NAVAL EXPERIENCE WITH MAIN PROPULSION LUBRICATING OILS 1974–79

BY

J. J. DUNFORD, B.SC., C.ENG., R.C.N.C.
AND
P. R. ROBINSON, B.SC., C.ENG., R.C.N.C.
(*Ship Department*)

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Introduction

The majority of Royal Naval warships are propelled by combinations of steam and/or gas turbines, connected to the propeller shaft by a reduction gearbox. A common oil, supplied from a main propulsion forced lubrication system, is used to lubricate the gearing, the main thrust bearing and the power turbine of the prime mover. Since 1962 the oil used in this system has been OEP69—the only approved supply of which consisted of an inhibited mineral oil containing a powerful chlorine-based extreme-pressure (ep) additive. In 1974, after twelve years of apparently satisfactory service, four major failures occurred in warship main machinery which were directly attributable to this oil. This paper describes these failures and the work done to find an effective solution to them. The paper starts with a brief description of the equipments involved and the background to the adoption of OEP69.

Machinery Involved

As far as propulsion machinery is concerned the fleet can be split into four main classes as shown in TABLE I. Details vary but a typical installation would

TABLE I—*Propulsion machinery of major warship classes*

Ship Class	*No. of Ships*	*Prime Movers/Shaft*		*Number of Shafts*	*Means of Reversal*
		Type	*Power (hp)*		
ROTHESAY and LEANDER	37	Steam turbine	15 000	2	Astern turbine
TRIBAL	7	Steam turbine G6 gas turbine	12 500 7500	1	Astern turbine Fluid couplings
COUNTY	8	Steam turbine HP LP 2 × G6 gas turbine	8000 8000 2 × 7500	2	Astern turbine Fluid couplings
AMAZON SHEFFIELD BROADSWORD	8 7+ 2+	Olympus gas turbine Tyne gas turbine	25 000 4250	2	CP propellers

(+ = Numbers increasing due to active building programme).

contain about forty journal bearings in each shaft set, with speeds ranging from 200 to 5600 rev/min and mean pressures up to 500 lbf/in^2 (3·4 NM/m^2); a smaller number of tilting pad thrust bearings; several trains of double reduction gearing rated up to a Lloyds K factor of 500 lbf/in^2 (3·4 MN/m^2) (exceptionally 819 lbf/in^2 (5·6 MN/m^2)) and, in the case of the COUNTY Class destroyers and TRIBAL Class frigates, two or four scoop-controlled fluid couplings. Several installations also include self-shifting synchronizing (SSS) clutches. Detailed descriptions are provided by references 1 and 2. The oil flow required by these systems varies from 250 gal/min (19 l/s) for the LEANDERS up to 800 gal/min (61 l/s) for the COUNTY Class.

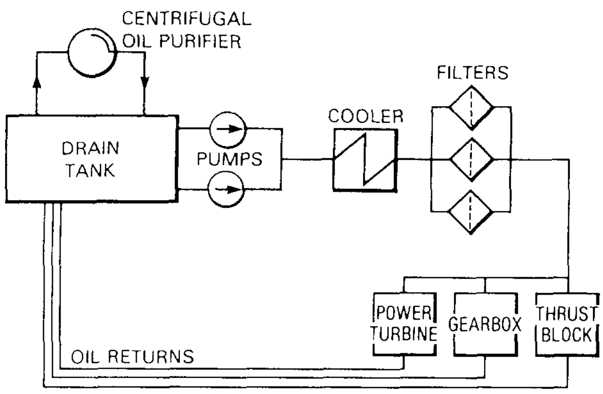

FIG. 1—SCHEMATIC DIAGRAM OF A TYPICAL MAIN PROPULSION LUBRICATING OIL SYSTEM

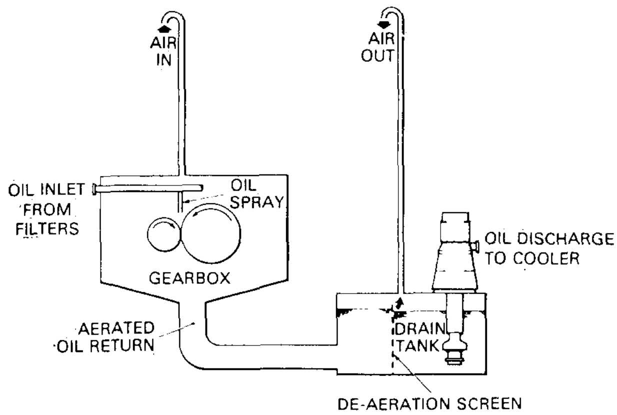

FIG. 2—DE-AERATION AND VENTING ARRANGEMENTS

The supply of oil for lubricating and cooling main propulsion machinery is provided by the main forced lubrication system (FIG. 1). Oil is pumped from the gearbox drain tank, then cooled and filtered before distribution to individual items of machinery. A second, standby pump is normally provided to reduce the risk of interruption to the oil flow. After passage through the machinery the oil returns by gravity to the drain tank. The drain tank is designed to permit separation of entrained air from the oil and is provided with a vent to permit the air to escape to atmosphere (FIG. 2). While the propulsion machinery is running, the oil is continuously renovated by centrifugal purifiers which take suction from, and return the oil to, the drain tank (FIG. 3).

For logistic reasons the main propulsion lubricating oil is also used for much of the auxiliary machinery carried on board. Arrangements for the supply of oil to auxiliaries vary widely. Complex machinery such as steam turbine-driven generator sets incorporate systems similar to those for main propulsion machinery, although centrifugal purifiers are not fitted. At the other end of the scale, equipments such as plummer bearings employ simple bath lubrication. The lubrication of diesel engines is outside the scope of this paper.

