PREVENTING GEARBOX EXPLOSIONS

by

L.M. RUDD BENG (HONS) CENG MIMECHE
DR D.J.ROSE PHD CCHEM MRSC
DR M.H.HOLNESS PHD CCHEM FRSC M.INST.PETROL
(Fuels and Lubricants Division—DRA Pyestock)

ABSTRACT

A number of gearbox explosions have occurred worldwide since the 1950's. Condition monitoring equipment has been introduced since that time, based on temperature sensors. However, not all possible failure modes can be monitored in this way. This paper discusses the development of a second line of defence that may be employed to monitor the state of the gearbox atmosphere itself. This has the advantages that it is a completely separate instrument that monitors a large area of the gearbox, is independent of the physical constraints that restrict the use of thermocouples and its sensitivity may be tuned to suit the local environment. When used in conjunction with temperature sensors, it provides a comprehensive hazard warning system.

Introduction

A number of gearbox explosions took place in the late 60's and early 70's.[1,2] The most damaging of these involved the starboard gearbox in H.M.C.S. *Kootenay*; where nine men were killed.[3] At that time, little was understood about the flammability of gearbox atmospheres. Assumptions were made that atmospheres were always flammable and that only an ignition source was needed for an explosion to take place. Indeed, this could be the commonsense view when considering a gearing system containing many thousands of litres of oil. In fact, although so much oil is contained within the system, the oil is not in a condition which would make it available for ignition. A number of gearbox and other machinery trials which took place at that time clearly established that gearbox atmospheres were too lean in oil to burn. Since this is the case, a change in the normal conditions in a gearbox must have taken place to produce the flammable atmosphere which eventually ignited and developed the explosion.

Flammability of lubricating oil

Lubricating oil is not normally considered to be a flammable material but, if it is heated sufficiently (in excess of approximately 200°C) it will vaporize and a flammable atmosphere can be produced as long as the temperature can be maintained. The vapour content of gearbox atmospheres, at about 50°C, is therefore extremely low. However, if a localised hot spot should occur, oil vapour can be generated and condense in the form of very small droplets (oil 'mist') which can persist in the atmosphere even at low temperatures. The process is analogous to a steam cloud from a boiling kettle. Temperatures considerably in excess of 200°C (greater than 500°C) are required to generate significant concentrations of oil mist. These conditions could be met by a mechanical failure dissipating large quantities of heat which would raise the temperature of its surroundings. The findings of the H.M.C.S. *Kootenay* enquiry were that some 6000 kW were lost at the failed bearing, resulting in a temperature rise to at least 650°C. The heat generated would be capable of producing copious quantities of mist and the temperature of the surfaces could then act as an ignition source.

Atmosphere monitoring

Gearbox temperature monitoring was, in 1969, very rudimentary, although since then monitoring has been improved significantly, as recommended by the MoD Gearbox Explosions Working Party.[4]. In spite of this, an explosion took place in the gearbox of H.M.S. *Illustrious* in 1985 (FIGS. 1&2). This gearbox was fully instrumented according to the proposals of the Gearbox Explosions Working Party. All bearing were monitored; however the site of the failure in this instance was not instrumented since no mechanical contact was expected.[5] The question then arises of whether the failure on H.M.S. *Illustrious* could have been detected. The flammable mixture is invariably oil mist, although the failure itself produces heat. If it is not possible to detect a temperature rise, then a mist detector is the next line of defence. Although mist detectors are secondary monitors, compared to thermosensors, they can operate at a greater distance and thus monitor a wider area. Mist detectors were not recommended by the Gearbox Explosions Working Group because instruments available at that time were not well enough developed for this application.

