INTEGRATED HEALTH ASSESSMENT OF ROYAL NAVY DIESEL ENGINES

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ABSTRACT

Diesel engine prime movers are utilized in all Royal Navy warships for power generation purposes. Additionally the new generation Type 23 frigate and minehunters etc. use diesel power for main propulsion. The cost effective use of these important and expensive capital assets is vital for both weapon and propulsion system performance and availability. There is much potential for improving the cost effectiveness of marine diesels through enhanced failure prediction, extending hours run between overhauls, reduced material costs etc. This article describes the RN's diesel engine oil sampling and analysis programme, utilizing advanced 'expert decision support' software and illustrates how traditional methods and advanced technology can be used to advantage.

Introduction

Diesel engines have always been important to the Royal Navy both as electrical generator prime movers, particularly since the introduction of gas turbine powered warships, and for main propulsion. Cost effective use of these assets has not always been possible for a variety of reasons:

- Fuel quality.
- Material shortcomings.
- Operating profiles etc.

Overall, however, the reliability of diesel engines in the RN has improved over recent years through:

- Better design.
- More effective maintenance.
- Training.
- Monitoring systems.
- Operator awareness.

Despite these improvements failures do still occur and engines are also removed for overhaul based on hours run rather than condition.

Analysis of lubricating oil condition, wear debris and contaminants has been used successfully in many areas including aero engines. The incorporation of a computer based Expert Decision Support (EDS) system to help interpret oil analysis results and subsequently diagnose faults is not so common. This article will concentrate on the development of the RN's programme.

Background

Traditionally the health of diesel engines in the RN has been assessed by a combination of:

- Monitoring operating parameters.
- Routine maintenance.

- Oil consumption and condition using a simple Go/NoGo test kit on board ships, which measures the physical properties of the oil.

A brief trial with Spectrographic Oil Analysis (SOA) for diesels was undertaken in the early 1970s. Unfortunately small sampling rates, long lead times for lab reports and difficulties in sensible interpretation of results led to its early demise. Despite the fact that the Fleet Air Arm had successfully used SOA for a number of years to monitor the condition of helicopter and fixed wing aircraft engines and transmission systems, diesel condition monitoring reverted to existing methods.

The importance of diesel engines increased dramatically, however, with the introduction of gas turbine warships: by the mid 1980s they were the prime mover for the majority of electrical generators in the fleet. In addition all minor war vessels e.g. fishery protection vessels and the newly introduced Type 23 frigate had diesel propulsion systems.

Achieving design reliability and maximizing the in service life of these important assets became a higher priority. Recognizing the logistical problems of failure prediction from previous trials, it was decided to attempt to maximize engine life through integrated health assessment techniques i.e. in:

- SOA.
- EDS system.
- Vibration Analysis.
- Performance etc.

A trials programme was proposed in October 1991 to take oil samples from 11 PAXMAN VENTURA 1MW generator engines fitted to Type 22 frigates and Type 42 destroyers. If an extension of hours was considered then a more informed judgement could be made on the engine's suitability. Additionally, with effective and timely logistic arrangements, failure prediction could also be achieved in a realistic timescale.

Rationale for oil analysis

There are many competing Condition Monitoring (CM) techniques available. In the early days of machinery use human senses alone were employed, indeed even today these senses are extremely important and often overlooked. Many modern CM techniques are little more than highly sensitive versions of those senses.

Many aspects of a diesel engine's condition have to be inferred from measurements of certain parameters which may be influenced by a number of environmental conditions and processes. In order to make sense of condition related information, often skilled personnel and sophisticated equipment are required.

All diesel engines wear to some extent. The product of that wear, debris, is normally carried along with the oil, although some may remain embedded in bearing material etc. The size, quantity, morphology and composition of wear particles can produce a signature of the wear process and provide clues as to engine health and location of defects. Different techniques are more suitable for a range of particle sizes. At the smallest (0—10um), spectrometric oil analysis is employed. Oil samples are passed through an analyser to establish the concentrations of wear metals, trace elements and contaminants. As normal wear products are generally small in size, say less than 10um, and spectrometers are capable of quantifying levels of contaminants too, it increases the potential for successful trending of a diesel engine's condition and invariably provides an early warning of impending faults. Therefore, combined with measurement of physical properties, oil analysis techniques are seen to be a suitable method to assess engine health.

