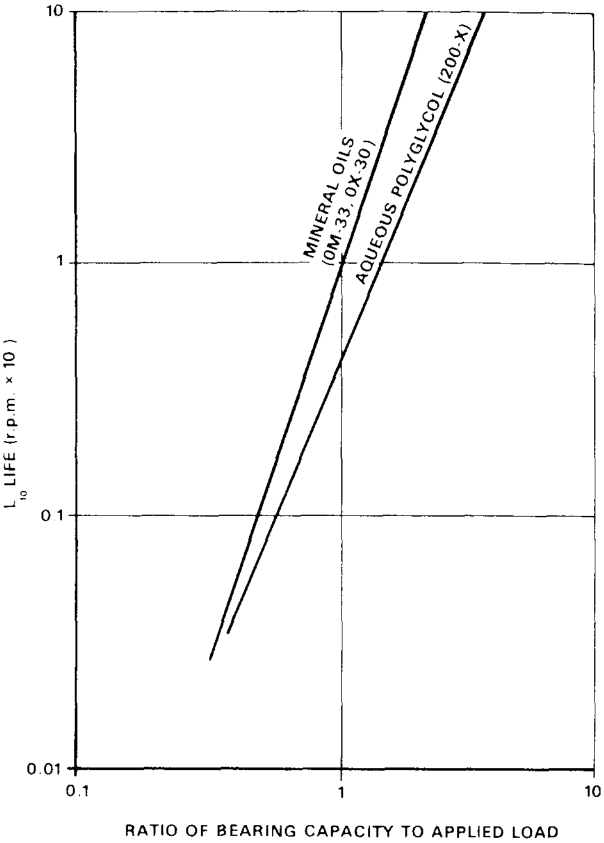

FIG. 3—ROLLING CONTACT BEARING LIFE IN TESTS USING OM-33, OX-30, AND 200-X

200-X contains corrosion inhibitors which will protect most of the materials commonly used in hydraulic systems. However, aqueous polyglycol fluids will attack the light metals (e.g. zinc, cadmium, non-anodized aluminium) so these should be avoided[3]. 200-X can accept up to 10% sea water without forming precipitates but, under these conditions, wear rates and rolling contact fatigue lives are likely to be adversely affected. The fluid is denser than mineral oils and so pump suction requirements are more critical. Bulk modulus and thermal conductivity are higher than for mineral oils, so the systems are expected to be more responsive, compressibility losses are reduced, and systems tend to run cooler.

Pumps

Several vane, gear, and piston pumps have been endurance tested with the new polyglycol fluid 200-X, and to date over 35 000 hours running of pumps up to 75 kW have been accumulated[4]. The problems encountered have very broadly been proportional to the design complexity of the pump. Vane and gear pumps have presented fewer problems than piston pumps, bearings have predictably[5] been the cause for most concern, and plain journals endure better than rolling contact bearings. There have also been small areas of cavitation near valve ports (FIG. 4), fretting of some keys and splines, and some minor problems with springs. It is apparent from this work and reports of the work of other organizations, such as National Coal Board, British Steel Corporation, and some oil companies[6], that some pumps are much better suited to operation with water-based fluids than others, and that selection does not fall simply into pump type categories. Experience has demonstrated that for many pumps it is necessary to derate the performance in terms of speed and pressure in order to achieve an acceptable life.