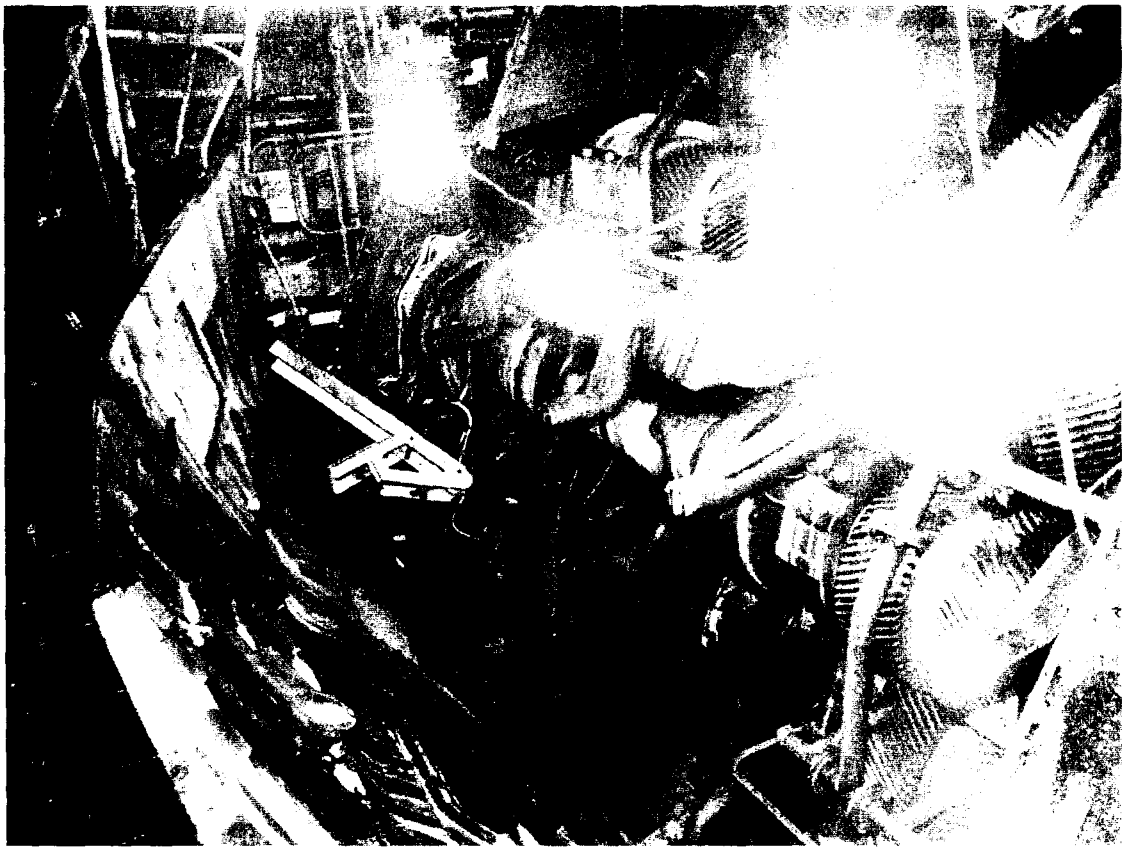


FIG. 1—DAMAGED GEARBOX OF H.M.S. 'ILLUSTRIOUS (PORT SIDE)
LOWER INBOARD COVERS ARE BLOWN OUTWARDS.
THE EFFECT ON THE STARBOARD SIDE WAS ALMOST IDENTICAL.

As stated above, oil mist is produced by evaporation followed by condensation. High temperatures are required to produce concentrated mists and the mist 'cloud' migrates outward from the hot zone. Inside a gearbox in normal conditions there is, of course, a great deal of oil in the atmosphere. The distinction between 'normal' atmospheric oil and the dangerous oil mist is entirely dependant on droplet size. Most of the oil in normal operation consists of large drops with only a very low concentration in the size range defined as 'mist', i.e. droplets less than 10 µm in diameter. Mist produced by condensation is almost mono sized at approximately 3µm diameter. The size of the droplet is important because this

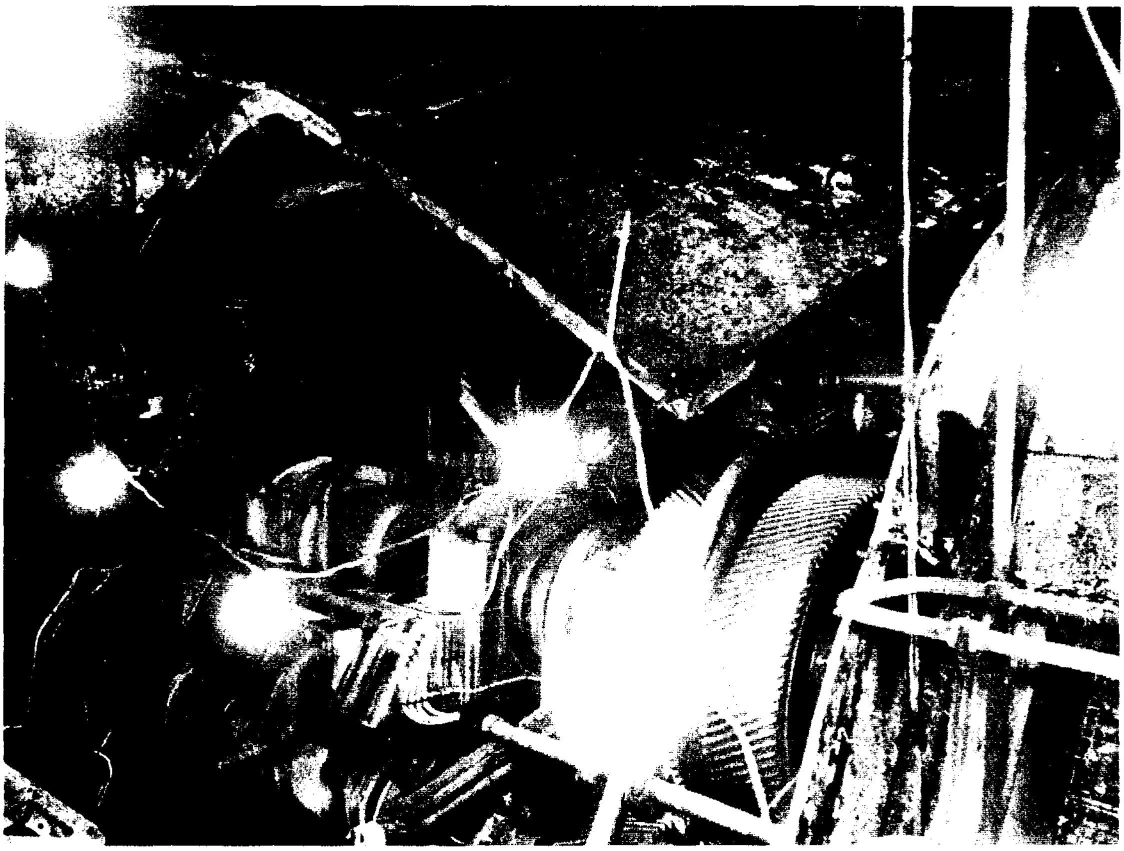


FIG. 2—TOP COVERS ARCHED UPWARDS
AGAIN THIS WAS MIRRORED ONTHE OTHER SIDE OF THE GEARBOX

determines its ease of ignition; droplets less than 10 μm vaporise very readily and therefore ignite with similar ignition energy to vapour. Larger droplets require extra energy to produce vapour before a flammable condition is achieved. Under operating conditions, the presence of large drops of oil, moving at high speeds, acts to remove mist droplets by impaction. This so called 'scrubbing' mechanism is very effective in reducing oil mist concentrations. The conditions inside a gearbox present a complex dynamic picture which, under normal running conditions, is in balance and not flammable. The presence of a failed component can move this balance until the mist concentration has risen to become flammable, and, at the same time, can present an ignition source.

