Selection of a Fire-resistant Fluid for Hydraulic Systems in Royal Navy Ships

Captain R. N. M. Paige LVO, BSc, RN
Procurement Executive, Ministry of Defence

SYNOPSIS

In the mid-1970s the Royal Navy decided to examine the possibility of reducing the fire risk in ships by replacing the flammable mineral oil in hydraulic circuits by a fire-resistant fluid. The approach is described whereby the special requirements of the fluid for RN use were analysed, the properties of the various possible fluids were examined and the choice of an aqueous polyglycol was made. Having selected the fluid certain properties required closer attention, or refinement through additives, in order to cover such things as contamination by sea water (which is particularly relevant to submarines), material compatibility, component preservation, contamination control etc. Some properties such as lubrication are inherently worse than those of mineral oils and are dealt with in more detail, including a description of the associated extensive trials programmes which aim to establish, inter alia, which type of typical hydraulic components are best suited to the new fluid and to prove their endurance. Although the programme is not complete, some equipment has satisfactorily undergone over 5000 h at 207 bar and no insurmountable problems have been identified. Some aspects such as the means of contamination control are not yet fully resolved. The aqueous polyglycol fluid is now specified for all hydraulic systems in the new Type 23 *Frigate.*

INTRODUCTION

Oils and fuel have been second only to electrical equipment in being the most common source of ship-board fires in peacetime and they are the most likely cause of the fire developing into a major incident. The heat from fires may cause expensive damage to equipment and fittings but more importantly the smoke and fumes are a hazard to personnel and can greatly increase the scale of the incident by creating serious containment and fire-fighting problems.

Hydraulic oils and systems are particularly hazardous because of the comparatively low spontaneous ignition temperature of the oil and the high system pressures, which can lead to the formation of fine droplets or atomised oil over a wide area adjacent to a system. A pin-hole in a pipe containing oil at 207 bar (the normal operating pressure) can cause a jet which will travel many metres. The hydraulic system also has inherent weaknesses because of the vulnerability of such components as coupling 'O' seals and flexible hoses, both of which have life limitations and are unavoidable features, particularly in naval applications where shock and noise considerations play an important part.

In the mid-1970s the Royal Navy (RN) took note of the growing interest in fire-resistant fluids and, bearing in mind the obvious advantages, decided to investigate their possible use in warships. Drawing on the experience of the French coal mining industry and the National Coal Board in particular, together with unsuccessful attempts to introduce an aqueous polyglycol into submarine systems, an extensive research and development programme was put in hand. This has now developed to the stage where a fire-resistant fluid is specified for all hydraulic systems in the new *Type 23* Frigate.

BACKGROUND

The RN has traditionally used a mineral oil designated OM33 for surface applications. In submarines a variant of this designated OX30 is used, containing an emulsifying additive that tolerates some contamination by sea water, and in aircraft applications the oil is designated OM15 (DTD 585). What makes these mineral-based oils particularly attractive are their good lubricating properties, their ready availability and their moderate cost. As mentioned already, their disadvantage is their flammability.

Captain Paige was awarded a BSc degree in Engineering by the Royal Naval Engineering College in 1964 and completed the Naval Advanced Marine Engineering Course in 1968. He joined the Procurement Executive as Assistant Director in charge of Mechanical Handling Systems and Machinery in November 1984. His responsibilities include the policy for hydraulic systems in both surface ships and submarines.

Fires may develop in a number of ways:

1. The fracture of a joint, pipe or casing, probably caused by shock or direct damage.
2. The failure of a coupling. Although much emphasis is placed nowadays upon eliminating couplings from systems, some will always be necessary. In less accessible areas these will be of the swaged or cryogenic type, but dismantlable couplings with 'O' rings will be required elsewhere. The 'O' ring is the weak link not only because it can fail to form a satisfactory seal in certain circumstances but also because in a fire it will eventually melt. A simple laboratory test using a gas burner on a screw coupling has demonstrated that failure will occur after about 10 min at 400–500 °C. It is readily apparent that a hydraulic system adjacent to a fire poses a real hazard and can be the cause of a major escalation of the incident.
3. The failure of flexible hoses. Again these hoses cannot be avoided in most hydraulic systems and certainly not where shock and noise considerations are important. They have

limited lives depending upon the application and environment and they may be particularly vulnerable to damage.