Background

The requirement for an extreme pressure oil first became apparent in the early 1950s when the post-war steam frigates of the WHITBY and BLACKWOOD Classes experienced scuffing of their secondary gears during early running. The search for a suitable ep oil continued throughout that decade involving intensive laboratory testing and widespread ship trials. This work culminated in September 1961 with the issue of specification DGS6920 for OEP69. From 1962 onwards this oil was used as the normal main propulsion lubricant for Royal Naval warships. Naval gear designers took advantage of the availability of an effective ep oil by using heavily loaded case hardened gears in later designs. The trials and discussions leading to the adoption of OEP69 are fully described in reference 3.

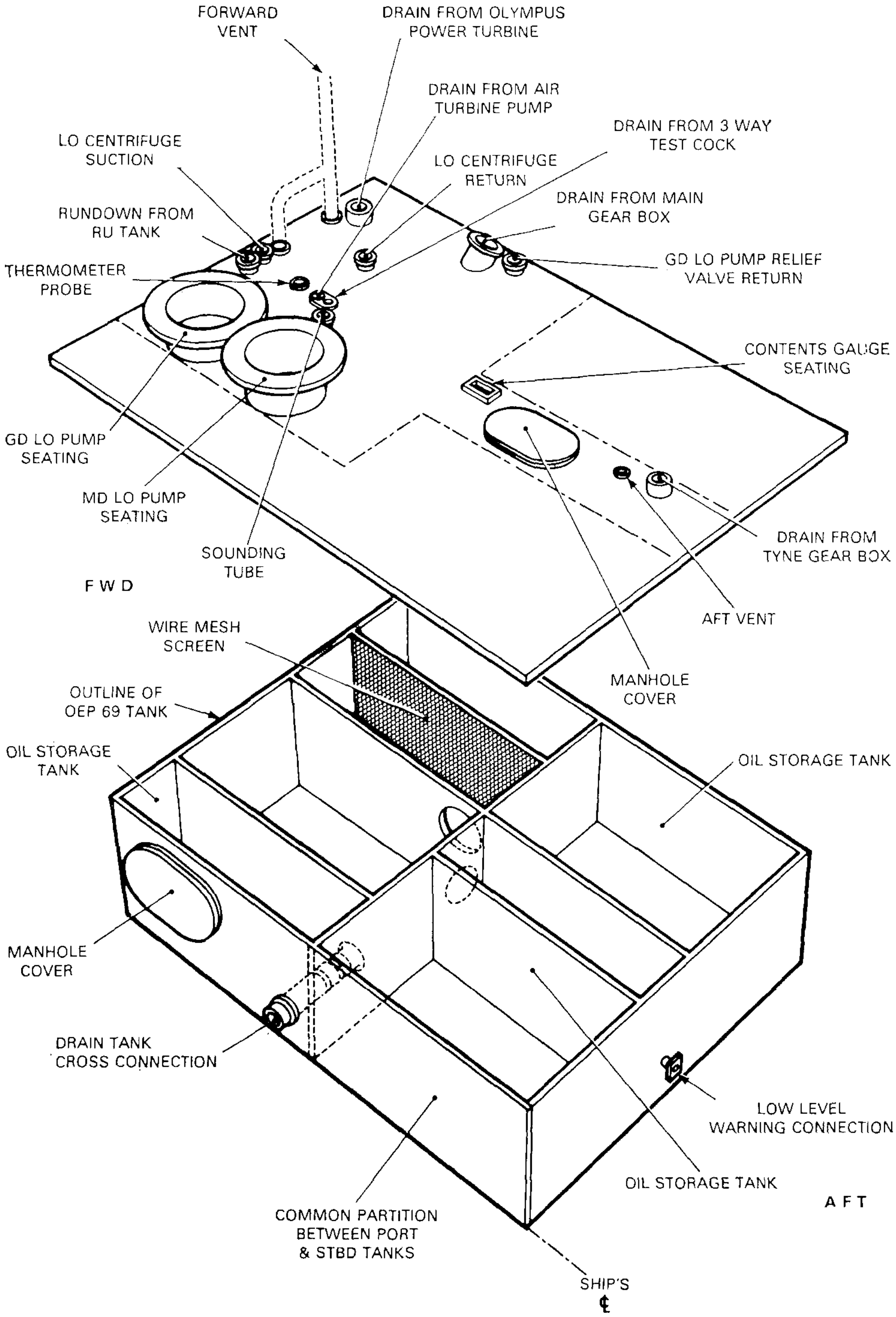

FIG. 3—A TYPICAL OIL DRAIN TANK

Throughout the 1960s this oil gave apparently satisfactory service. Minor logistic difficulties arose and some concern was expressed as to its poor demulsifying properties, particularly where it was used in auxiliary machines, There were also several instances of sticky sludges forming. These trapped dirt and occasionally caused blockage of the fine clearances within the SSS clutches. Brown staining of bare metallic parts was also commonly observed but caused no apparent problems. During the early 1970s however, reports began to accumulate of the blackening of white metal bearings, and in 1975 two major bearing failures occurred which were attributed to this cause: the first in H.M.S. *Hampshire*, involved a secondary pinion journal bearing, the second in H.M.S. *Leander*, the main thrust bearing.