In order to become flammable the mist concentration must rise to produce a mixture of suspended oil and air within the flammable range. Extensive experimentation has been done at the Defence Research Agency (DRA), Fuels and Lubricants Division, to establish the lower concentration limit of flammability for gearing oils. For this work a special flame tube was constructed, which could be filled with mist/air mixtures of known composition. Flammability was tested with a high energy igniter. The oil mist was generated with an electrically powered mist generator to simulate a failed component. The details have been published elsewhere[2]. The Lower Flammability Limit (LFL) for lubricating oils is 48 mg/litre by weight oil in air. For comparison, a normal gearbox atmosphere usually contains about 2 mg/litre suspended oil mist.

An atmosphere monitoring system for gearboxes can be designed, based on the same principles as that used for diesel engine crankcase atmospheres.[6] Mist sensing systems are usually optical and rely on one of two techniques, both employing a light emitter and detector:

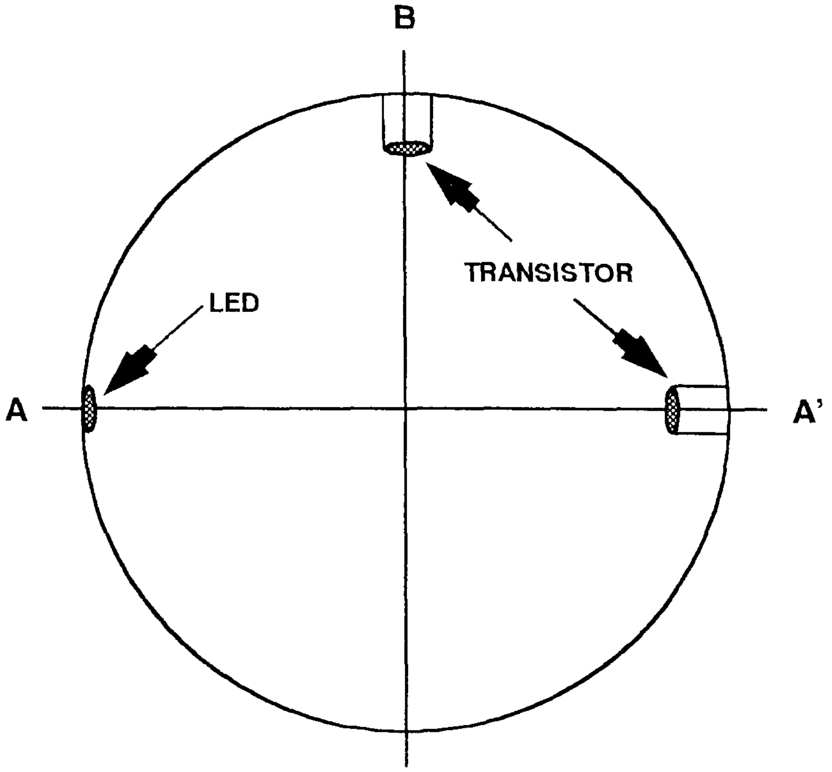
First

Probably the simplest approach, is to measure the decrease in light intensity transmitted to the detector. The emitter and detector are directly in line with one another, so that the decrease in signal recorded by the detector is due to the light absorbed and scattered by the oil mist droplets. Oil mists can be very dense and special optics are required for efficient light penetration. It is interesting to note that the light from a 800 W halogen lamp will not penetrate a 15 mg l^{-1} density oil mist, whilst a 240 mW at 880 nm, Light Emitting Diode (L.E.D) source is more than adequate.

Second

Detects the scattered light and places the detector at an angle, usually perpendicular, to the emitter to prevent any incident light being detected. This is not the most efficient scattering angle, however the signal generated by the detector is then solely due to scattered light. This approach is more versatile as it is more selective than obscuration. Light scattering tends to suffer from signal noise less than the obscuration detectors, especially in environments where large droplets are present. This is because larger droplets will obscure the detectors while not scattering light effectively. When the oil mist becomes very dense the scattered light detector loses response due to multiple scattering and absorbed light. In these instances, the response of the detector passes through a maximum at a given mist density and then decreases with increasing mist concentration.

Oil Mist Detectors (OMDs) may operate on either of these principles, but whatever the means of detection, the output signal needs to be calibrated with respect to gravimetric determinations. One type of detector employs both principles to enable a calibration correction to be made as the unit becomes dirty (FIGS. 3&4).