Although fluid may escape from any of the above sources the story does not end there. If the fluid is under pressure and there is an ignition source within the spray area, then instantaneous ignition may occur, but an equally dangerous situation can arise if there is an absorbent material such as lagging near by. This can become soaked and then subsequently, perhaps even when the hydraulic system is closed down, it can become heated above its spontaneous ignition temperature and ignite. Even if this is avoided, one's luck can run out later when hot oil is exposed to the atmosphere whilst attempts are being made to remove the soaked materials. The fires that result will produce vast quantities of smoke which greatly exacerbate the difficulties of extinction and quickly lead to an escalation of the incident, particularly in the close confines of a ship. There was a vivid reminder of this during the Falklands war, when hydraulic fluids from a breeched system fed fires on at least two occasions.

The RN is now firmly persuaded of the desirability of employing a non-flammable or fire-resistant fluid in hydraulic systems. However, for a fluid that will be used at sea, both in the close confines of the ship and when exposed to the elements on the upper deck, there are other properties that are also important:

- Freezing point. In the most hazardous conditions experienced by exposed equipment on the upper deck the fluid will need to remain stable down to very low temperatures. (both OM33 and OX30 have pour points of −30 °C.)
- Toxicity. The fluid should not contain any toxic elements nor should it produce toxic fumes when it burns.
- Lubricity. Equipment operating with the fluid must exhibit satisfactory endurance so that the mean time between failures (MTBFs) remains acceptable.
- Miscibility with sea water. This applies in particular to submarine systems, some of which operate outside of the pressure hull. The fluid should form emulsions with sea water to such an extent that a dilution of at least 10% can be accommodated.
- Corrosion protection. Some means must be provided for giving corrosion protection to equipment that is empty either before or after fitting in a system. If the fire-resistant fluid itself does not contain the necessary properties then a separate preservative fluid must be provided. This fluid must be compatible with both the testing fluid that the manufacturer uses (probably a mineral oil) and the fire-resistant fluid.
- Material compatibility. The fluid must be compatible with all materials that will be found in hydraulic systems such as pipework, couplings, seals etc.
- Maximum operating temperature. The fluid must be capable of operating satisfactorily at the maximum possible system temperature without being degraded.
- Contamination control. It must be possible to control the contamination levels in the system both by detection and by filtration.
- Cost. The through-life cost of any option must be taken into account.

At this stage it is interesting to note that if the British Steel Corporation were to draw up a similar list of requirements a different picture might emerge. For instance, they would probably have no requirement for any miscibility with sea water, toxicity would be less important because of the vast spaces that normally surround the equipment, low operating temperatures would be of little concern and cost would be a more prominent factor in the equation because of the quantity of fluid contained in the long runs of pipework. This demonstrates that each application must be looked at in its own right and it explains why the RN would not be able to rely solely upon the experience and knowledge built up in areas such as the coal and steel industries.

CHOICE OF FLUID

The choice of fluid is made from four main options:

1. Dilute emulsions. These contain about 95% water and 5% soluble oil/additives to assist lubrication, corrosion protection etc. They offer very good fire resistance but are poor lubricants and therefore they are more suitable for lightly loaded low-pressure conventional hydraulic systems. They cannot be used below 0 °C but they are relatively inexpensive.
2. Invert emulsions. These 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 slight and they cannot be used below about −10 °C. The cost is about one and a half times that of mineral oil.
3. Aqueous polyglycols. These contain about 40% water, the remainder being a mixture of glycols and polyglycols to give the required viscosity, and also additives to improve wear and corrosion resistance. Their lubricating properties are generally slightly poorer than those of the invert emulsions but they offer much better fire resistance (particularly in the spray ignition hazard) and have very good low-temperature properties. The cost is about three times that of mineral oil.
4. Synthetic fluids (eg phosphate esters). These can have lubricating properties which are similar to those of mineral oils. The degree of fire resistance depends upon the chemical composition, although commonly they will burn with difficulty but produce smoke and toxic products of combustion. They tend to be unpleasant to handle and they are not compatible with many standard elastomers, paints, plastics etc. The cost is some six times that of mineral oil.

