MARINE GEARBOX EXPLOSIONS

A REVIEW

BY

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This article is based on a presentation given by Mr. D. McNeill of Y-ARD Ltd., Dr. M. H. Holness of NGTE, Cobham, and the author to the Institute of Marine Engineers on the 2nd March 1981, and with whose agreement it is reproduced here.

Background

In October 1969, a major explosion occurred in the gearbox of the Canadian frigate *Kootenay*. In June 1970, an explosion occurred in the gearbox of a shore-test set for a R.N. machinery installation. Consequently, in July 1970, the Director of Engineering of the Ship Department set up a Working Party with the following terms of reference:

(a) To investigate previous instances of explosions in gearboxes.

(b) To investigate the causes and mechanisms of such explosions.

(c) To recommend lines of investigations to be carried out to reduce the risk of a future explosion in a gearbox.

The eventual membership of this Working Party comprised representatives of three major marine gear manufacturers in the U.K.—David Brown Gear Industries, GEC Marine and Industrial Gears, and Vickers; of the Admiralty Oil Laboratory (now NGTE, Cobham) and the Admiralty Materials Laboratory (now AMTE, Holton Heath); of the gearing and scientific advisory sections of the Ship Department; and of Y-ARD Ltd. The Gearing Section of the Canadian Defence Headquarters was kept informed of the progress of the investigations and they assisted in providing information and comment. Co-operation was received from the staff of the Safety in Mines Research Establishment at Buxton, Derbyshire, from Lloyd's Register of Shipping, and from various individuals in shipping and industrial companies, in universities, in other research establishments, and in the MOD(PE).

The initial investigations and preliminary conclusions of the Working Party, based on work to the end of 1972, were presented in an Interim Report in the spring of 1973, and the final report was published in January 1980. Most of the work referred to in this article was published in classified reports during the lifetime of the Working Party, and the progress made up to 1977 was presented to the World Gearing Congress in Paris in June of that year[1].

The Working Party, having set in hand a number of activities in parallel, could not always await the confirmed outcome of one investigation before starting the ensuing one. However, with the benefit of hindsight, it is now possible to attempt to give a logical progression which, of necessity, could not always be followed at the time. This article analyses the causes of recorded incidents of gearbox explosions and, because of the predominance of bearing failures, examines the design and installation of bearings. But why do such failures sometimes cause major explosions, sometimes minor explosions, and sometimes merely oil ignition without explosion? The article describes the efforts made to learn more about the atmospheric conditions in a marine gearbox but, however much better this is understood, there is no guarantee

TABLE I—*Summary of gearbox explosion incidents*

Item	*Date*	*Installation*	*Oil Ignition Inside Gearbox*	*Gearbox Explosion*		*External Fire*	*No. of Casualties*		*Probable Cause*
				Minor	*Major*		*Dead*	*Injured*	
1	28 Feb 48	H.M.S. *Devonshire*	Yes	Yes	No	No	Nil	Nil	Bearing and/or gear tooth failure
2	28 Nov 60	H.M.S. *Hampshire*	Yes	Yes	No	No	Nil	Nil	Rub in manual clutch
3	Mar 62	S.S. *Verena*	Yes	No	Yes	Yes	6	Nil	Flexible coupling failure
4	21 Mar 63	H.M.S. *Kent*	Yes	Yes	No	No	Nil	Nil	Rub in manual clutch
5	Dec 64	S.S. *Seatrain New York*	Yes	No	Yes	Yes	Nil	Nil	Coupling bolt or gear rim failure
6	16 Sep 65	H.M.S. *Hampshire*	Yes	Yes	No	No	Nil	Nil	Bearing failure following oil starvation due to maloperation
7	Sep 65	S.S. *Malmöhus*	Yes	Yes	No	No	Nil	Nil	Journal bearing failure
8	Aug 66	Rolling Mill	Yes	Yes	No	No	Nil	Nil	Tapered roller bearing failure
9	15 Feb 67	R.F.A. *Regent*	Yes	Yes	No	No	Nil	Nil	Overheated due to loose component fouling main turning gear clutch
10	1967	CEGB Tilbury 'B'	Yes	Yes	No	No	Nil	Nil	Thrust bearing failure
11	30 May 68	Naval Transmission Test Facility	Yes	Yes	No	No	Nil	Nil	Overheating in fluid coupling due to excessive windage in absence of cooling oil supply
12	23 Oct 69	H.M.C.S. *Kootenay*	Yes	No	Yes	Yes	9	53	Failure of all bearings on primary pinion line
13	30 Jun 70	Naval Machinery Test Facility	Yes	No	Yes	Yes	Nil	Nil	Journal bearing failure
14(a)	18 Sep 69	Industrial	Yes	Yes	No	No	Nil	Nil	Tapered roller bearing failures
(b)	31 July 70	Pump	Yes	No	No	No	Nil	Nil	
(c)	21 Aug 70	Drive	Yes	Yes	No	No	Nil	Nil	
15	16 Apr 71	U.S.N. *Caliente*	Yes	Yes	No	No	Nil	Nil	Journal bearing failure
16	4 Jun 71	H.M.C.S. *Skeena*	Yes	No	No	No	Nil	Nil	Journal bearing failure
17	8 Jun 71	H.M.C.S. *Chaudiere*	Yes	No	No	No	Nil	Nil	Locating thrust bearing failure
18	26 Oct 71	M.V. *Maihar*	Yes	No	Yes	Yes	Nil	Nil	Rub in vicinity of clutch
19	Nov 71	H.M.S. *Zulu*	Yes	Yes	No	No	Nil	Nil	Journal bearing failure
20	8 Dec 75	S.S. *London Pioneer*	Yes	No	Yes	Yes	Nil	2	Flexible coupling failure

that oil ignition will not occur. The article therefore also examines the various means of limiting subsequent damage and the provision of warning and corrective devices. Finally, the conclusions and recommendations of the Working Party are given.