AA' - LIGHT ABSORPTION PATH   AB - LIGHT SCATTERING PATH

FIG. 3—SCHEMATIC OF THE ABSORPTION/SCATTERING MIST DETECTOR

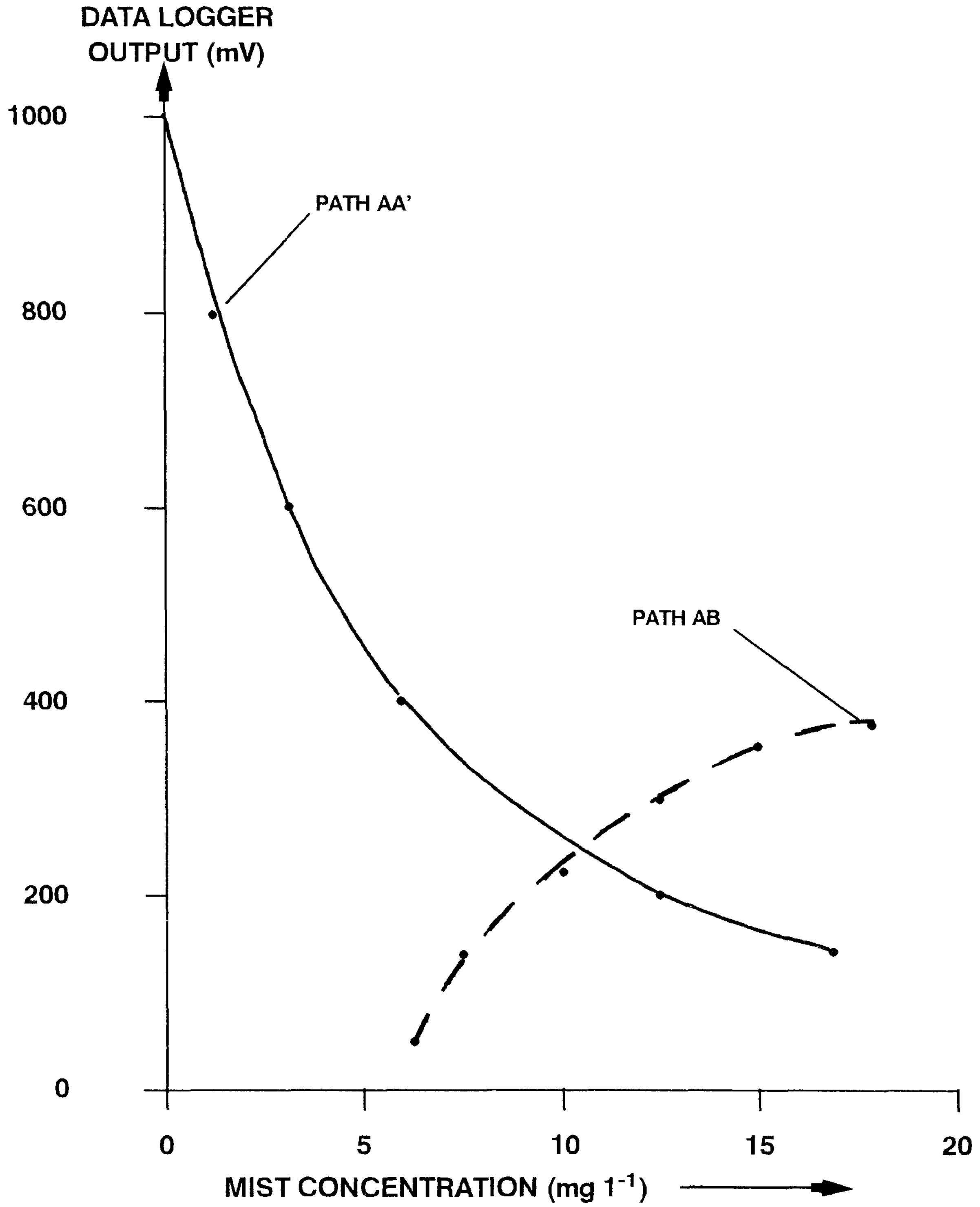


FIG. 4—DETECTOR RESPONSE CURVES

Gearbox atmosphere monitoring, to a certain degree, lost its impetus, after the results of the Gearbox Explosions Working Party were made available. This was partly due to the improved monitoring instrumentation fitted to ships as a result of the Party's findings. The H.M.S. *Illustrious* incident[5] renewed general interest in monitoring gearbox atmospheres once more and so after a span of nearly 20 years, a new market survey of oil mist detection systems was initiated.

Market survey and design evaluation

On review of the five oil mist detection systems available, the candidates were classified in two categories based on their mode of operation. These were:

1. Simultaneous site sampling and real time data computation.
2. Sequential site sampling and signal averaging.

Of the five systems available, one fell into the first category and four into the second. For the sake of economy only one candidate was selected from the second category. This was chosen on the basis of design maturity. As a basis for design evaluation[7] various parameters were chosen with which to assess the two candidates. These were:

1. Sensitivity towards oil mist concentrations.
2. System sensitivity.
3. System response time.
4. Alarm level range.
5. Accuracy and repeatability.
6. Reliability.
7. Application in RN gearboxes.

Description of the systems

System A

A schematic of the system is shown in (FIG. 5). The system was configured for simultaneous site sampling and real time data computation by measuring the oil mist concentration at every sampling site, at half second intervals and displaying real time results specific to each site. It consisted of a control unit and separate Detector Units (DU's) that could monitor up to 12 remote sampling sites. The measuring DU's were connected to a central control unit by cable, relaying power to the DU's and oil mist data back to the control unit. The measuring technique employed in this system was the scattering method. To draw oil mist into the DU