None of the options offers the ideal solution but after some careful analysis at the Royal Aircraft Establishment the most

Table I: Variation of viscosity with temperature

	Mineral oils		*Polyglycol*
Fluid Properties	OM33	OX30	200X
Viscosity (mm^2/s)			
at 40°C	26/33	26/30	35/40
at 0°C max.	500	630	300
Pour point (°C max.)	−30	−30	−50 (typical)

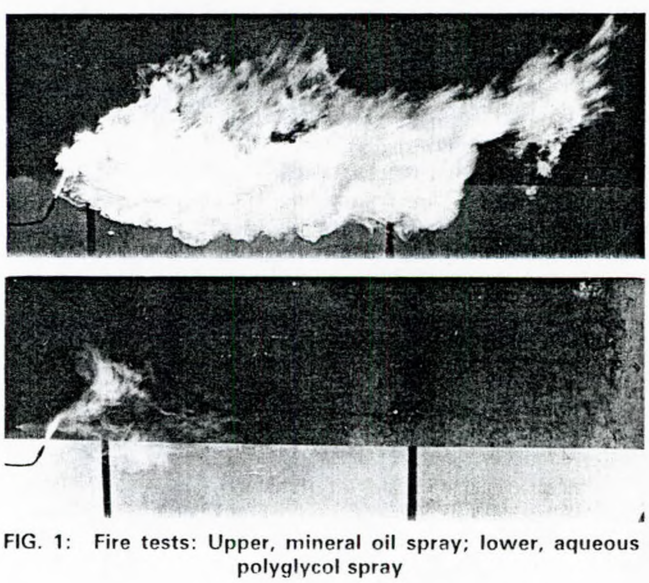

FIG. 1: Fire tests: Upper, mineral oil spray; lower, aqueous polyglycol spray

promising candidate for RN use was eventually selected. The dilute emulsions were soon eliminated because of the relatively high freezing temperature. In the same way the synthetic fluids were finally regarded as unsuitable because of the undesirable toxic properties, the incompatibility with certain materials that are in common use in RN hydraulic systems and the costs. It is not possible to eliminate the materials problem because it is necessary to employ certain flexible elastomers in such things as joints to cater for the special environmental and operational conditions that are experienced in naval applications, eg vibration.

This left invert emulsions and the polyglycols. The former offered only a marginal improvement in fire resistance over mineral oil at the expense of a poor low-temperature performance and so they were eliminated in preference to the aqueous polyglycols, which seemed to provide the optimum compromise. The fluid that was selected has been designated HS 200X.

Aqueous polyglycols (HS 200X)

A number of trials have been conducted to ascertain the detailed properties of the aqueous polyglycols, to identify possible additive improvements for RN applications and to examine the effect its use will have on the performance, reliability, preservation etc. of hydraulic systems and equipment. The programme of work continues but much has already been learnt about the fluid's special features.

Toxicity

Some of the water + glycol fluids are potentially carcinogenic since the nitrite and amines present tend to combine to form nitrosamines. In the fluid destined for use in the RN (HS 200X) the nitrite additive has been removed so no toxic problems are anticipated. The fluorescent dye that is added to give the fluid its distinctive colour is present in all common aqueous polyglycols and is also safe in this respect.

Maximum temperature limitation

Above about 60 +C the water will start to evaporate off if allowed to, causing the dilution of the glycol to reduce and its properties to change. In particular it becomes more flammable and therefore its main advantage is eroded. Means of combating this feature are discussed later. This raises a cautionary note: if a system develops a slow leak on to hot absorbent material such as lagging, then the water will evaporate off leaving neat glycol, which is just as flammable as mineral oil (Fig. 1).

Viscosity

Above operating temperatures of about 40 °C it has a similar viscosity to mineral oils but its variation with both temperature (Table I) and pressure is less. The effects of this are two-fold. First, systems will be easier and quicker to start from cold than with mineral oils because of the relatively low viscosity at low temperatures (usually this affect will be insignificant) and, secondly, the comparatively low viscosity at high pressures, such as experienced in certain elasto-hydrodynamic bearing applications, leads to poorer lubrication and therefore higher wear.