Just as investigations into bearing corrosion were getting underway, a second oil-related failure made itself apparent in the TRIBAL Class frigates when the rotor of the main steam turbine in H.M.S. *Mohawk* suffered rapid machining wear in way of an oil baffle. Later in the year a second similar failure occurred in a sister ship, H.M.S. *Ashanti.*

Enquiries to ships and refitting authorities revealed that the blackening of bearings in equipments using OEP69 was widespread. The corrosion had been observed for many years but had not previously been associated so clearly with a major bearing failure. In most ships the corrosion progressed quite slowly, typically at ·0005 inch/year (·013 mm/year) or less, but, in others, the rate was more rapid and was sufficient to produce a dangerous hard black film in less than two years. Inspection of the turbine oil baffles in the TRIBAL Class frigates showed that hard carbon deposits were present in four of the seven ships and similar deposits of carbon were also discovered in the steam baffles of four steam turbo alternators and in a steam turbo fuel pump. It was also realized that in 1973 the formulation of OEP69 had been changed. Against this confusing background a programme of laboratory work, machinery inspections and ship trials was started with the aim of identifying the causes and finding a solution to these two damaging problems.

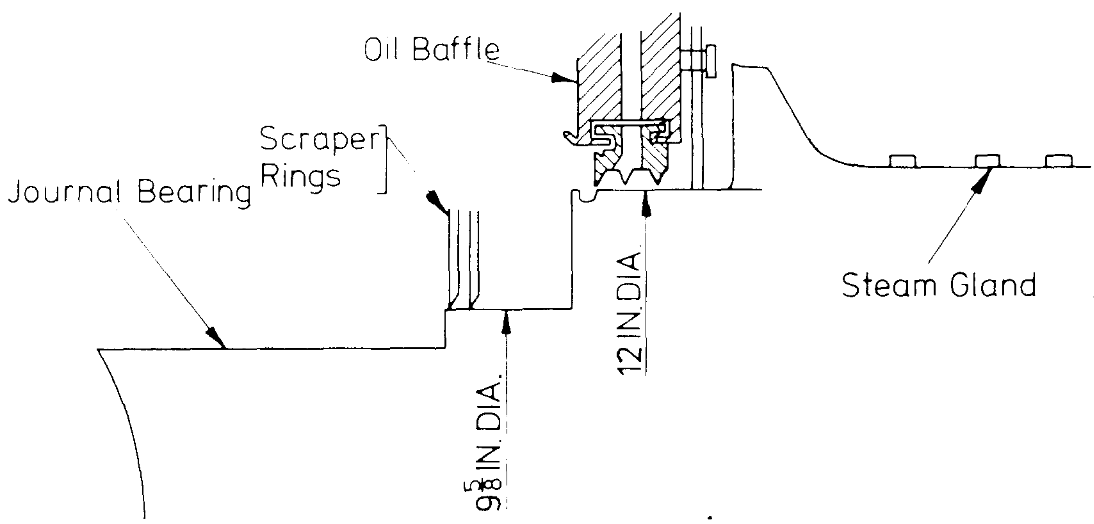

FIG. 4—TURBINE OIL BAFFLE—TRIBAL CLASS FRIGATES

FIG. 5—CONDITION OF MAIN STEAM TURBINE ROTOR IN WAY OF OIL BAFFLE

Carbon Build-up

Although more limited in extent, the carbon build-up problem was certainly the more spectacular of the two. The general arrangement of the GP frigate turbine oil baffle is shown in FIG. 4. The condition of the rotor underneath a baffle which has suffered from carbon 'build-up' can be seen from FIGS. 5 and 6 which show the shaft before and after the hard mass of debris was cleaned away, revealing a $1\frac{1}{2}$-inch (40 mm) groove in what was previously a $6\frac{5}{8}$-inch (170 mm) diameter shaft. The debris formed a complete collar which could be

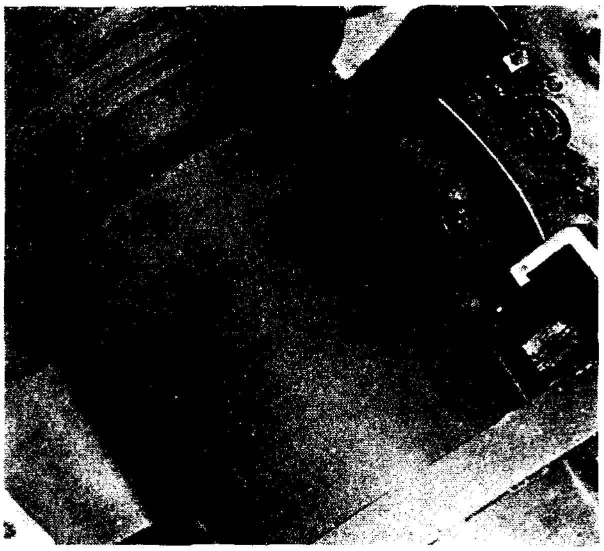

FIG. 6—CONDITION OF ROTOR AFTER CLEANING AWAY DEBRIS

Photograph by courtesy of Rolls-Royce Ltd.