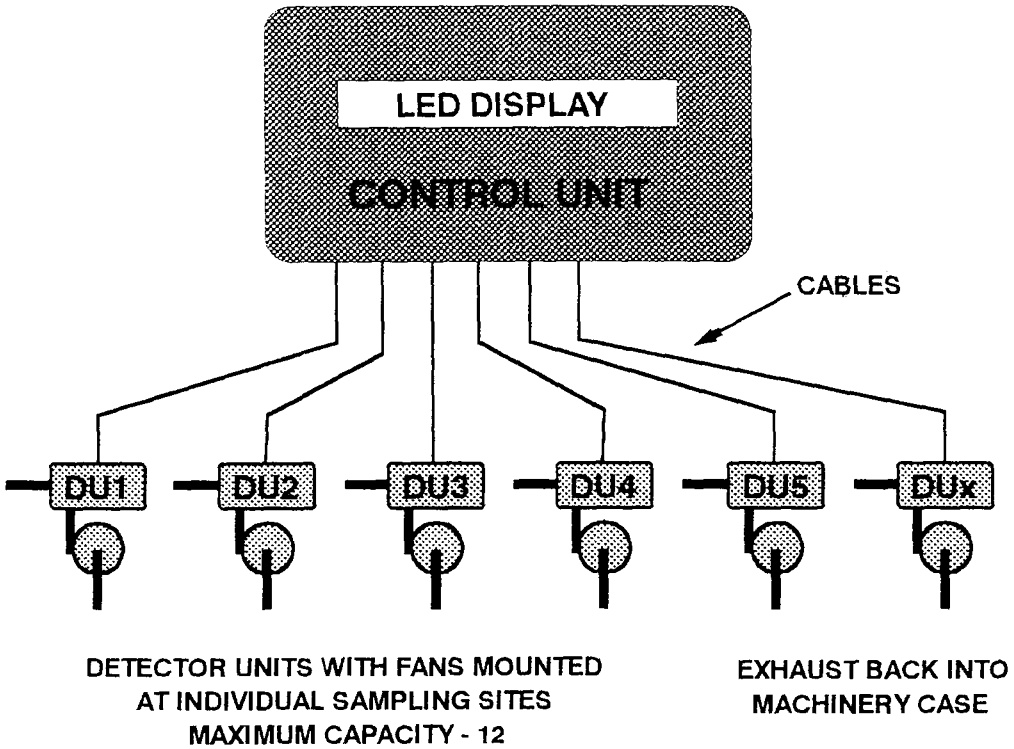


FIG. 5—SCHEMATIC OF SYSTEM A

measuring chambers either, a central fan, or individual fans mounted with DU's could be used. The exhaust gases from the fan or fans were fed directly back into the gearbox casing. The control unit included LED based display to indicate the condition of each site:

Green — System normal.
Amber — Greater than 50% of alarm level.
Flashing Amber — Greater than 80% (or greater than 50% with the mist concentration increasing at a rate greater than 0.5 mg/l per second).
Red — Greater than 100%.

The device could be set with an alarm level specific to each sampling site and included provision for a selective display. This was considered useful if a site required rigorous monitoring, such as after fitting a new bearing. Regarding resolution, in the range nil oil mist to 35% of a preset alarm level it was 1%, thereafter it was 5%. The alarm level range could be varied from 0.5 mg/l to 1.3 mg/l. Various relays were available to control external devices in the event of an alarm condition.

System B

A schematic of this system is shown in (FIG. 6). This system was configured for sequential site sampling and signal averaging by measuring oil mist concentration cyclically around sampling sites at one second intervals. The system had the capacity to monitor 10 individual sites, achieved by connecting pipes from each site to a central control unit. Oil mist was drawn from the sampling sites via a central system fan to a central measuring chamber, where the concentration of the mist sample was determined using the obscuration method. Again the exhaust gases were piped straight back into the gearbox casing. The system calculated a moving average of the oil mist concentration and compared this to a preset alarm level each time a measurement was made. If the average value exceeded the alarm value the device indicated the alarm condition via a display and control relays. The alarm indication was also made if the difference between a specific sampling site measurement and the average exceeded a user defined deviation limit, thus allowing one particular site, or set of sites, to be more critically monitored. System B had a nominal resolution of 5% of the preset alarm level which could be varied between 0.3 mg/l and 1.3 mg/l.

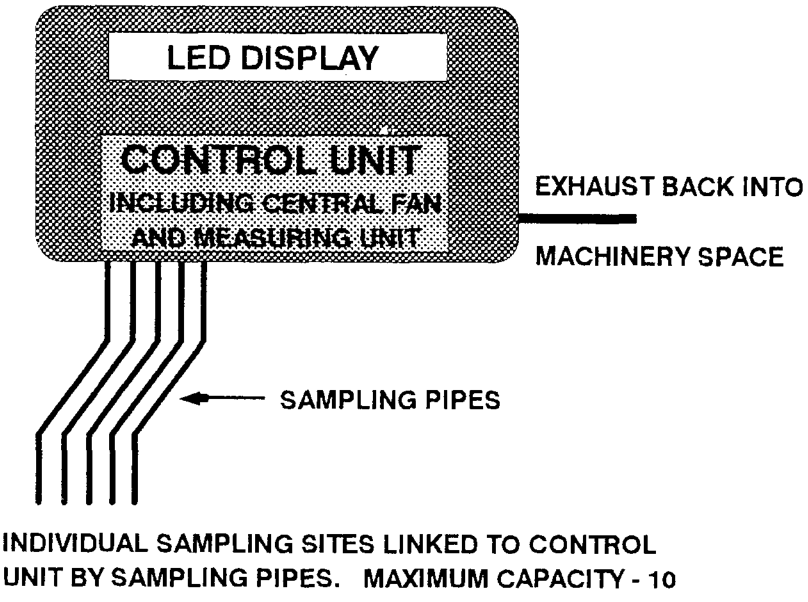


FIG. 6—SCHEMATIC OF SYSTEM B

Sensitivity to oil mist concentration

For each system, the response of the output signal with respect to oil mist concentration was exponential—a growth signal in the case of system A using the scattering method and a decaying signal for system B using the obscuration method. It was assumed that the manufacturers would have made best use of the response nature of either method in their respective instruments and that regarding this parameter there would be little difference in performance.