This latter feature is one of the main disadvantages of the aqueous polyglycols and is a major cause for the fairly extensive equipment trials programme that is now underway.

Lubricating properties

The effect of the viscosity characteristic on the lubricating properties has already been mentioned but the aqueous polyglycol is also a relatively poor lubricant in its own right. Laboratory tests have indicated that wear in sliding contact will depend significantly on the mating materials, and the results suggest that while steel on steel gives very high rates of wear, steel on phosphor bronze produces less wear than with mineral oil (Figs 2 and 3). This is a surprising result and could possibly be used to advantage in future equipment designs.

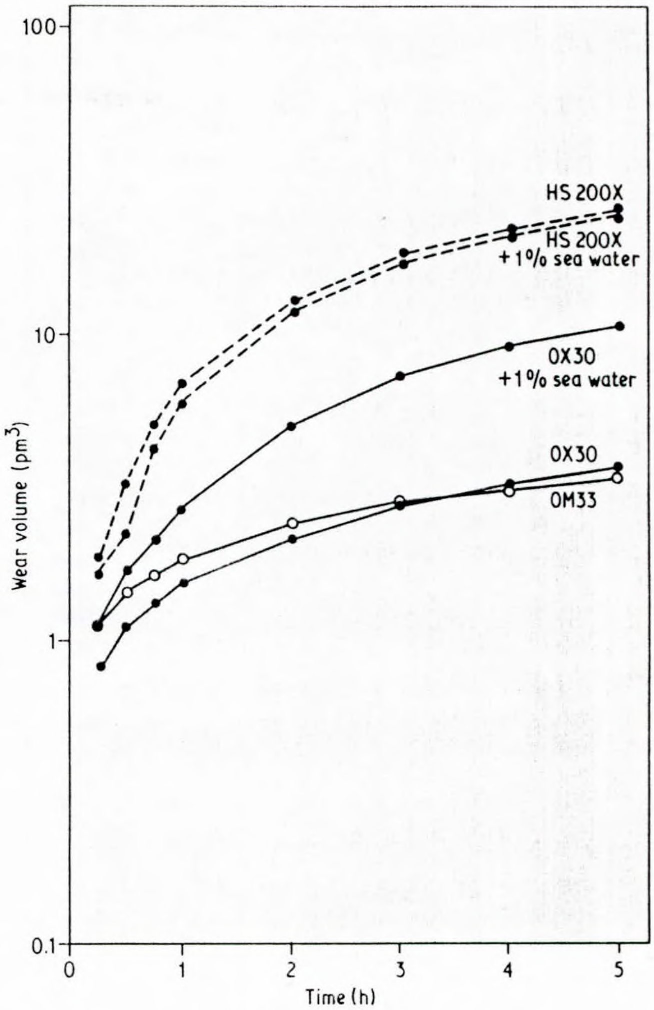

FIG. 2: Wear test, steel on steel

Tests have also been conducted to examine the effect of HS 200X on the fatigue life of rolling contact bearings. Again the achieved lives are found to be significantly worse than with conventional mineral hydraulic oils and there is no marked improvement in life with reduced load. The plot in Fig. 4 uses the C/P ratio as an indicator of severity since its value is available from catalogues: C is the dynamic capacity of the bearing and P is the applied load. Taken on their own these laboratory results give cause for concern, but equipment tests to date have been encouraging and suggest that current designs tend to have an ample built-in safety margin.

Miscibility with sea water

The earlier brands of aqueous polyglycols, which have been used extensively in the USA and in the early RN nuclear submarines, suffer from a few disadvantages, one being the formation of a precipitate when salt water is present. By using suitable additives this can be avoided and fluids can be formulated that will be completely miscible with sea water up to a 50 + 50 mixture. As explained earlier, this is particularly important in submarines. If possible such dilution will normally be avoided because it tends to have a detrimental effect on the lubricating properties of the fluid.

Compatibility with materials

Polyglycol-based fluids are liable to attack metals such as magnesium, aluminium, zinc and cadmium, mainly because of the water present and particularly when the pH value is high.