Recorded Incidents

Despite intensive enquiries of many authorities in the industrial and in the marine fields, relatively little evidence of the causes of explosions in gearboxes came to light, although it became clear that the incidence of explosions was greater than originally thought. Lloyd's Register of Shipping reported five such occurrences during the period from 1960 to 1978.

Twenty explosions in gearboxes in the Merchant Navy, Royal Navy, and Industrial environment are given in the Appendix and are summarized in TABLE I. The basic qualification for inclusion as an incident is ignition of the oil inside the gearbox. Of the twenty incidents recorded, twelve led to minor explosions (those contained within the gearcase) and six led to major explosions involving violent rupture of the gearcase. In the other two events, oil ignited but there was no subsequent explosion.

The major explosion in H.M.C.S. *Kootenay* and the non-explosive incidents in three other Canadian vessels, *Skeena, Chaudiere,* and *Fraser,* are discussed in an article by Mr. D. K. Nicholson also in this issue of the *Journal.*

The major explosion in a shore test facility in 1970 occurred when the gearbox combining the output of two steam turbines was operating in a one turbine only, ahead, full-power condition. The main gearwheel forward journal bearing failed because of a complicated interrelationship of many factors including the influence of static and dynamic forces emanating from the main shaft flexible coupling and the orientation of the journal attitude relative to the bearing joints and oil gutterways in this particular operating mode.

The explosion occurred after approximately one hour's running under the above conditions. Before the explosion, no recorded data indicated impending failure or malfunction of the gearbox; no unusual noise was heard; and the airborne noise level was low. Instrumentation fitted to each main gearwheel journal bearing consisted of one Admiralty-type spring-loaded thermocouple contacting the back of the medium wall bearing shell located at the position of minimum film thickness for two-turbine, full-power, ahead operation. Throughout the trials immediately before the explosion, the thermocouple in the forward main gearwheel journal bearing recorded virtually constant temperature below that of the lubricating oil supply temperature, indicating a possibility that this thermocouple was open circuited and reading cold junction temperature.

After the explosion, examination revealed that the forward main gearwheel journal bearing had suffered a major wipe, exposing the steel backing, with evidence on the journal and bearing of steel-on-steel contact. The after bearing showed no signs of wiping. Examination of the thermocouple in the forward bearing did not confirm that it was open circuited and, when heat was applied to the whitemetal surface, the thermocouple responded; also, when check calibrated, the thermocouple was apparently satisfactory. The low temperature recorded immediately before the explosion has not yet been fully explained, but it may be associated with the fact that the location of the thermocouple was well away from the position of maximum temperature of the bearing under the particular single-turbine, ahead operating condition, and that the thermocouple more readily read the termperature of the heat sink formed by the bearing housing than the local hot spot within the bearing itself.