System sensitivity

In comparison, it was concluded system A was more sensitive than B simply due to the characteristics of the mode of operation. The advantage lay with system A, because unlike B, it could provide indication based on real time data, with associated benefits in terms of system response time. In comparison, B's signal averaging method damped signal transients, yielding it less sensitive.

System response time

Before reviewing this critical parameter, the factors comprising system response time are worth noting. These are:

(*a*) The time taken by a body of mist to travel from an oil mist generation point to a sampling site. This is a function of the mist front velocity and the mist generation rate.

(*b*) The time taken by a body of mist to travel from a sampling site to the measuring optics.

(*c*) Measuring circuitry response time.

(*d*) Mode of operation.

(*a*) is entirely dependant on the environment and has merely been highlighted for academic interest. As in the design evaluation, its effect was considered to be constant and independent of either system. Research could have been conducted to study its effect and the implications for design optimization. However, given the terms of reference of the study, likely complexity and high costs of such research, work on this topic was not undertaken. In preference, attention was focused on the effectiveness of system design and in particular the three system orientated factors and their effect on response time.

In comparison to (*b*) and (*c*), (*d*) was considered negligible and similar for each system.

Considering (*b*), both flow rate and pipe length were primary considerations. Although the fan flow rate for each system was not equal, they were sufficiently similar and low, leading us to ascribe most influence to the pipe length. Consequently, on a qualitative basis, it was envisaged system A would yield smaller travelling times, as its DU's could be placed in close proximity to the sampling sites with very short pipe lengths. In comparison, with B, longer pipe lengths would be necessary to carry a mist sample to the central measuring unit with a consequential increase in travelling time and a slower system response.

However, the main comparison between the two instruments was based upon the difference in their respective mode of operation. On this basis it was considered that system A was superior to B, simply because with B, if a hazardous mist increase occurred at a site coincidentally with the end of sampling, it would not be indicated until a full cycle around the remaining sampling sites was completed. Given the sampling rate of one second and the capacity to monitor 10 sites, in a worst case scenario, this would equate to a 10 second delay. In comparison with system A, which samples all sites simultaneously at half second intervals, such a hazardous situation would at worst be indicated within half a second. Regarding this critical parameter alone, it was concluded system A would yield a faster system response than B.

Alarm level range

Both systems had a maximum alarm level of 1.3 mg/l. However, from previous work[8] on marine gearboxes, oil mist concentration levels of 2.0 mg/l were reported. Therefore, attention was focused on the ease of modification pending the determination of an alarm level range ascertained by future trials. The manufacturers of system B stated that they could not alter their instrument range above 1.3 mg/l. System A had the capability to prescribe alarm levels for individual sample sites and therefore was considered superior to B in this respect.

Accuracy and repeatability

No data was given concerning accuracy or repeatability in either system specification. However, given the sophisticated optical cleanliness compensation facilities of both systems and that the primary role of an oil mist detector is comparison, as opposed to absolute measurement of condition, it was concluded accuracy and repeatability would be adequate for the purpose.

Reliability

Consideration on this topic spanned several areas and in particular the occurrence of false alarms. This was taken to be a function of:

- The stability of the system electronics.
- Integrity of the optical cleanliness compensation method.
- Non-hazardous oil mist transients exceeding preset alarm levels.

The first was considered to be adequate for both systems. Regarding the cleanliness compensation, it was considered system A had a slight advantage as compensation was achieved by comparing the change in relative response of the scattering and obscuration measuring circuits for each measurement, resulting in real time compensation. In system B, a compensation factor was calculated every 10 minutes by inducing a 'clean' charge of air in to the measuring chamber.

However, the main area of concern was non-hazardous oil mist transients. It was assumed these would be related to speed changes, clutch operation and normal thermal transients increasing oil mist concentration. It was assumed transient frequency and level would be specific to individual gearboxes and indeed sampling sites. Unfortunately, useful information was not available and consequently consideration was made of how effectively the candidate systems could accommodate such transients, pending future trial data. Although system B would damp transients by the averaging method, it was concluded A had the advantage in that each individual DU could easily be set with a specific alarm level. Consequently, if the transient character of a particular sampling site was determined, then the DU monitoring that site could be 'tuned' to suit.

A further consideration was the fault indication equipment available. Both systems provided a comprehensive self test and indication facility, including automatic and operator induced indication of lens cleanliness. In this respect system A again held the advantage as indication could be made for a specific DU, which could be cleaned without disabling the whole system. By comparison if system B made a similar indication the whole system had to be disabled while the central measuring cell was cleaned.

In terms of redundancy, system A was concluded to be superior to B, as risk of total system failure was less, given that it included a measuring system at each sampling site and could be configured with an induction fan for each DU, which was not the case with system B.

Application in RN gearboxes

System B's installation requirements were more extensive than A's, it included:

- The necessity of long and cumbersome sampling pipe runs.
- Electrical power.
- A filtered air supply at a set pressure.

By comparison, A required:

- Electrical power to the control unit and fans.
- Light cabling between the DU's and the control unit.
- Shorter pipe runs.

Although the advantage lay with A, one restriction was that DU's had to be mounted vertically to enable the DU's to be removed for cleaning.

Regarding compatibility in a marine environment, both systems were originally designed for marine diesel engine use and were both named by Lloyds as appropriate for this purpose. Aspects like oil splash contamination and vibration isolation had received attention.

Although both devices included external control relays to indicate and activate alarm action, however neither provided an electrical output signal of any kind. Therefore, regarding development potential and integration into a ship control system, it was judged system A would be more flexible, it being more software based than B. This was confirmed in the subsequent ship trial.