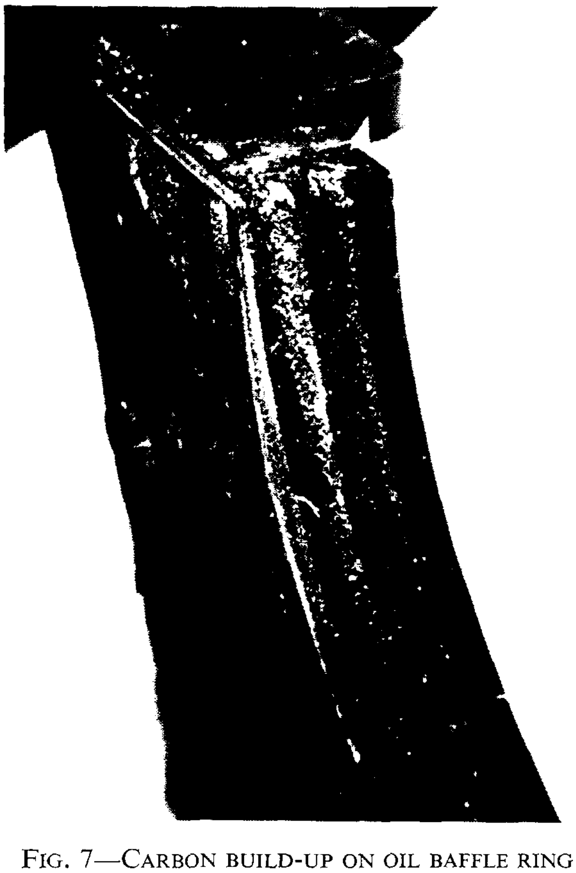

FIG. 7—CARBON BUILD-UP ON OIL BAFFLE RING

rotated on the shaft. It was described as a black/brown gritty substance which became progressively softer deeper in the groove, having the consistency and appearance of a rich brown soil. Several pieces of metal were embedded in it, some of which formed complete bands of 'wire' encircling the shaft. Similar deposits were found in the oil baffle itself but these were much harder and had to be removed with a chisel. There was, however, no evidence of the baffle rubbing on the shaft. Chemical analysis of the deposits showed them to be 70 per cent. carbonaceous matter with the remainder comprised of steel corrosion products with traces of nickel, chromium, calcium, copper, zinc, silicon, and manganese.

It was obvious from visual examination that the first step in the process was the build-up of hard carbon deposits in the oil baffle rings (FIG. 7). The possible causes of this included:

High baffle temperatures
Poor drainage
Assembly /manufacturing errors
Change of oil formulation

A survey of existing equipments and historical records showed that the incidence of carbon deposits had risen sharply since the introduction of the modified oil and an early decision was taken to revert to the original formulation.

The breakdown of oil in oil baffles had been studied previously by Fowle[4]. Both plain and ep oils were found to degrade in this manner, the latter at a lower temperature. A baffle temperature limit of 130°C had been recommended, and it was noted that oil drainage arrangements and the rate of air flow through the baffle had an important influence. Measurements taken in the TRIBAL Class frigates showed that the affected oil baffle reached a maximum temperature of 204°C and a review of the design showed that the drainage channels were small and tortuous. These discoveries whilst indicating why this particular baffle should be affected did not explain why the failures had only occurred after many years in service. The only change which looked as though it could have caused this problem was the addition of two anti-oxidants to OEP69 in 1973. This had been done to meet the requirements of another customer of the base stock and although the modified oil had performed adequately against the OEP69 specification tests, concern was felt that the testing may not have been fully representative of service conditions. Accordingly the National Gas Turbine Establishment (Cobham) (NGTE(C)), was asked to investigate any difference in the carbon forming tendencies of the original and modified OEP69 formulations. Unfortunately there were no standard tests for assessing the carbonization tendencies of turbine oils, so it was necessary to investigate a number of methods that might show thermal instability in the oil.

Among the possible test procedures investigated were the thermal stability tests for FFO ASTM.D.1661, the thermal stability test for aviation turbine fuel ASTM.D.3241, and a test used to assess carbon forming tendencies in aircraft turbine oils, commonly called the Top Hat Test, D.Eng R.D.2497 Test Method No. 16.

These methods did not appear to differentiate between the oil with the extra additives and the original formulation, and also did not really simulate conditions under the oil baffles on the rotor shaft. After considering one or two other pieces of apparatus for testing thermal stability it was decided to try apparatus called a Panel Coker used to assess carbon formation tendencies of IC engine oils. This is method 3462 in Federal Test Methods Standard No. 791B, in which the oil under test is allowed to trickle down over a heated aluminium plate.

Method 3462 lays down a test period of eight hours and a panel temperature of 600 + 5°F (316 + 3°C). It was considered that the specified temperature was rather high in comparison with the rotor shaft temperature and that an 8-hour test temperature would only enable one test a day to be run. After some trial runs varying both temperature and time, a two-hour test with a plate temperature of 275°C was adopted. Some twenty-one samples from batches of OEP69 supplied to the R.N. over a four-year period, and spanning the time from which the two additional additives (an antioxidant and a copper passivator) were included in the oil, were tested by the panel coker. Oils containing the additional additives produced a heavier, more adherent, and a harder coke. Additional testing using the original formulation oil and adding separately the additives showed that only one, an amine antioxidant, was responsible for the enhanced coke formation.

FIG. 8—TIN OXIDE CORROSION

Some tests were also carried out on the effect that the metals—iron, copper, and zinc—have when present in the oil on its coking tendencies. Both zinc and iron tended to cause an increase in coke formation but did not show up any significant difference between the two oil formulations.

In response to criticisms that the panel coker test gave poor repeatability and did not realistically simulate the shaft temperature, work is being undertaken to see if a lower temperature, coupled with a longer test period, can produce enough carbon to give a similar differentiation between the various oils.

Tin Oxide Corrosion

The effect of tin oxide corrosion is the formation on the bearing surface of a hard black layer consisting of a mixture of stannous and stannic oxides (FIG. 8). Bearings corroded in this manner can cause machinery failure, either by the inability of the bearing to imbed dirt or, in more severe cases, by the generation of abrasive particles due to spalling of the corroded surface itself. In order to reduce the risk of unplanned machinery failures, which are unacceptable in an operational warship, it was necessary to examine bearings at regular intervals and renew those found corroded. This resulted in a large increase in the work-load placed on the Royal Dockyards, with the accompanying risk of accidental damage each time machinery was stripped.