EDS system

Expert systems are a branch of the science of Artificial Intelligence (AI). They are designed to embody the collected knowledge/experience of one or more human experts in a particular area. The system, a fully integrated suite of computer programmes, sorts data/information, and emulates the experts by handling expertise and reasoning which assists or advises decision makers. Expert systems cannot replace human beings but have the ability to routinely sort many thousands of pieces of information and provide likely solutions to problem areas.

The Ministry of Defence raised a contract in March 1992 for an EDS system capable of handling diesel engine health data, automatically analysing SOA results, interpretation and diagnosis of faults (FIG. 1).

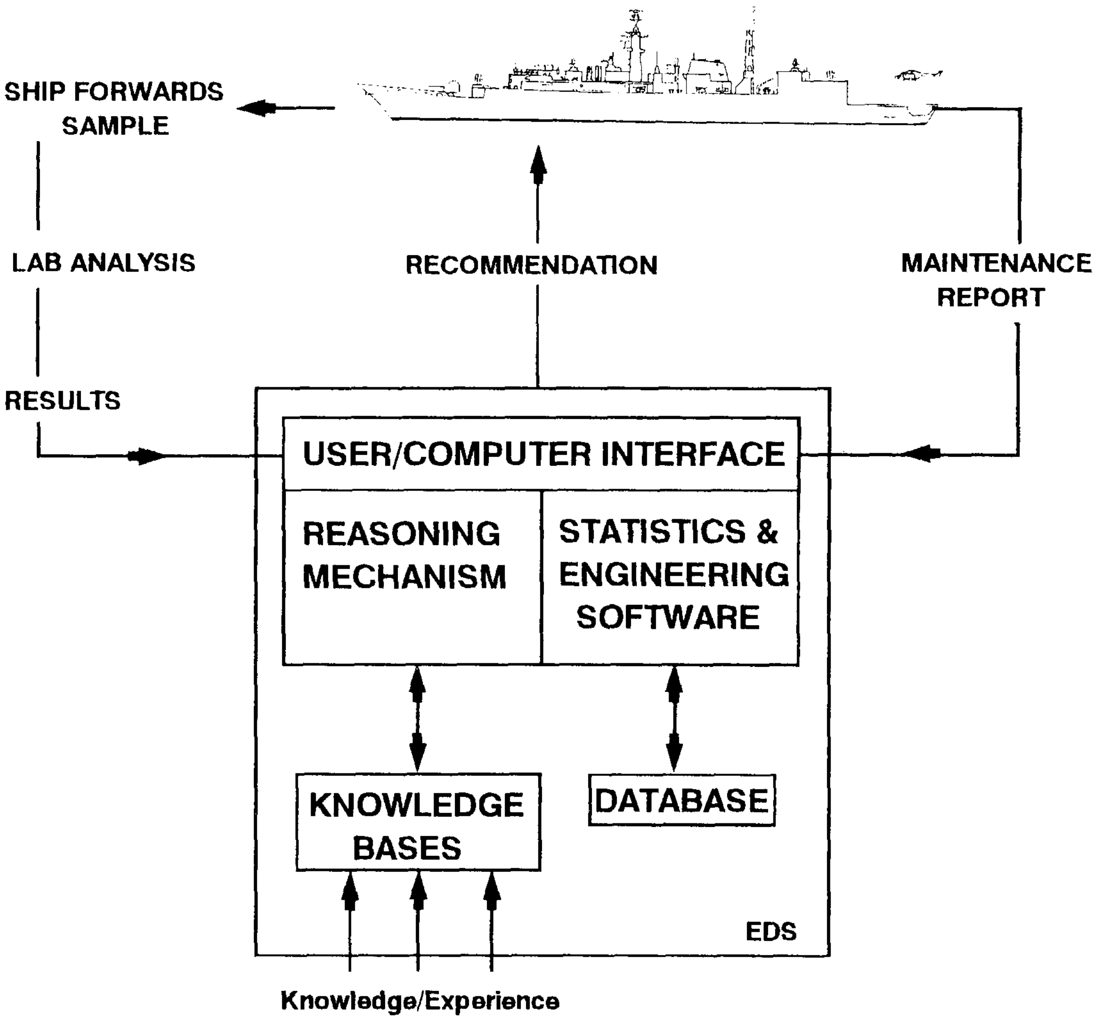

FIG. 1—OUTLINE EXPERT SYSTEM

The computer support package comprised a Dell PC 486/33MHz computer with 8MB RAM, 100MB hard disc, 5¼″ & 3½″ disc drives, super VGA colour monitor, Keyboard and Hewlett Packard Deskjet 500 printer. The system operated MS-DOS v 5.1 and was installed with an ORACLE relational database. The support package was provided to the RN before the start of the programme together with a standard EDS programme using relevant demonstration data sets to enable operators to become familiar with its capabilities.