Laboratory Trials

Having reviewed both systems it was concluded that system A would probably be the most likely to fulfill the need for RN marine gearbox atmosphere monitoring. Consequently, laboratory based trials[7] were completed to confirm this and economically develop objectives for the subsequent ship trial. The main objectives, of the laboratory based experimental work were:

1. To compare the detector responses against one another and thermocouple response during a catastrophic bearing failure.
2. Confirm the suitability of one system for further investigation with a view to final RN use.

Test Facility description

For this section of work, a multi purpose model marine gearbox test facility was used at DRA Pyestock (FIGS. 7&8). The rig was similar in scale to a typical marine gearbox and comprised of salvaged Type 42 destroyer gear elements; simply one primary pinion driving a wheel with a gear ratio of 4.13:1. The rig was basically a 'spin' test rig, powered by a 150 KW electric motor, capable of forward and reverse rotation at 1500 r.p.m. or 3000 r.p.m. A test shaft/journal bearing was located at the other end of the pinion shaft. The test bearing was a steel backed white metal bearing with a diameter of 100mm and an l/d ratio of 0.5. In the bottom half of the test bearing and on the centre line, two K type thermocouples were located as shown in (FIG. 9). The thermocouple beads were located 3–4mm below the bearing surface. The bearing was loaded by an internally mounted hydraulic cylinder capable of producing a maximum bearing load of 185 kilo Newtons. A nitrogen purge system was incorporated into the rig to ensure the necessary degree of safety during experiments. The approximate free volume of the rig was estimated at two cubic metres and inspection windows were included for video tape recording.