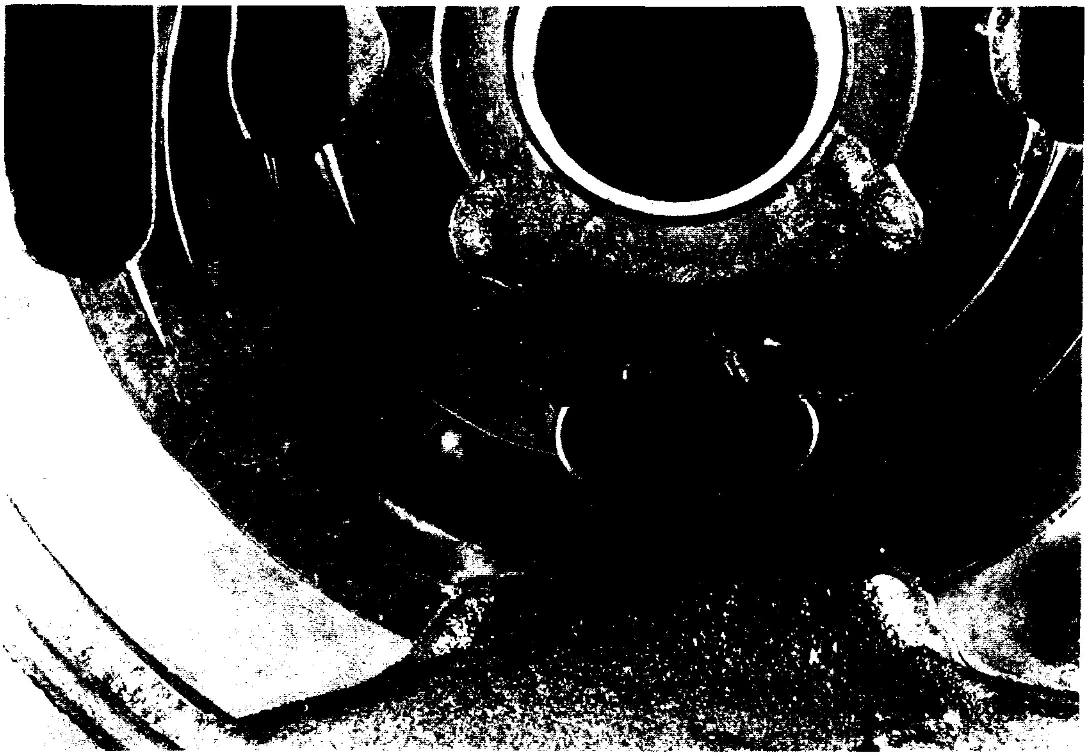

FIG. 4—Axial piston pump, showing cavitation near valve ports

Valves and Motors

To date very little experimental work has been carried out on the performance of hydraulic valves and motors with polyglycol fluids. From investigations made by other organizations, chiefly on emulsions[7], material selection appears to be fairly critical if erosion of spool and poppet valve lands is to be avoided. Lubrication problems, similar to those encountered in the pump tests with 200-X, are also anticipated with hydraulic motors, particularly under conditions of high torque and low speed. Over the next 12 months it is intended to determine the extent of these problems and the need for derating, on purpose-built rigs.

Contamination Monitoring

The reliability of hydraulic equipment is very dependent upon the monitoring and control of contamination. The standard Comparison Microscope procedure has not been successful with 200-X. A very high pressure differential is developed across the 0.8 μm membrane filter which causes the backing pad to collapse, effectively shutting off flow. The sampling kit is currently being modified to limit the pressure build-up over the membrane when sampling from a high pressure system.

Problems have also been experienced with automatic particle counting when using a light blockage type sensor, a technique which is now standard for filter performance assessment. Three sample preparation techniques have been tried in order to reduce the viscosity to acceptable levels for the sensor and to improve the air release characteristics so as to avoid false counts[8].

Filtration of Polyglycols

Associated with the contamination measurement problem is the need to examine the performance of hydraulic filters with 200-X. A large number of filters has been evaluated jointly with the National Coal Board, all the work to date having been carried out with mineral oils. Work is now in hand to compare the filter efficiencies and pressure drop/flow results, with identical tests on selected filters using 200-X. The hot soak test will be used to assess material compatibility with this fluid. The difficulties experienced with 0·8 and 5 μm membrane filters used for sampling could indicate that problems may be encountered with fine (less than 5 μm) filters. The filters employed in the pump test rigs have given satisfactory service over the several years they have been in use; the elements are resin-bonded paper material of 15 μm nominal efficiency, and are changed at normal intervals.