Investigation of the scope of the problem and a literature survey of bearing problems revealed the following possible causes:

(*a*) *Sea-water contamination:* this had been identified as the cause of many reported cases of severe bearing corrosion in auxiliaries, such as feed pumps and plummer bearings, in warships and in commercial vessels. These were invariably accompanied by the formation of large sludge deposits. The corrosion problem could therefore be due to widespread salt contamination of the oil in service.

(*b*) *High electric potentials:* these can be developed between rotor and casing of turbine-driven machinery. Cases had been reported where this had caused corrosion damage to bearings by an electrolytic process.

(*c*) *Increased bearing temperatures:* the development of modern highly-loaded gearboxes involved increasing bearing loads and temperatures. Thrust bearings tend to operate at higher temperatures than journal bearings and also seemed to corrode more quickly. Therefore, the corrosion process seemed to be temperature dependent and the emergence of the corrosion problem throughout the fleet may have resulted from the introduction of modern designs of gearbox into service.

(*d*) *Direct Oxidation* of the white metal by the oil.

Electrochemical Corrosion

Since the oil used in main forced lubrication systems is continuously renovated by a centrifuge, gross contamination of the oil by sea water is a rare and short-lived occurrence. Bearing corrosion was found even in the gearboxes of ships with exceptionally 'clean' and 'dry' lubricating oil, so gross salt-water contamination was dismissed as the cause of the problem. Electric potentials were also dismissed by a simple shipboard trial in which only minute potentials were detected; these were the wrong polarity to cause corrosion of the bearing surface. A comprehensive account of the analytical work into the remaining possibilities has been given by Hiley[5] and the rest of this section describes salient points of this work.

X-ray diffraction and X-ray fluorescence analysis of bearings which had corroded in service showed that the hard corroded layer consisted of stannous and stannic oxides mixed in varying proportions. In an initial test, small squares cut from a whitemetal bearing shell were exposed to extreme pressure and to conventional oils at 140°C. Soft black layers were produced within 100 hours. However, no oxides of tin were present in this layer which probably consisted of deposited carbon. Direct attack of the whitemetal by the oil was therefore eliminated as a cause. Also, the test temperature was higher than that at which bearings operate in service, so the corrosion problem could not be attributed to the increase in bearing loads.

TABLE II—*'Beaker Test' procedure*

Clean 50 ml beaker
Clean specimen of whitemetal on steel
40 ml of test oil + ½ ml of de-ionized water or test electrolyte
Test temperature 80°C
Test duration 750 hours restirring daily and topping up with de-ionized water or test electrolyte if necessary

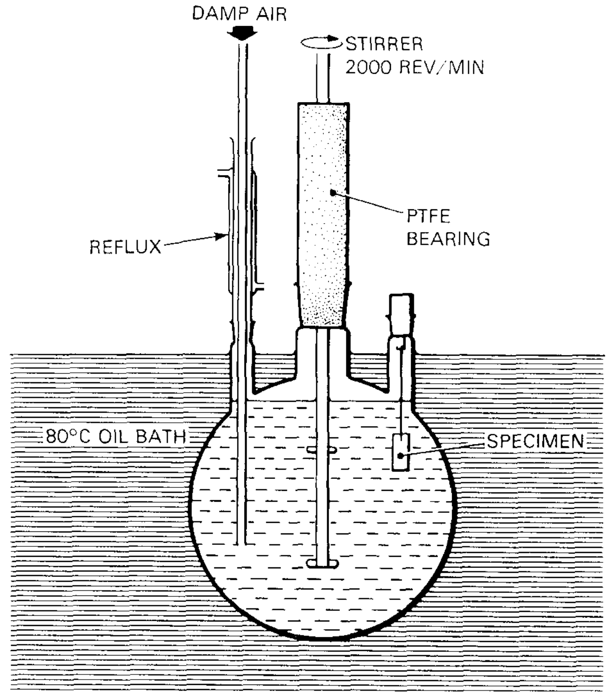

FIG. 9—THE 'FLASK TEST' PROCEDURE AND APPARATUS (HILEY[5]):
Test Conditions:
Clean specimen of whitemetal on steel
Test oil with 500 ppm de-ionized water
Test temperature 80°C
Test duration 500 hours
Top up periodically with de-ionized water

A 'beaker test' was devised which could reproduce hard layers of tin oxide corrosion similar to those experienced in service. The test conditions are listed in TABLE II. In a series of experiments the corrosion of a small range of whitemetal types in a large range of electrolytes and oil/additive packages was investigated. These tests showed that the corrosion process is electrochemical in nature and that chloride ions are necessary, in addition to oxygen and water, as they inhibit the formation of a passive oxide film, which would stifle the corrosion reaction. As the amount of water contaminating the lubricating oil in service is generally very much less than the 1/80 concentration used in the 'beaker test', further experiments were conducted using a 'flask test' (FIG. 9). By reproducing corrosion under conditions similar to those experienced in service, these tests confirmed that electrolytic corrosion would still occur in oil which was apparently 'dry'.

With existing equipments it is impracticable to maintain the water contamination levels in warship main lubricating systems lower than the 500 ppm used in the flask test, or to exclude oxygen. Chloride ions also will always be present to a small extent from the general marine environment but to a much larger extent from thermal degradation of the chlorinated-wax extreme-pressure additive in OEP69 lubricating oil. Bearing materials based on metals other than tin are unsatisfactory for other reasons so the two potential solutions to the corrosion problem which remained were:

(*a*) Change the type of oil to one which in use does not release chloride ions.