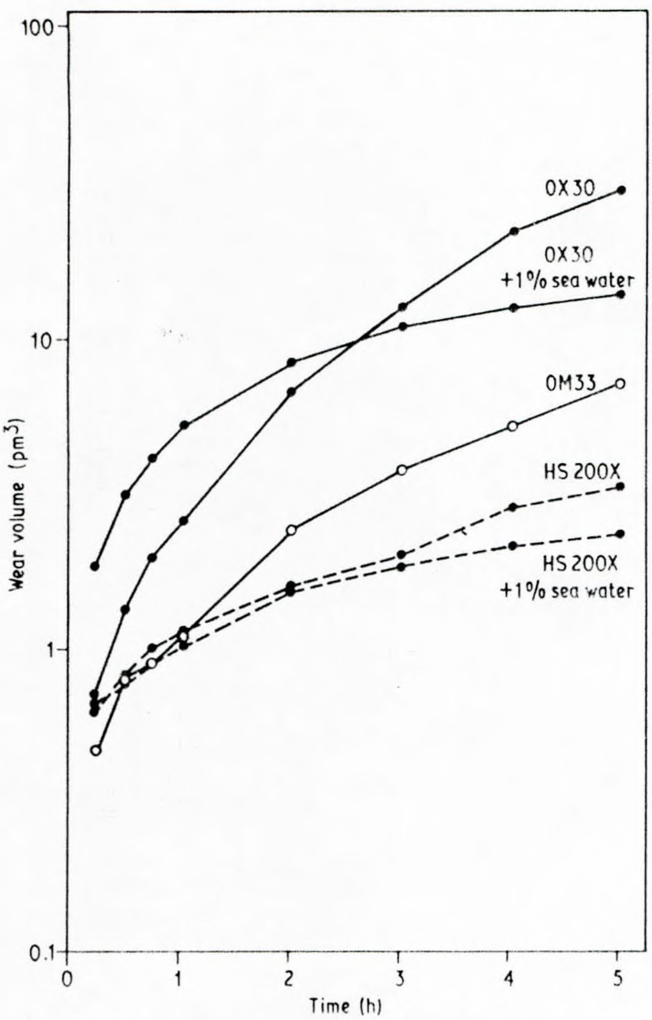

FIG. 3: Wear test, phosphor bronze on steel

This is countered by the use of suitable additives. The systems used in the trials have incorporated typical materials found in service applications, such as tungsten or copper nickel pipe-work and ferrous couplings; no problems have been encountered.

With regard to seals, packings and paints, all the commonly used material such as nitrile, fluorocarbon elastomers, neoprenes etc. are compatible with the new fluid.

Aeration

Aeration will increase the compressibility of the fluid and may result in more cavitation and poorer lubrication. In general, aqueous polyglycol fluids have longer de-aeration times than mineral oils, which will have to be taken into account in the design of tanks and systems not only to reduce the amount of aeration that occurs but also to provide sufficient time for the de-aeration to take place.

Some aeration was experienced during trials and it was noticed that newly filled systems take longer to vent. Nevertheless there has been no discernible effect on the performance or condition of the circuit components.

Contamination control

For some years the RN has recognised the importance of maintaining high standards of cleanliness in hydraulic systems commensurate with the duty performed. Clear limits have been laid down but the whole procedure has depended upon the use of satisfactory field and laboratory sampling techniques. The former have relied upon a simple comparative analysis of the dirt collected on a membrane when the sample is passed through it and the latter have employed automatic particle-counting procedures, spectrographic oil analysis (SOAP) or ferrography to determine the contamination levels.

There is every reason to believe that good system performance will require the same standards of cleanliness when using HS 200X, but problems have been encountered with measuring the contamination levels in this fluid accurately, particularly in service. When passing the fluid through a standard membrane, high differential pressures build-up causing it to collapse. This has necessitated the use of a special membrane material and a device for controlling the pressure. Trials are still proceeding in this area but the results obtained so far are promising.

Automatic particle-counting procedures did give spurious unrepeatable results, probably because of the long molecular chains present in the fluid which tended to scatter the light sources, but a suitable dilutant has now been employed and it appears to have overcome this at the expense of a rather laborious procedure. SOAP and ferrography appear to work quite satisfactorily.