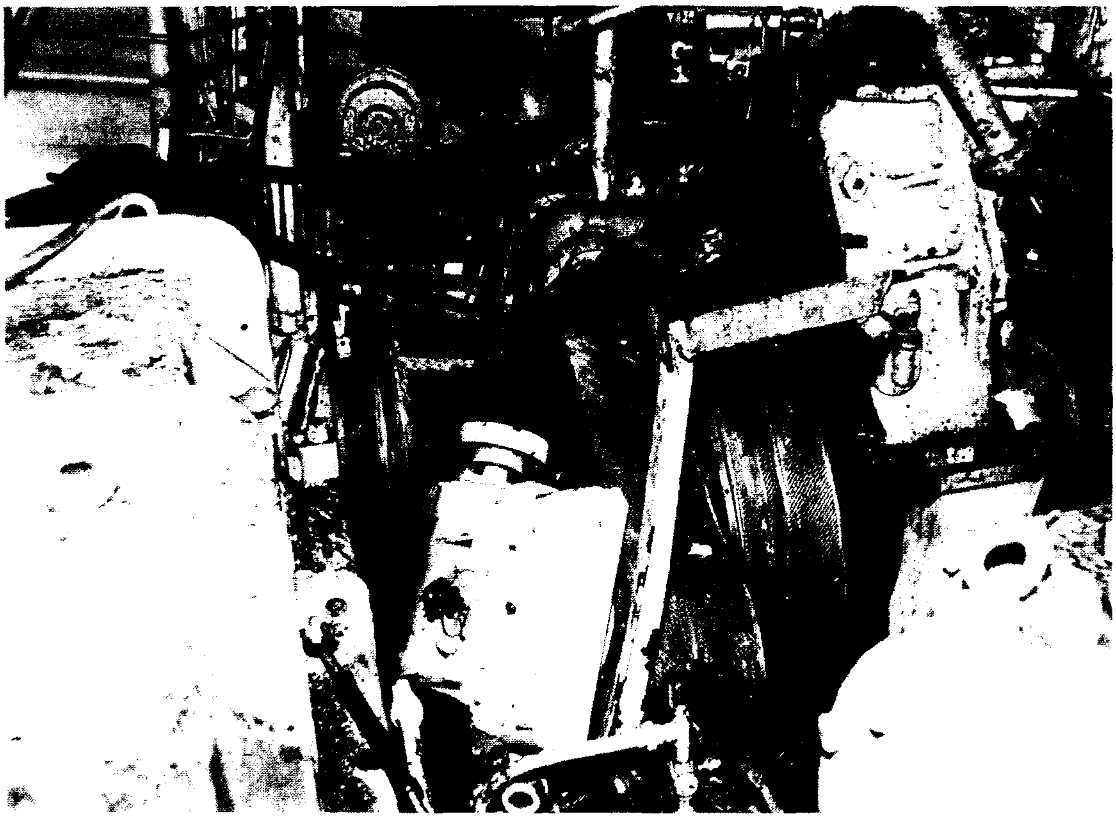

FIG. 1—'SEATRAIN NEW YORK' GEARBOX

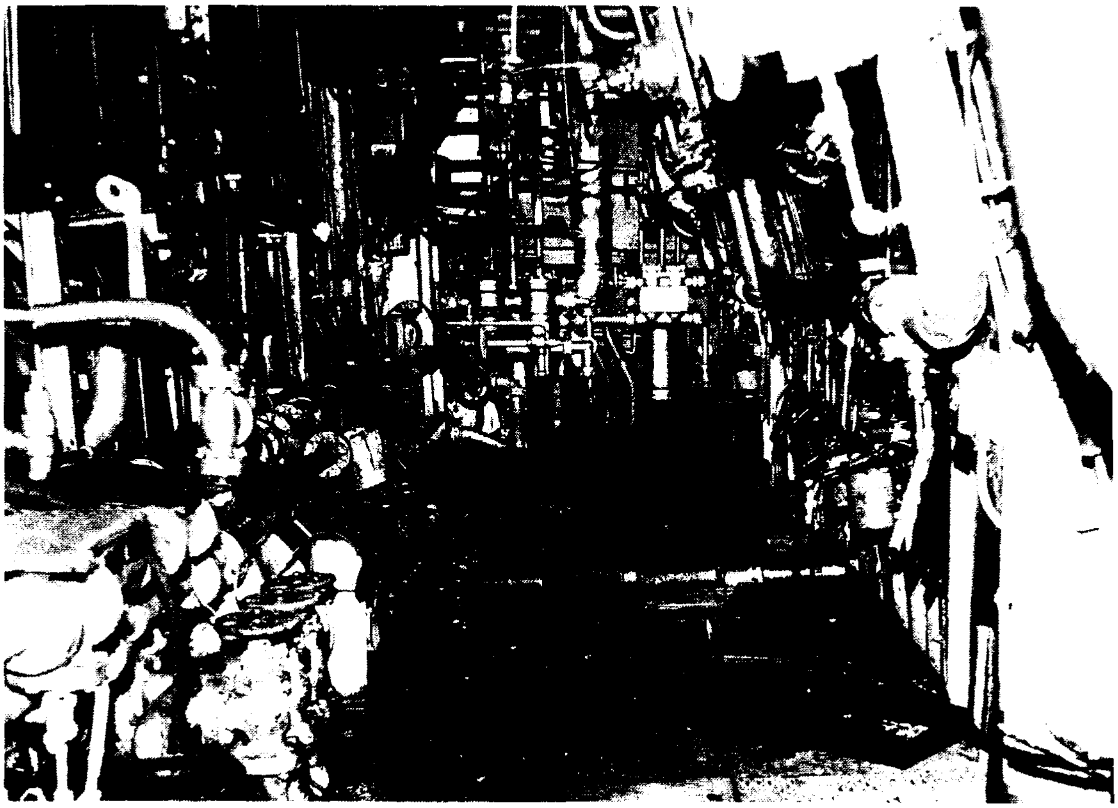

FIG. 2—'SEATRAIN NEW YORK' FIREROOM

At the time of the explosion, an identical prototype gearbox was also undergoing trials and had apparently operated successfully under similar single-turbine, full-power conditions for a period of four hours. Examination of this gearbox, undertaken as a result of the explosion, revealed that a minor wipe had occurred in the forward main gearwheel journal bearing at the same position as the major wipe on that of the gearbox in which the explosion had occurred.

In the matter of loss of life or injury, the more serious of the five incidents in merchant marine vessels were those in *Verena* and *London Pioneer,* but it is interesting to note that there were no casualties in the *Seatrain New York* despite spectacular damage (FIGS. 1 and 2) because machinery was being operated from a remote control room. By comparison, other incidents have been minor and very little factual evidence was available as to the precise conditions existing at the time. Generally, the attitude of many of those concerned with these cases was that the malfunction which gave rise to the explosion was obvious and, after design changes were effected, the matter was forgotten.