Research

One of the most crucial phases of the programme was the research required in order to create the knowledge base. Intensive interviews with overhaul specialists, oil laboratories, user/maintainers and manufacturers were all required. The first stage was to take a holistic view of the engine, its purpose, operating pattern, construction etc. The general process of knowledge acquisition is shown at (FIG. 2).

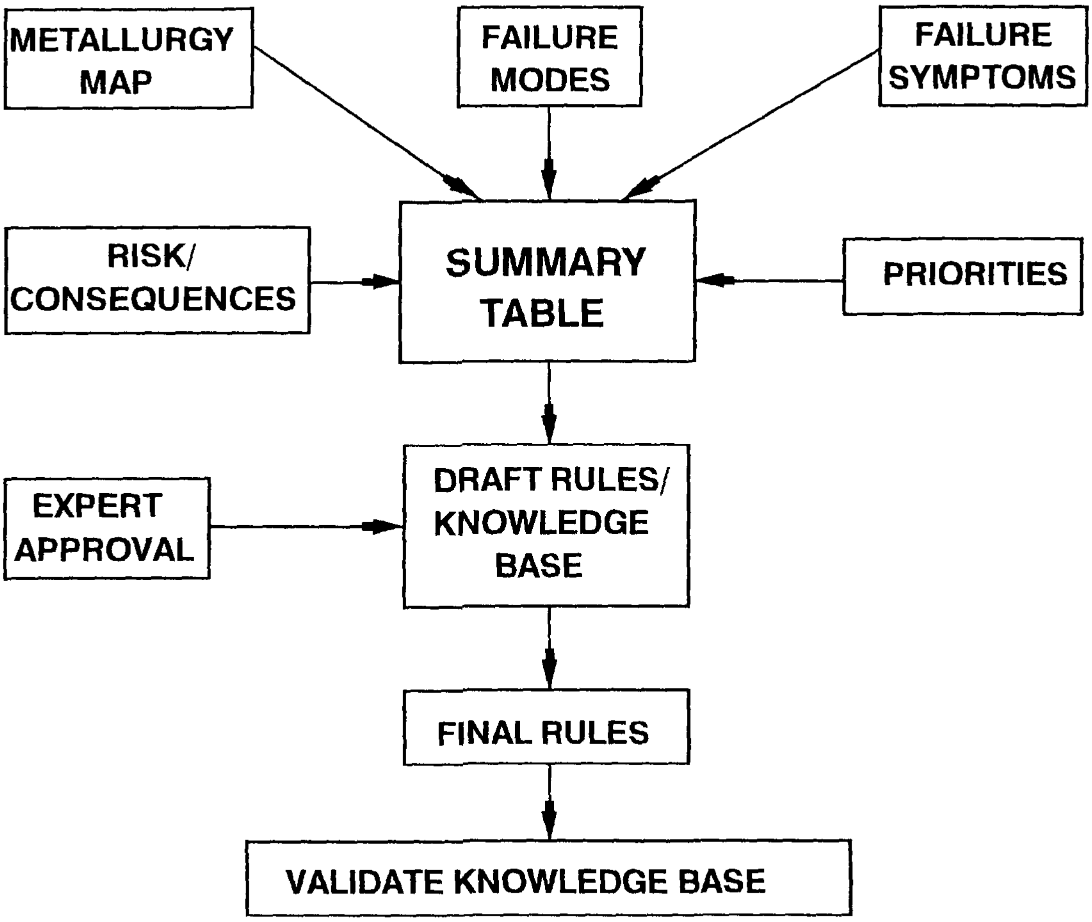

FIG. 2—KNOWLEDGE ACQUISITION

Metallurgy Map

Each individual material/component had to be assessed for the likelihood of a spectrometric technique's ability to measure effectively and expert system rules subsequently written. For some wearing components, such as piston rings, iron would naturally be easily measured. However for others such as large end bearings, the position was not quite so clear. These bearings are steel backed lead bronze with a lead/tin flashing:

The flashing is 90% lead 10% tin
and
The bearing 22% lead 4.5% tin 73.5% copper

Combinations of wear components also needed to be assessed. Aluminium in isolation, for instance, could come from a piston or turbocharger:

If in combination with iron, then piston & rings would be suspect.
If in combination with iron & chrome, then liner wear is also inferred.