This area has not yet been fully explored but there is every reason to believe that satisfactory solutions to the various problems will be found.

Corrosion protection

Corrosion is liable to occur at the interface between the fluid and the air, and when a system is left in a drained-down condition. This situation may arise prior to commissioning, if the equipment has been tested using HS 200X, but it is unavoidable during a refit when it will be necessary to drain-down systems both for safety reasons and so that work can be carried out on them.

Systems running on mineral oils such as OM33 do not suffer from this problem because the oil is a natural preservative and it is also the oil used by many manufacturers during production tests. Unfortunately, OM33 is not miscible with HS 200X and therefore it is not possible to drain it down and refill with HS 200X later.

The solution is to find a suitable preservative that is miscible both with mineral oil and HS 200X; such a fluid is now undergoing tests. If successful, we envisage it being used as a test fluid in place of mineral oil (or it could be flushed through the equipment on completion of the test) and then, when bringing the system into use, it will be necessary only to top up with HS 200X before going through the normal commissioning procedures. During refit or on any other occasion when systems are run down for a significant period of time they will have to be flushed through with a new preservative fluid after draining the HS 200X.

Fluid consistency

It has been noted already that water will tend to evaporate off in time, particularly at high temperatures, but the water content must be controlled carefully if the particular properties are to be maintained. The tank design can help in this respect by keeping the area of liquid surfaces to a minimum and if possible by keeping the space enclosed by means of a diaphragm or the equivalent in the tank vent.

The means of gauging the consistency of HS 200X has not yet been decided, but a simple viscosity measurement seems to be the most appropriate method at this stage. Demineralised water can be added to bring the viscosity into the required range, as shown in Fig. 5. A family of such curves may be drawn to accommodate the effect of temperature.

Other physical properties

Compared with the normal hydraulic mineral oil, aqueous polyglycols have a lower specific heat and a higher density and bulk modulus. These have the effect of making systems more sensitive to inlet conditions at the pumps and more liable to retain contamination in suspension, but in general cooler and with lower compressibility losses.

TRIALS RESULTS

An extensive series of trials has been conducted to examine the performance of a hydraulic system operating on the aqueous polyglycol fluid, and there is now confidence that no insurmountable problems will arise.

The heart of the system is the pump. Here the programme of tests on typical operating cycles stretches back to 1978 and some 53 000 h running of various pumps on aqueous polyglycol fluids have now been completed. The experience has been mixed but the results largely as expected. Despite the concern expressed by some manufacturers, it was insisted that the pumps were tested at the full system pressure of 207 bar.

Examples of all the common types of equipment (gear, vane, axial piston and radial piston) have been examined in both variable- and constant-displacement modes where applicable. As might be expected the sensitive area has proved to be the highly loaded bearings such as ball or roller or the swash plate bearing. Less severe wear not affecting performance has occurred on valve plates and slipper pads due to erosion and on the teeth of internal gear pumps due to the effects of cavitation. Examples of a vane pump, an axial piston pump and an internal gear pump have all successfully completed over 5000 h running and the latter is now past 8000 h

A programme of motor testing is less advanced and so far the endurance test has been successfully completed on just two of the radial piston type. The test cycle is designed to resemble a typical service usage and the duration of 1000 h is equivalent to an eight year interval between refits. All the