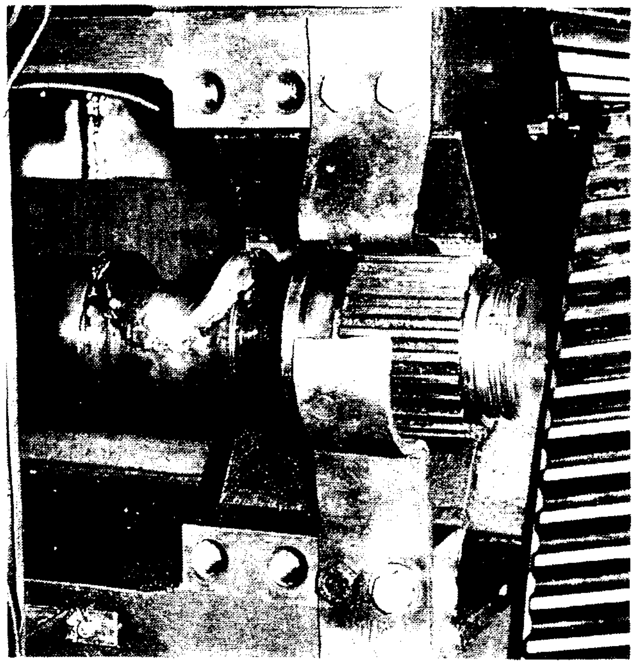

FIG. 3a—H.M.S. 'ZULU' JACKSHAFT BEARING JOURNAL

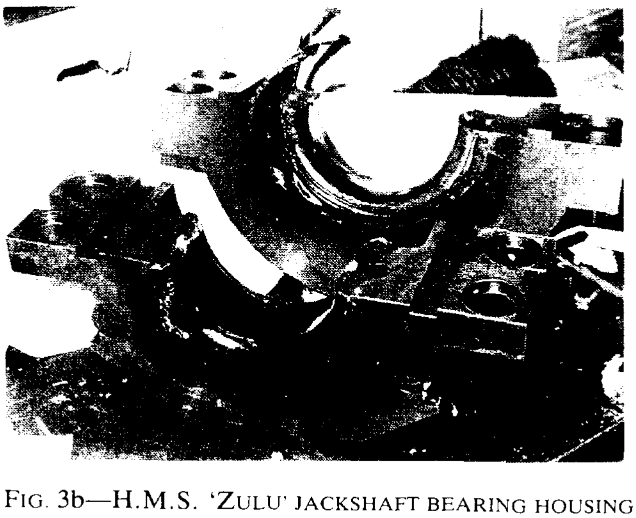

FIG. 3b—H.M.S. 'ZULU' JACKSHAFT BEARING HOUSING

A better documented example of oil ignition contained within the gearcase is that in H.M.S. *Zulu* (FIG. 3) when a lightly-loaded steam-turbine jackshaft bearing failed. Popping noises and discharge of smoke through joints were reported, followed several minutes later by a heavy grinding noise. 'Flashing' or 'sparking' at some distance away from the bearing in distress, visible through clutch inspection sight ports, was also reported.

An unusual cause was diagnosed for a minor explosion that occurred during the shore trials of another Royal Naval machinery installation: overheating was caused by windage and churning in the astern fluid coupling when the cooling oil supply was interrupted while the coupling was being operated in an off-design condition. Subsequent inspection revealed no evidence of any rubs.

TABLE I summarizes the probable causes of the heat source leading to ignition. No differentiation is made between a heat source igniting an already present flammable atmosphere and a heat source creating the flammable atmosphere and then igniting it. Of the six major explosions, two were probably caused by bearing failure, one by rub by a clutch disc carrier, and three by failure of mechanical components.

Of the twelve incidents involving minor explosions, eight were caused by bearing failure, three by rubbing, and one by heating due to windage. The two cases of oil ignition with no subsequent explosion are also associated with bearing failure. The design and installation of bearings are therefore worthy of attention.

Bearings

Detailed discussion of bearing design is outside the scope of this article but, as wrongly assembled bearings and incomplete recognition of off-design and abnormal operating states are included among the causes of oil ignition, the Working Party recommended that detail design of gearing in respect of calculations and proposals for journal and thrust bearings and shaft seal arrangements should be subjected to independent audit. In particular, the review of the design of journal bearings should include checks of:

(a) the position of bearing load lines and lines of minimum oil-film thickness under all modes of operation of the prime movers including no load condition;

(b) the location of oil inlets and line of bearing split;

(c) the location, number, and type of bearing sensors;

(d) the method of location of bearing shells to ensure that bearings cannot be assembled incorrectly either on initial build or after opening up for maintenance.

It was also recommended that detailed and thorough analysis of system dynamic performance should be undertaken at the design stage with the object of identifying the steady and transient conditions on all thrust and journal bearings. This should be followed by practical measurement at the prototype trials stage, with further analysis and measurement of any subsequent modifications.

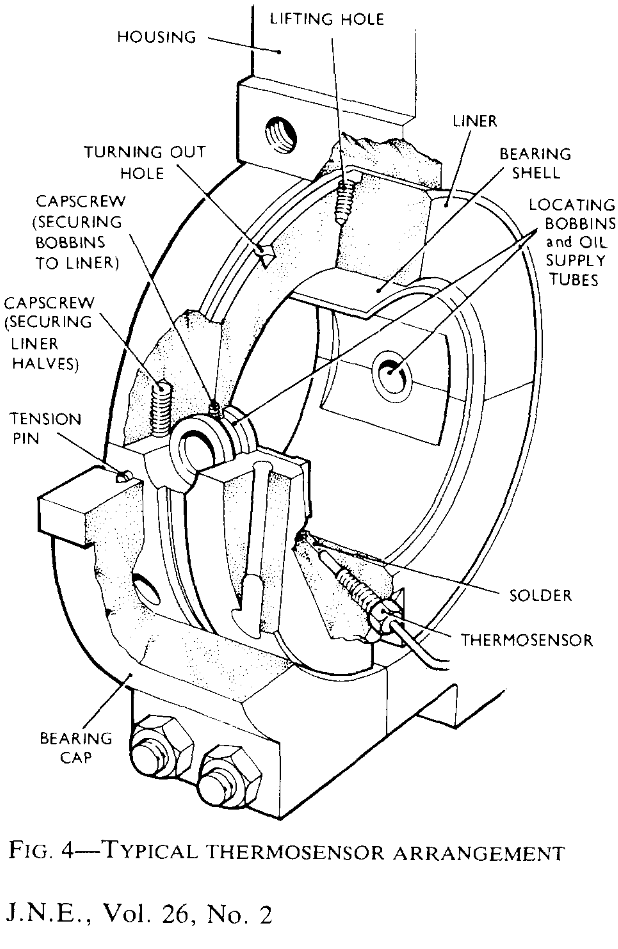

FIG. 4—TYPICAL THERMOSENSOR ARRANGEMENT

In some cases where bearing failure was the probable cause of oil ignition and where bearing indication was fitted, there was no apparent warning of rapid temperature rise.