(*b*) Dilute the electrolyte by regular washing of the lubricating oil with de-ionized water in service.

Changing from OEP69

Although the laboratory tests provided a useful understanding of the mechanism of tin oxide corrosion and carbon build-up the practicability of the possible solutions had yet to be established. In changing from OEP69, two options were available. The first was to revert to OM100, the high-quality inhibited mineral oil which had been used by the Royal Navy for thirty years. The alternative was to adopt one of the newer marine ep oils which had become available since 1962.

Reverting to OM100

As the quality of naval gearing had improved significantly since the 1950s it was hoped that at least the majority of existing gear designs would be able to operate safely without ep protection. Nonetheless, the decision to undertake a series of ship trials with OM100 was not an easy one. Theoretical assessments of scuffing risk, based on the Integral Temperature Criterion[6] and a development of the Neimann and Seitzinger method[7], indicated that the ROTHESAY, LEANDER, AMAZON, SHEFFIELD and BROADSWORD Classes could operate safely on this oil. The TRIBAL Class frigates were assessed as 'marginal' and the gears in the COUNTY Class destroyers, which had the highest tooth loadings, were predicted as likely to scuff. Such predictions, however, are notoriously unreliable—indeed later work revealed some errors in both programmes—and laboratory tests such as the IAE Gear Test Rig, indicated only too clearly the extent to which safety margins would be reduced when the powerful ep protection of OEP69 was removed.

Fortunately further data on the risk of scuffing was available both from the early post-war experience and from certain foreign navies which operated similar machinery on OM100. The gearing in the ROTHESAY and LEANDER Class frigates is a direct development of that used in the WHITBY Class which had suffered scuffing during early running on OM100. Loadings and speeds were almost identical but gear accuracy and alignment were improved and the EN26 (826 M40) through-hardened pinions were replaced by case-carburized elements in EN36A (655 M13). These improvements, coupled with the knowledge that all previously reported cases of scuffing in naval gears had occurred progressively rather than catastrophically, provided the confidence to justify a series of limited, carefully monitored, trials with OM100 in selected ships. The trial and inspection programme is shown in TABLE III.

TABLE III—*Summary of in-service oil trials*

Class/Trial	*1968–9*	*1976 1977 1978 1979*	*Outcome of Trial*
H.M.S. *Grafton* OM100 trial	H.M.S. *Grafton*		Successful
TRIBAL OM100 trial		—— H.M.S. *Gurkha*—— - - - - —H.M.S. *Ashanti*—— - - —H.M.S. *Mohawk*——	Successful: Class converting to OM100
ROTHESAY/LEANDER OM100 trial		——H.M.S. *Apollo* —— - - - - ——H.M.S. *Rhyl* —— - - - - -	Successful: Class converting to OM100
WHITBY Mild ep oil trial		—H.M.S. *Torquay*— - - -	Successful: but Class continuing with OEP69
COUNTY Mild ep oil trial		—H.M.S. *Fife* —— —H.M.S. *Antrim*—	Unsuccessful: Class continuing with OEP69
AMAZON/SHEFFIELD/BROADSWORD OM100 trial		—H.M.S. *Arrow*——	Continuing

Prior to each trial, the OEP69 was drained off and a flushing charge of OM100 was circulated for six hours. The system was emptied again and an operational charge of OM100 embarked. An oil sample was then taken and tested by NGTE(C) to determine the residual oil content. Typically this was below 2 per cent. The datum condition of the gears was recorded by taking plastic replicas of selected teeth. Trial ships were required to undertake a period of at least two hours at maximum power and a series of severe manoeuvres in an attempt to induce scuffing. After an inspection, the ships returned to their normal operational programme.

To date the OM100 trials have been an unqualified success. Scuffing was observed on one ship (H.M.S. *Gurkha*) but this was later attributed to a massive contamination of the lubricating oil by fuel from a G6 gas turbine. Confidence was further boosted when replacement primary gears were successfully run-in from new following an unrelated failure in H.M.S. *Rhyl*. After a combined total of thirty-six months satisfactory running the decision was taken in March 1978 to change all the ROTHESAY and LEANDER Class frigates to OM100. This change has now been successfully completed. Action is also in hand to change the remainder of the TRIBAL Class frigates, although these are now passing into reserve and may not be caught in time.

The decision to use OM100 in the modern gas-turbine ships (AMAZON, SHEFFIELD, and BROADSWORD Classes) must await the outcome of the trial in H.M.S. SOUTHAMPTON where the oil is to be used from new. OM100 was not tried in the COUNTY Class destroyers as the scuffing risk was too great.

Alternative ep Oils

Whilst the feasibility of reverting to OM100 was being tested by shipboard trials, a programme of laboratory work was initiated to find an alternative ep oil. Enquiries to the oil companies showed that there were a large number of ep oils available, and to narrow the field the following criteria were applied:

(*a*) The oil should have been in use for several years and of proven suitability as a marine turbine lubricant.

(*b*) The oil should have similar physical properties to OEP69 and, as far as possible, should meet the DGS Specification in all aspects other than load carrying capacity.

(*c*) It should not promote tin oxide corrosion.

(*d*) It should show a lower tendency to form carbon in oil baffles than OEP69.

(*e*) It should be available worldwide and potentially suitable for NATO standardization.

(*f*) It should be likely to be commercially available for several years to come.