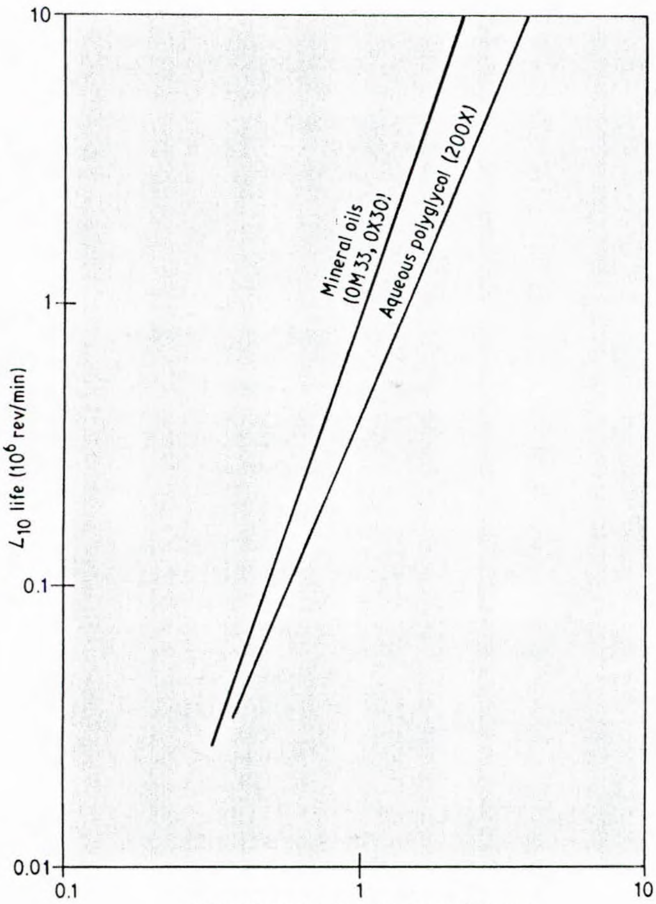

FIG. 4: Rolling contact bearing life in tests using OM33, OX30 and 200X

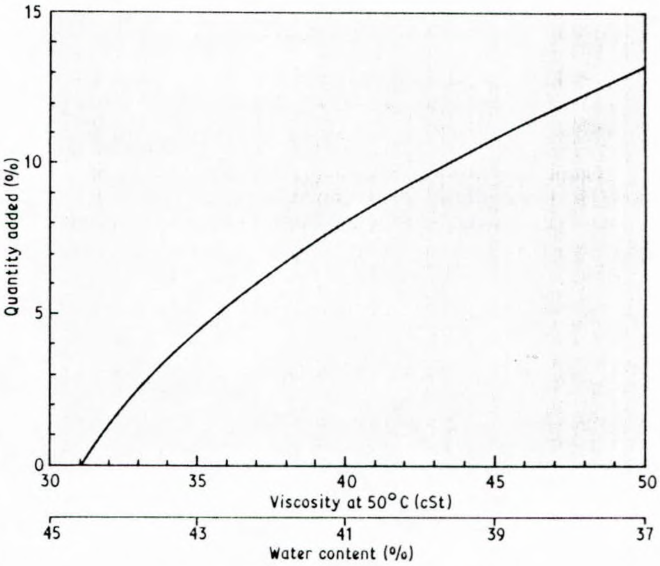

FIG. 5: Water content adjustment

motors have been down-rated by 50% on the recommendation of the manufacturers but when the current round of tests has been completed it is intended to extend the evaluation to investigate whether such a cautious approach is really justified. As there have been no significant failures or signs of deterioration that are likely to be attributable to the fluid, it appears that a higher rating could be tolerated quite comfortably.

A series of tests has also been conducted on servo valves, which might be used for pump swash control in variable delivery systems or for proportional/directional control in a fixed delivery system. All the five valves tested so far have successfully completed the 1000 h trial so there appears to be no cause for concern in this area.

Evaluation of filter performance on the new fluid is being frustrated by the difficulty in taking accurate particle counts. An automatic HIAC instrument has been used successfully during the series of extensive tests with OM33, but unfortunately, as mentioned earlier, it has given unreliable results with HS 200X. Tests may have to be progressed using the laborious and protracted back-projection microscope methods of particle counting but it is hoped that new procedures now being evaluated for use with the automatic process will prove satisfactory.

CONCLUSIONS

Following many years of evaluation the RN is now committed to the introduction of a special brand of aqueous polyglycol fire-resistant fluid, designated HS 200X, into the new class of surface ship, the *Type 23*. The fluid will be slightly more expensive than the mineral oil used previously but it presents a minimal fire risk. It has been established that all pumps to be filled can achieve their target lives comfortably and no problems are anticipated with other components.

The motors will initially be down-rated (and therefore bigger for any particular application than if running on mineral oil) but with no failures so far the trials' results suggest it should be possible to lift this restriction in future system designs. The fluid will be handled much as a mineral oil would be and systems will perform in a similar manner. Slightly different procedures will need to be introduced for contamination control and for system preservation when it is in a drained-down or partially full condition.

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