In the gearing of R.N. surface ships of the 1960s, medium-wall steel shell bearings with thermocouples spring loaded against the back of the shell were used. Compared with earlier methods, this introduced a longer path between the surface of the bearing whitemetal and the sensing device, but the introduction of PTFE-insulated wiring greatly improved the overall reliability over that of earlier systems which were subject to oil penetration. However, it is clear from some of

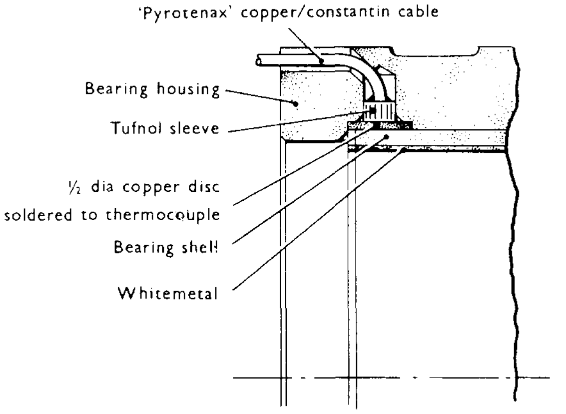

FIG. 5—TYPICAL THERMOCOUPLE ARRANGEMENT
Assembly Procedure:
Feed couple through liner from inside and press disc into seating. Scrape face of disc until nearly blending with curvature of bore. Lightly punch edge of seating in shell at diametrically opposed points to key disc in place. Finish scrape disc to blend into bore.
Note: Good contact of disc face with back of thin shell bearing is essential

the investigations that poor contact on the back of the bearing has given rise to spurious low-temperature readings. In the 1970s, the R.N. changed, in some installations, to resistance thermometers with the thermosensor spring loaded to the back of the bearing shell by an arrangement that was dimensionally interchangeable with that of earlier ships. FIG. 4 illustrates a typical thermosensor arrangement.

R.N. submarines have retained thermocouples in journal and thrust bearings for temperature monitoring. Where thin- or medium-wall shell type bearings are used, the thermocouple junction is made into the form of a disc (FIG. 5) rather than the more usual pencil-like probe, and this is press fitted into the housing so that there is a positive contact with the back of the bearing shell. In journal bearings of the thick-wall conventional type, the bearing sleeve is drilled to within, or close to, the whitemetal and a thermocouple having a small junction is secured by a screwed arrangement.

The introduction of propulsion machinery with more than one independent prime mover per shaft brought about multiple modes of operation and hence more than one load line and line of minimum oil-film thickness. This made it difficult to select a bearing oil inlet position and also made it necessary for the gear designer to choose one particular operating condition for which the thermocouple or electric thermosensor would be correctly placed. Usually the choice was for the full-power condition and this meant that the response to the cruise or other condition would be less than ideal. Current policy is to provide temperature measurement at all the major operating mode bearing attitudes. There is, moreover, a trend to recommend the provision of some redundancy by placing additional sensors axially displaced along the bearing, thereby avoiding the need to open up the gearbox just to replace a thermosensor which had failed (perhaps due to damage caused by a previous opening up).

Thus in modern naval gearboxes there is a marked increase in the number of temperature measurements, calling for sophisticated systems to sweep continuously the many measuring points and compare the results with preset values so that warnings or alarms may be initiated when deviations occur.

Flammability of Gearbox Atmospheres

Certain conditions must exist for the atmosphere inside a gearbox to ignite:

(a) The concentration of combustible matter must lie within its flammable range.

(b) An ignition source must be available. Whenever an ignition has been observed in a gearbox, it has been possible to discover a malfunction which could produce heat. This suggests that either the heat source ignites a flammable mixture or it creates a flammable mixture and then ignites it.

Mineral oil is not a highly flammable material and, unless heated well above normal ambient temperature, will not burn in air. However, in certain circumstances, flammable mixtures in air can form, and therefore an investigation was conducted to study these circumstances.

Two approaches were used for this investigation: first, to make measurements on the atmospheres inside running gearboxes to arrive at the 'normal' concentration of combustible material; second, to make measurements in the laboratory to study the way in which lubricating oil can be made to burn and to relate this with possible practical situations within a gearbox.

Preliminary work sampling gearbox atmospheres on board and at shore installations showed that gearboxes running without malfunction contain only small amounts of combustible material in their atmospheres. Oil drops are naturally plentiful in such gearboxes but these large droplets need not be considered to be important in establishing the conditions for ignition. The other effects of large droplets and their importance (realized later) are described below. Measurements were made of vapour content as well as droplets and these served to confirm that vapour contents are low and are related to the expected vapour pressure at the temperature in question.

In the laboratory, many attempts were made to produce a flammable atmosphere from lubricating oil by generating mist. Various spray nozzles and other mechanical means of mist production were tried, but in no case could a flammable atmosphere be produced. Such oil could, of course, be burnt as in a pressure jet burner but this was not considered to be relevant to the interior of a gearbox. When, however, a thermal method of drop generation was tried, flammable atmospheres were easily obtained.