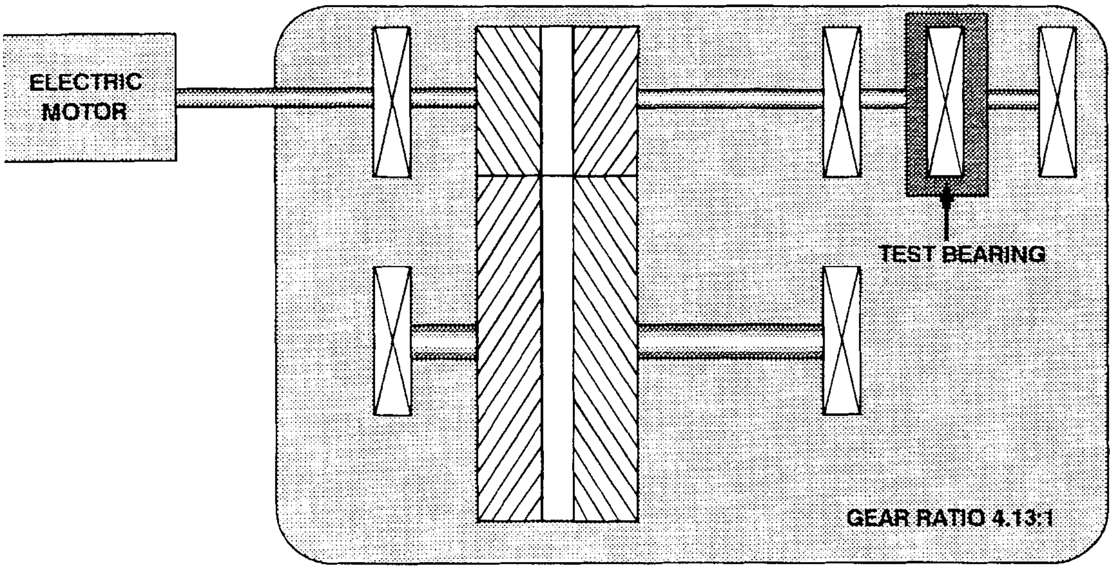


FIG. 7—SCHEMATIC OF THE MODEL MARINE GEARBOX TEST FACILITY

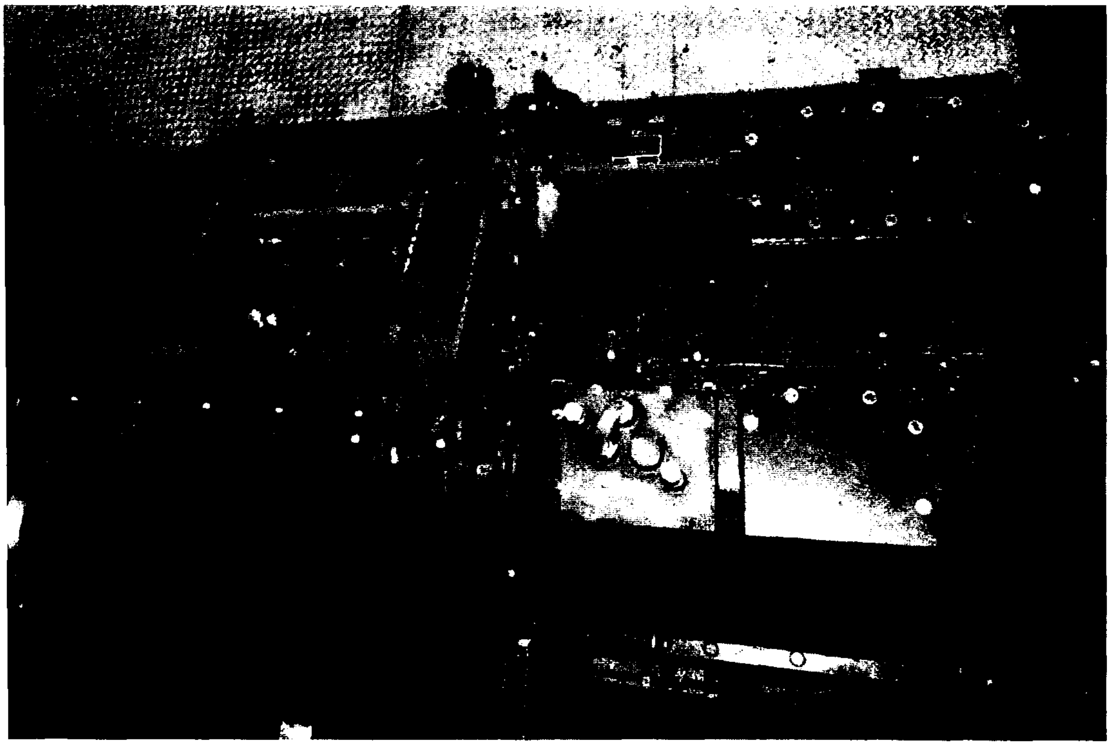


FIG. 8—THE MODEL MARINE GEARBOX TEST FACILITY

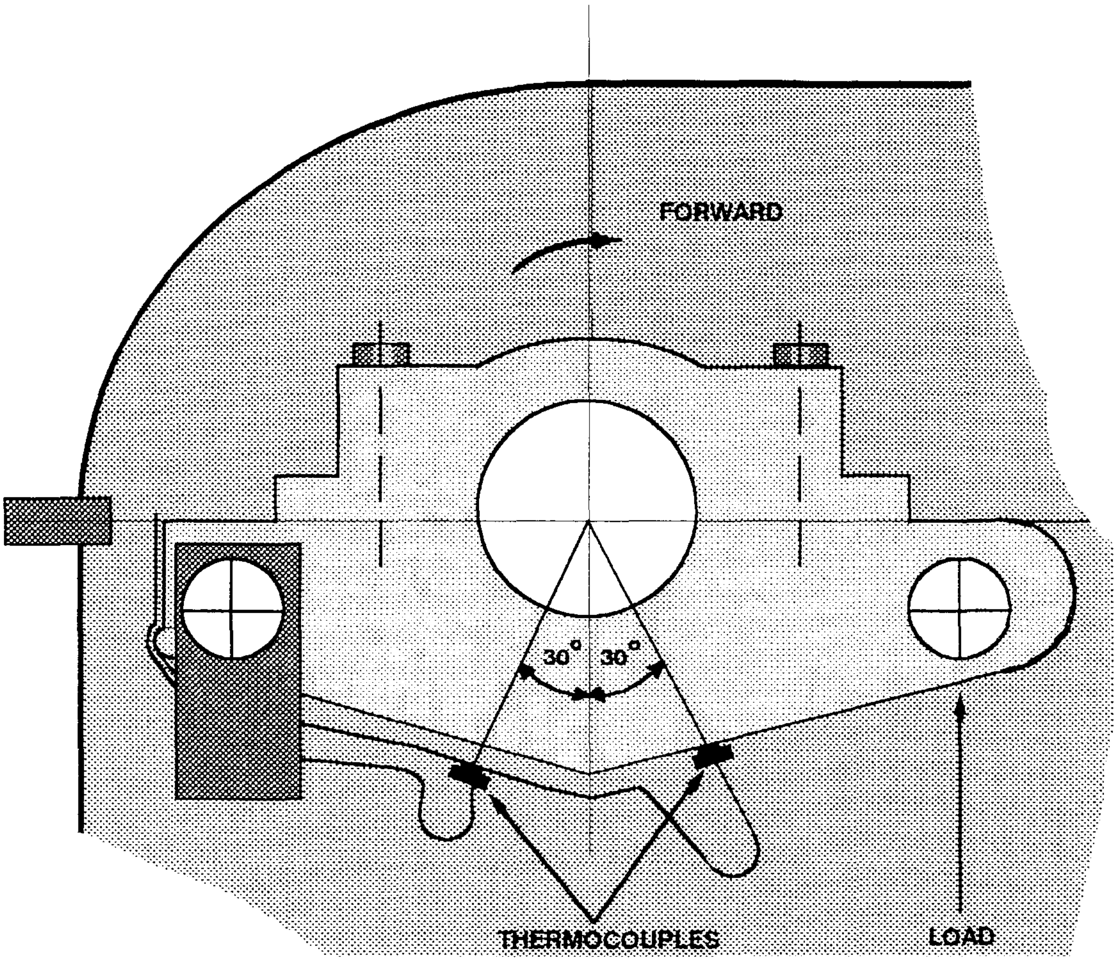


FIG. 9—THE TEST BEARING THERMOCOUPLE LOCATIONS

The OMD mounting site is shown in (FIG. 10). The mean centre was located 700mm from the test bearing and 200mm from the wheel gear coupling flange. The latter caused splashed and sprayed oil to intrude into the detector site to promote a realistic working environment. For system A, two standard DU's were available, therefore to achieve a fair test and assess the maximum response of B, it was re-configured to monitor only two sites.

A video system was used to record systems A's display, as it had no electrical signal output facility. On this film a clock and the test bearing thermocouple digital display were also recorded. For similar reasons, with system B a parallel connection was made at the measuring cell differential comparator and a thermo-graphic oscilloscope used to record this, the test bearing thermocouple outputs and the status of both system external control relays. Another video system was used to record mist generation from the test bearing via an inspection window.

Test procedure

Two identical tests were completed with the facility. A step input to the OMD systems was effectively imposed, as this was considered the most appropriate way to establish the required response comparisons. The step input was achieved by applying a single load to the test bearing sufficient to cause immediate thermal overload and bearing failure, resulting in oil mist generation. Prior to this steady state information was acquired.