Six oils were selected for testing at NGTE(C), the majority of them from the Qualified Products list for the American specification MIL–L–17331F which is already used by many NATO navies. All the samples were tested to the OEP69 specification DG Ships 6920B and to four additional tests:

(*a*) IP 280—Oxidation stability of inhibited mineral turbine oils.

(*b*) IP 229—Oxidation stability of steam turbine oils by rotating bomb.

(*c*) FTM 791B Method 3462—Coking tendency of oil.

(*d*) Beaker test for tin oxide corrosion as reported[5].

With the exception of the IAE Gear load test IP 166, the oils generally satisfied the requirements of DGS 6920B. Two oils failed marginally on rust prevention, and one on demulsification. Significant differences did, however, emerge on the IAE rig, the panel coker test, and beaker tests as shown by TABLE IV.

When all the test results were considered Oil B was selected as the one most suitable for ship trials although it was noted that the demulsification number and the viscosity were both higher than the specification limit at 330 (limit 300)

TABLE IV—*Load capacity, corrosion performance, and coking tendency of alternative extreme-pressure oils*

	OEP 69 Original	*OEP 69 Modified*	*A*	*B*	*C*	*D*	*E*	*F*	*OM100*
IAE Lever load (lb min) (kg min)	96 44	96 44	65 29	60 27	51 23	51 23	62 28	55 25	35 16
Tin oxide corrosion (Order of merit)	4	4	3	1	2	2	3	3	3
Panel coker FTM791B (Mean wt. of coke, mg)	8·5	14·1	11·4	5·8	9·6	10·9	9·4	8·4	5·0

(Source: NGTE (Cobham) Memorandum 78202, January 1978).

and 1187 cSt (limit 1000 cSt at 0°C). Full details of all the tests are given by Carpenter[8].

Oil B was tested in two ships—a COUNTY Class destroyer, H.M.S. *Fife*, and one of the old post-war frigates, H.M.S. *Torquay*. The same procedure was used as for the OM100 trials. The trial in H.M.S. *Torquay* was entirely successful but, in H.M.S. *Fife*, scuffing was discovered on a small area of one of the gas astern pinion to idler meshes at the routine inspection three months after the change-over. The trial was allowed to continue and subsequent inspections showed the scuff to be slowly polishing out. In January 1979 a sister ship, H.M.S. *Antrim*, was nearing completion of a refit and the opportunity was taken to extend the use of Oil B. In October 1979, shortly after recommissioning, a signal was received from *Antrim* reporting scuffing on the gas astern idler pinion and on the steam turbine secondary pinions/mainwheel of the port gearbox (FIG. 10). A power limitation was imposed but the scuffing did not improve and, indeed, showed signs of spreading. Accordingly the trial was terminated by reverting the ship to OEP69.

FIG. 10—SCUFFING ON GAS ASTERN IDLER—H.M.S. 'ANTRIM'
PHOTOGRAPH OF TOOTH REPLICA × 2

Certain other aspects of the trial with Oil B are also worth a mention as service experience confirmed the laboratory indications. The time required to remove water from the system following contamination or deliberate water washing increased significantly, in line with the demulsification number, although the centrifuges still proved capable of maintaining an adequately dry oil in the main system. The higher viscosity of Oil B also had practical consequences as it resulted in increased bearing temperatures leading to the requirement to reduce oil supply temperature at high powers. Losses at full power appeared to increase by about 500 hp. Aeration also proved to be a problem, not in the main lub.-oil system, but in the turbo generators where it caused difficulties when setting governors. Subsequent laboratory tests confirmed that Oil B was drastically inferior to OEP69 in this respect.

In view of the problems experienced it has been decided that Oil B is not suitable for widespread use as a naval lubricant. Accordingly the COUNTY Class destroyers will continue to use OEP69.

Dilution of the Electrolyte

Accordingly to Bryce and Rochner[9], diluting the electrolyte by washing the oil with distilled water had effectively solved the bearing corrosion problem in a range of merchant ships. Two lines of enquiry were followed to assess the effectiveness of this approach on reducing the corrosion in naval vessels using OEP69. A journal bearing test rig was used to assess the effects on the rate of corrosion in a loaded journal bearing of deliberately wetting and of water-washing the oil. The tests were run for 250 hours although one test was extended to just under 500 hours. All the test bearings displayed slight darkening but the surface layer was too thin either for its composition to be reliably identified or for significant conclusions to be drawn on the variation in corrosion rate.

In parallel with this work a series of shipboard trials was carried out. In the first of these trials, an assessment was made of the amount of chlorides resident in the main forced lubrication systems of a large number of ships which use either OEP69 or OM100 lubricating oils. On each of three successive days, two gallons of de-ionized water were added to the drain tank while the oil was being circulated around the system. One hour after the water addition, the centrifuge was run to clarify the oil. A sample of the water thus extracted was tested for chloride contamination using the standard on-board test method. A further sample was sent to the National Gas Turbine Establishment, Cobham for more detailed chemical analysis. The following conclusions could be drawn from the large amount of test data produced:

(*a*) The amount of chlorides present in the system, as indicated by the degree of chloride contamination in the separated water, varied widely across the fleet from 50 ppm at best, up to 5000 ppm in the most severely contaminated ships.

(*b*) The on-board test method for assessing the level of chloride contamination of the separated water was unreliable.

(*c*) Ships systems could harbour gross contamination which was not detected by the routine test procedure. In some cases it was found to be necessary to wash the oil charge five times with 10 per cent. additions of de-ionized water in order to reduce the chloride contamination to an acceptable level.

(*d*) There was no clear correlation between the amount of chloride present in the system and the known corrosion rates.