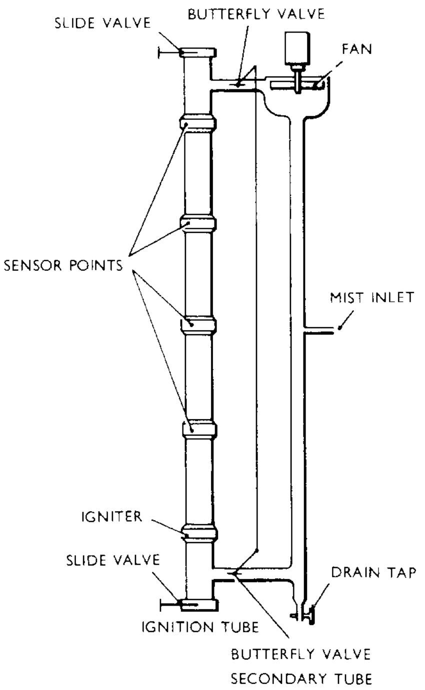

Fig. 6—Mist flammability apparatus

Apparatus was set up to study thermally produced mists. Mist was generated using a hot zone ($>$400°C). When oil came into contact with the hot zone, it evaporated and then recondensed as a mist with a droplet size of about 3 μm diameter. The condensed mist was substantially at room temperature and optically very dense and persistent in still air. Firstly, measurements were made of the constitution of the oil in the mist in order to determine whether any changes had taken place during its formation. No oxidation or thermal breakdown products were detected. Using the apparatus in Fig. 6, measurements were then made of the lower flammable concentration limit and this was found to be about 48—52×10^{-3} kg/m^3. This result did not vary beyond this range for a number of oils of different viscosity and additive content.

Using the knowledge gained in these experiments, trials were conducted on a Y100 (Whitby Class) gearbox driven by an electric motor (Fig. 7). These trials are described in detail in the Reference. The objects of the trials were:

(*a*) to make a thorough survey of the gearbox atmosphere in terms of mist and temperature;

(*b*) to inject thermally produced mist into the inerted gearbox to determine the distribution of mist within the gearbox.

Mist detectors were fitted to the gearbox in fifteen positions so that all the most likely portions of the interior were monitored. The results confirmed