Conclusion

A measure of equipment performance, with a fire-resistant fluid can be obtained over a few hours of laboratory testing. Reliability prediction however needs to be evaluated over much longer periods; pumps for example ideally need to be tested under realistic operating conditions in the laboratory for several thousand hours. A considerable amount of data exists from equipment manufacturers and large user organizations such as the National Coal Board, regarding the performance of hydraulic components with oil/water emulsion, but there has been little incentive for industry in the U.K. to carry out similar work with water-glycol hydraulic fluids. The Ministry of Defence test programme is therefore necessarily lengthy, involving not only component performance and reliability, but a wide range of other more fundamental aspects such as the tribology of bearings, contamination measurement, filter performance, and other specialized and often contentious areas.

Because of the extensive component investigation programme, the material compatibility problems, and the considerable difficulty of completely removing all traces of the original mineral oil fluid, the most expedient and cost-effective means of improving the fire resistance of existing designs of warship hydraulic systems, is along the paths of better design and maintenance. New design of hydraulic systems allows both the time and the scope for the use of an aqueous polyglycol fluid. Material incompatibilities can be avoided, components can be selected on the basis of realistic laboratory testing, and techniques can be developed for monitoring and maintaining such systems in service.

The incidence of fires in R.N. ships during peacetime is fortunately very low. However, in those cases where pressurized oil systems have been involved, the consequences have usually been serious, the fires being extensive and difficult to control and fumes from the ignited fluid a further hazard. Recent events in the Falklands have dramatically highlighted the catastrophic effects of fire and structural damage to warships under hostile conditions. The additional fire hazard posed by the presence of any pressurized combustible fluid will therefore be considerable. Hydraulic systems are no exception and, even with the best design features, will continue to be an appreciable fire hazard while mineral oil remains as the working fluid.

The introduction of the aqueous polyglycol fire-resistant fluid 200-X can reduce the fire hazard most significantly under these conditions. The penalty paid for this reduction in fire hazard is a fluid with poorer lubricating qualities, which ultimately means the need to derate sensitive fluid power components in terms of pressure and speed. Optimizing the relationship between the derating factor and equipment reliability is the prime aim of the current work.

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References

1. Eastaugh, P. R., Holness, M. H., and Collis, R. G.: Hydraulic fluids for Royal Navy Systems; *Conference on Hydraulic Engineering in the Fleet,* R.N.E.C., Manadon, 1982.
2. Onions, R. A.: An Investigation into the possibility of using fire-resistant hydraulic fluids for Royal Naval systems; *Institute of Petroleum International Symposium on Performance Testing of Hydraulic fluids,* London, 1978, pp. 439–458.
3. Blanpain, G.: The Use of polyglycols in French coal mines; *Institute of Petroleum International Symposium on Performance Testing of Hydraulic Fluids,* London, 1978, pp. 389–403.
4. Hargreaves, M. R. O., Newman, M. J., and Pearce, J.: MOD(Navy) pump and filter testing; *Conference on Hydraulic Engineering in the Fleet,* R.N.E.C., Manadon, 1982.
5. Kenny, P., Smith, J. D., and March, C. N.: The fatigue life of ball bearings when used with fire-resistant hydraulic fluids; *Institute of Petroleum International Symposium on Performance Testing of Hydraulic Fluids,* London, 1978, pp. 495–519.
6. Dalibert, A.: Fire-resistant hydraulic fluids; *British Hydrodynamics Research Association, Proc. 2nd Fluid Power Symposium,* 1971, pp. F3-29–F3-44.
7. Kelly, E. S.: Erosive wear of hydraulic valves operating with fire-resistant emulsions; *British Hydrodynamics Research Association, Proc. 2nd Fluid Power Symposium,* 1971, pp. F4-45–F4-63.
8. Tsai, C. P.: Particle counting in water based fluids using light blocking type automatic instrument; *British Hydrodynamics Research Association, 6th International Fluid Power Symposium,* 1981, pp. 87–94.
9. Jones, H. J.: Hydraulic systems—reduction of fire hazard; *Journal of Naval Engineering,* vol. 25, no. 1, June 1979, pp. 69-75.