A further pair of trials, of about one-year duration, were carried out on two ships which use OEP69 lubricating oil to assess the effect of water washing on the corrosion rate. In one trial, in H.M.S. *Kent*, arrangements were made to water-wash on a continuous basis by injecting 1 per cent. of de-ionized water into the oil stream entering the centrifuge, which was, as usual, running continuously while the propulsion machinery was in use. This was carried out on only one of the two independent propulsion machinery sets. Comparison of the bearings from both sets of machinery showed that water injection increased the rate of corrosion and it was concluded that the effect of removing chlorides by washing was more than offset by the inevitable increase in the wetness of the oil.

In the other trial, in H.M.S. *Torquay*, the oil charge was given a single monthly wash with 10 per cent. of de-ionized water. This succeeded in maintaining low chloride levels within the system, but nevertheless some corrosion still occured. Water washing in this manner seemed to reduce slightly the rate of corrosion but clearly did not stop it.

The effect of all these trials was to show that, for ships which use OEP69 lubricating oil, dilution of the electrolyte will not slow down the corrosion rate sufficiently to eliminate the problem. Washing is also impracticable on auxiliaries. The trials also demonstrated that ships accumulate chlorides in their systems with use and can harbour quite extensive levels of salt contamination which were undetected by shipboard test procedures, and that the on-board method of testing separated water for chloride contamination was unreliable.

Chloride Contamination Testing

The working charge of lubricating oil can become contaminated with sea water by a variety of routes, such as leaks in the main lubricating oil coolers or through failed seals in drain-tank fittings or vent and drainage pipework. The lubricating oil is therefore subjected to regular in-service tests for chloride contamination in order that these leaks can be detected and repaired, and the oil charge either changed or treated, to prevent rusting of the gearing.

The traditional test method was to mix a sample of the oil with a similar quantity of de-ionized water which is then allowed to separate out. The water is then tested for chlorides using elements of the boiler feed-water chemistry test kit. To do this the water sample is rendered neutral or slightly acidic by the addition of nitric acid with phenolphthalein indicator and then subjected to silver nitrate titration with potassium chromate indicator.

It was found that under certain circumstances some of the additives in OEP69 or the products of their decomposition, were soluble in the test water and could render the titration unreliable. A revised titration procedure, with fixed amounts of silver nitrate solution being added before a larger proportion of potassium chromate indicator, was developed and gave reliable results. This procedure only gives coarse results but these are sufficient to identify the 200 ppm and 500 ppm chloride contamination levels at which different corrective procedures must be carried out.

The investigation of water washing procedures as a means of inhibiting tin oxide corrosion revealed a further deficiency with the test method. The low solubility of salt in mineral oil resulted in many cases of dry oil containing only insignificant chloride contamination levels circulating within heavily contaminated systems. The contamination is assumed to take the form of solid deposits. A new test method was developed in which the water sample is first circulated around the system with the oil. This water sample is obtained in either of the following ways:

(*a*) If water is regularly being discharged from the system centrifuge, a sample of this is tested weekly.

(*b*) If no water is normally extracted from the system centrifuge, two gallons of de-ionized water are added to the drain tank once a month in order to wet the oil sufficiently to enable the centrifuge to separate out a water sample for testing.

However, in some ships, especially those with gas-turbine propulsion machinery, the flow of air through the gearbox vent provides a highly effective means of removing water vapour and it is impossible to obtain a water sample from the centrifuge. Also a centrifuge depends for its operation on a rotating water seal and therefore needs to be primed with water when started. In ships with gas turbine propulsion machinery, boiler feed water is unavailable and the centrifuge must be primed from the ships domestic water system. This can have high chloride contamination levels and any water sample obtained from the centrifuge could therefore bear little relevance to the contamination levels within the oil system.

It is possible that the coalescer action of the main forced lubrication filters could be exploited as an alternative means of recovering water from the system. This alternative is currently being evaluated in a further ship trial.

Concluding Remarks

The coincidence of two major problems related to the use of OEP69 has caused the Royal Navy to re-examine its need to use this oil. Shipboard trails of an alternative ep oil were unsuccessful but similar trials with OM100 have shown that the great majority of existing gear designs can operate safely without ep protection. Theoretical studies suggest that OM100 will also be adequate for the great majority of likely new designs but action is being taken to develop a milder ep oil as a fallback. The decision has already been taken to use OM100 in the ROTHESAY, LEANDER and general purpose frigates, and, if the forthcoming trial in H.M.S. *Southampton* succeeds, the modern all-gas-turbine ships will progressively switch to this oil. The COUNTY Class will remain on OEP69 but all new design will be based on OM100.

Although the risk of scuffing is increased by changing to OM100, this oil dramatically reduces the risk of bearing corrosion, with a corresponding reduction in maintenance and hazardous failures; it increases the margins against carbon deposition, provides a better oil for auxiliaries, and eases the problems of supply, particularly when operating with other NATO navies.

The work undertaken during the last five years has demonstrated both the power and the limitations of laboratory testing in establishing effective solutions to practical problems. Small scale experimental work has proved invaluable as a means of testing different theories of failure for problems related to lubricating oil but it is difficult to know whether all the relevant aspects of the service environment have been accurately simulated. Carefully monitored shipboard trials are therefore essential to build up confidence in any proposed solutions. Even when utmost care is taken, the complexity of the oil chemistry, coupled with the wide variety of conditions encountered in warships' machinery, create circumstances where no change to the lubricant can be made without some element of risk. As the tin oxide problem illustrates, that risk may take as long as twelve years to make itself apparent.

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