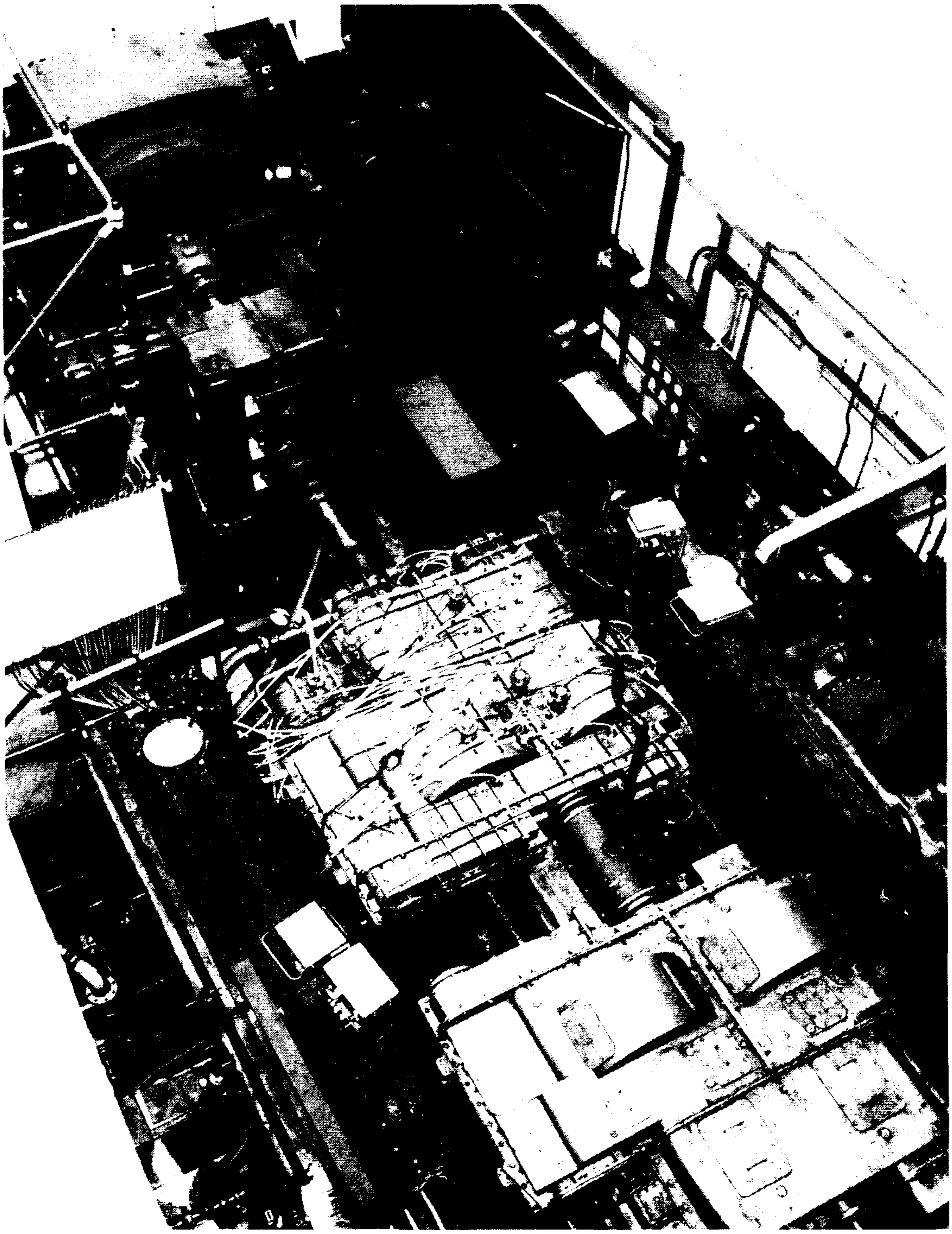

FIG. 7—MARINE GEARBOX ATMOSPHERE TEST RIG

those obtained in earlier trials on other gearboxes, namely that, when running normally, mist contents were very low—well below those necessary to form a flammable atmosphere. In the second part of the trials, when mist was injected into the gearbox, two specially built mist generators were used; each dissipated 12 kW and together produced mist at 0.4 m^3 per min. The gearbox was inerted with nitrogen during these experiments. With the gearbox stationary and with the lubricating system operating normally, the mist detector registered about 12×10^{-3} kg/m^3 when mist was injected. When the gearbox motor was started, the mist content fell almost immediately to the

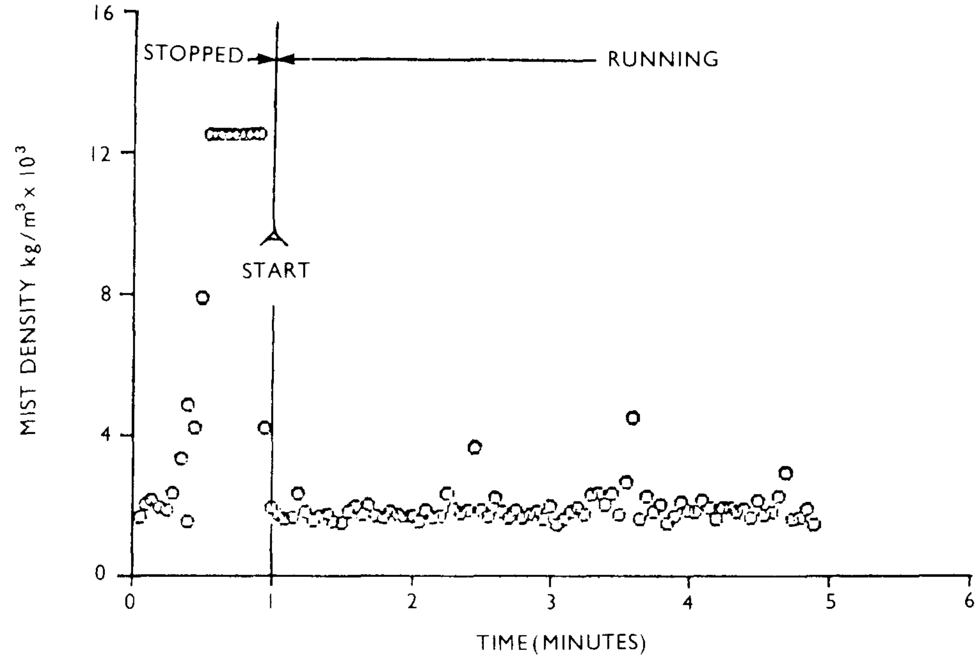

FIG. 8—VARIATION OF MIST DENSITY: STOPPED/RUNNING

values obtained without mist injection. FIG. 8 shows a mist detector read-out during this period indicating the rapid change in reading within seconds of the gearbox being started. This effect was repeatable and was undoubtedly due to the large oil drops impacting the mist droplets and so removing them from suspension.

Further laboratory work was done to demonstrate the effect of large drops on the mist. A quarter scale (compared with the Y100) model gearbox was built employing a double reduction system (FIG. 9). The gear surface speed was variable and included typical Y100 surface speeds. The gearcase was fitted with a mist detector and a mist generator which was capable of filling the gearbox with flammable mist while it was stationary. The same procedure was adopted as with the Y100 tests, i.e. the gearbox with lubricating system operating was filled with mist to the flammable limit and then the motor was switched on. The time taken for the mist concentration to fall to 10 per cent of the lower flammable limit was noted. The experiment was repeated at different speeds of the gearbox and it was remarkable that the mist was removed efficiently at speeds down to about one third of full speed. Thus, in the practical situation, if an abnormal bearing temperature or some other hot element that could give rise to oil mist was observed, the results suggest that the safest course for the operator to take is to reduce power but maintain sufficient gear speed to preserve the valuable 'scrubbing effect' of the large oil droplets.

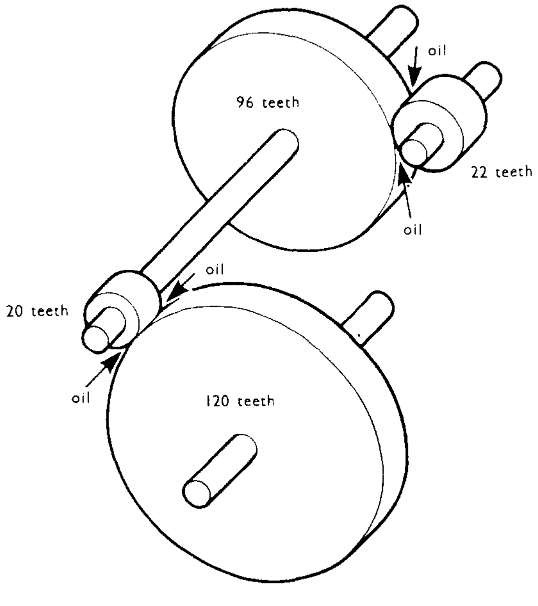

FIG. 9—ARRANGEMENT OF MINIATURE GEARBOX

Flame Suppression, Inerting, Containment, and Relief

However successful the efforts to eliminate the causes, the possibility of oil ignition must still be acknowledged. The potential defences against consequential disintegration of gearcases are:

(a) suppression of any flame in the immediate vicinity of the ignition;
(b) blanketing any flammable atmosphere with inert gas;
(c) containing any explosion with the gearcase;
(d) relieving any rise in gearbox internal pressure.

The Working Party sponsored the investigation and tests of flame arresters. These devices were intended to contain any flame generated by a failed bearing within the housing and to prevent the spread of flame throughout the gearbox. An open-celled reticulate foam made from a nickel-chromium alloy was tested and proved effective provided that the clearance between the shafting and the arrester wall was 1 mm or less. Such a clearance, however, increases the possibility of a rub between arrester and shaft. It was concluded that, on balance, it would be unwise to fit flame arresters in naval gearboxes operating under normal conditions for fear of doing more harm than good.

A signal from a bearing-termperature or oil-mist monitoring device could be used to trigger an inert-gas injection facility. The choice between nitrogen and carbon dioxide as an inerting medium depends on three factors:

Density:	Carbon dioxide is about one and a half times more dense than air, whereas nitrogen has almost the same density as air. A nitrogen/air mixture would be more stable.
Storage:	Carbon dioxide can be stored as a liquid; nitrogen is more difficult because of its low critical temperature. The volume of a nitrogen storage system would be about four times larger than that for the same mass of carbon dioxide.
Safety:	Expanding carbon dioxide produces dry ice crystals which carry electrostatic charges.

Trials of inert gas sponsored by the Working Party demonstrated that nitrogen and carbon dioxide were equally effective when used at the same mass-flow rate. Hence, there is a slight preference for nitrogen as an inerting as distinct from a firefighting medium because of the worries about static charges.

There remains the problem of choosing the siting and the setting of the device to trigger the signal so as to ensure sufficiently rapid inerting action without too frequent spurious initiation. The Working Party recommended that inert gas injection systems should not, under normal circumstances, be fitted to naval gearcases.

The maximum pressure generated by a major explosion is of the order of 0·95—1·035 MPa (140—150 lbf/in^2). In the past, gearcase covers have been designed purely as oil containment skins, and the yield strength of the weakest members of typical naval gearcase covers is of the order of 20—34 kPa (3—5 lbf/in^2). The weight penalty associated with any attempt to strengthen the gearcase to contain the maximum pressure generated by an explosion would be unacceptable. Thus, some form of relief system is required to moderate an explosion.

It is common practice in diesels to fit crankcase explosion relief valves. Research work by the British Internal Combustion Engine Research Institute has indicated a desirable relief area of 0·0685 m^2/m^3 (3 in^2/ft^3) of crankcase volume. The relief area required by Lloyd's Register rules, namely 0·0115 m^2/m^3 (0·5 in^2/ft^3) of crankcase volume, is based on a containment pressure of about 138 kPa (20 lbf/in^2), and would have to be increased by a factor of at least ten in order to cope with a major explosion in a gearbox. If it were decided to fit relief valves, a balance would need to be struck between relief valve area and increased resistance of gearbox covers. Undoubtedly, methods of designing gearcase covers can be devised so as to achieve more uniform strength but this may involve a weight penalty. At the same time, no significant improvement in strength can be made before the problem of pressure containment is transferred to other areas of the gearcase structure such as the oil sump or the oil drain tank. With relief valves, there would be the further problem of ensuring that the valves did not become flame throwers, particularly in compact naval installations.

The Working Party agreed that explosion relief valves were not the answer for a naval installation and that they might engender a false sense of security. It was agreed that, for new designs, an attempt should be made to design for more uniform strength and to aim at doubling the estimated yield pressure from 34 to 68 kPa (5 to 10 lbf/in^2). It was appreciated and accepted that this would involve a weight penalty compared with earlier designs.

Warning and Corrective Action

The earlier discussion on bearings emphasized the importance of early knowledge of temperature rise at the hottest spot in any bearing, and the need for many thermosensors per bearing to ensure that the hottest spot (likely to be a different spot for each operating condition) was covered.

In addition to monitoring bearing temperatures, other parameters that might be used in a gearbox health-monitoring scheme to provide warning include:

(a) gearbox atmosphere (oil mist detection);
(b) lubricating oil contamination;
(c) bearing oil flows;
(d) bearing housing vibration;
(e) journal vibration;
(f) journal attitude;
(g) gearbox noise level.

A commercial design of oil-mist detector tried at the controlled-atmosphere test facility was found to be unduly sensitive, but a simple modification to the electronics gave it an upper limit of detection of 3×10^{-3} kg/m^3 in its most insensitive form. Whilst this was acceptable for the gearbox at the test facility, a more complex gearbox might well produce transient concentrations of mist exceeding this alarm setting. A device with a wider range of alarm-level settings would therefore be desirable if oil-mist monitoring gained general acceptance. A compact unit could be designed to sense the gearbox atmosphere at, say, four positions carefully selected as a result of trials on a prototype gearbox. The problem remains, however, of choosing alarm settings to ensure that warning is timely without being spurious.

Contamination of lubricating oil is more appropriately a long-term indicator of problems rather than a warning of imminent explosion.

The measurement of oil flow in a bearing is likely to be of use only for investigation of a specific problem. Indication of a wiped bearing is more readily given by a reduction in the recorded bearing metal temperature or oil outlet temperature due to the greater oil flow through the increased clearance.

The measurement of journal vibration in the high-speed line or of gearwheel shaft attitude in the low-speed line would be a useful calibration