Lubricants and cooling fluids in use were also assessed and analysed for possible linking effects with metals. A high proportion of the oil additive package is zinc based, therefore any zinc from wear metals would be swamped and not detectable. Contamination of the oil by sea-water has a harmful effect on bearings, leaching out lead from the flashing.

Failure modes/symptoms

The likelihood of each component failing was assessed using:

- Fleet surveys.
- Diesel specialist's knowledge.
- Spares take-off.
- Manufacturer's statistics.

The speed of a fault developing and signs/symptoms of that fault and its effect on other faults also needed to be considered.

Risk, consequences, priorities

For each component/fault/scenario the risk of failure and its likely consequences were then assessed. Impact on availability, safety considerations and financial consequences needed to be included in that process. From these, priorities for action/recommendation in each given circumstance could be evolved. The possibility of a camshaft bearing failure, for example, was assessed to be fairly low; the consequences of failure, however, were serious as repairs would be difficult and time consuming to achieve. Push rod cup ends have a higher occurrence risk but repairs are relatively easy and quick.

Knowledge base/rules

A summary table was compiled from much of the research work. Drawing all the threads together and, after weighing the relative importance of each part, reasoning, consequences and recommended actions, rules were formulated. Over 450 were needed initially; these ranged from the simple element to the combination of different wear metals (FIG. 3).

RULE NUMBER: 447

IF:

(1) Test Data is Diesel Engine Fluids
and (2) Aluminium is above profile
and (3) Aluminium is increasing moderately or increasing rapidly
and (4) Iron is above profile
and (5) Iron is increasing moderately or increasing rapidly
and (6) Chromium is increasing moderately or increasing rapidly

THEN:

Aluminium is in combination and from piston assembly
and Iron is in combination and from piston assembly
and 630 CK piston assembly - value = 3/10
and Risk is danger

Note: If all three metals are present, piston problems are well developed. So the risk is upgraded here.

FIG. 3—COMBINATION RULE

Logistics

In view of the problems associated with logistics in the early 1970's trial much effort was expended in ensuring a smooth routine. Arrangements were made for samples to be forwarded before the EDS system was finalized. All engines were post top overhaul and from ships not expected to refit for some time.

Monthly samples were taken initially, the Defence Research Establishment (DRA) at Cobham provided bottles and containers. Instructions for obtaining samples were issued in order to ensure consistency.

DRA Cobham conducted physical tests and forwarded samples to DRA Woolwich for spectrographic analysis. There were a number of benefits in sampling before the system came on line:

1. Historical data could be produced to provide background material and test the validity of EDS (albeit in hindsight).
2. Ships staff would become used to taking and forwarding samples.
3. Laboratory routines/equipment could be proved.
4. Delays in the logistics chain would be highlighted early and resolved before going live.

Potential weaknesses which could jeopardize the success of the programme were indeed identified, the main points being:

1. Monthly sampling was too infrequent; weekly sampling gave a better chance of predicting a potential failure.
2. Identification of samples was not foolproof, labels became detached from bottles, two samples were given the same number, no ships name etc.
3. Once a sample had been received, delays between laboratories taking tests and collating results was evident.
4. Having obtained the results the mechanism for informing ships of problems was unclear.
5. Administrative effort by ships should be minimized.

The routine was eventually revised (FIG. 4). Essentially ships would forward samples direct to DRA Woolwich, who would carry out both spectrographic and physical tests. Results would be faxed direct to the RN's technical staff at Portsmouth, where the computer was installed. A proforma was produced which gave engine, sample and maintenance details. This was to be forwarded direct to Portsmouth. Self adhesive labels, identifying each sample (by engine, date and time of sample) were attached to both the proforma and sample bottle. Self adhesive address labels also saved some ship effort. Arrangements were made for ships to demand SOA bottles and transportation cartons.

Installation

In September 1992 the EDS software was installed. Over 100 sets of results were keyed into the system and interpretations made. At the first attempt 17 pages of recommendations appeared. After some effort a workable (and explainable) 3 pages of recommendations evolved. The other 14 pages were generated by:

1. Laboratory result keying in errors.
2. Some alarms too high/low.
3. Specifications for new oil were too tight.
4. In service depletion of additives incorrect.
5. Contaminant levels too low, particularly sodium.

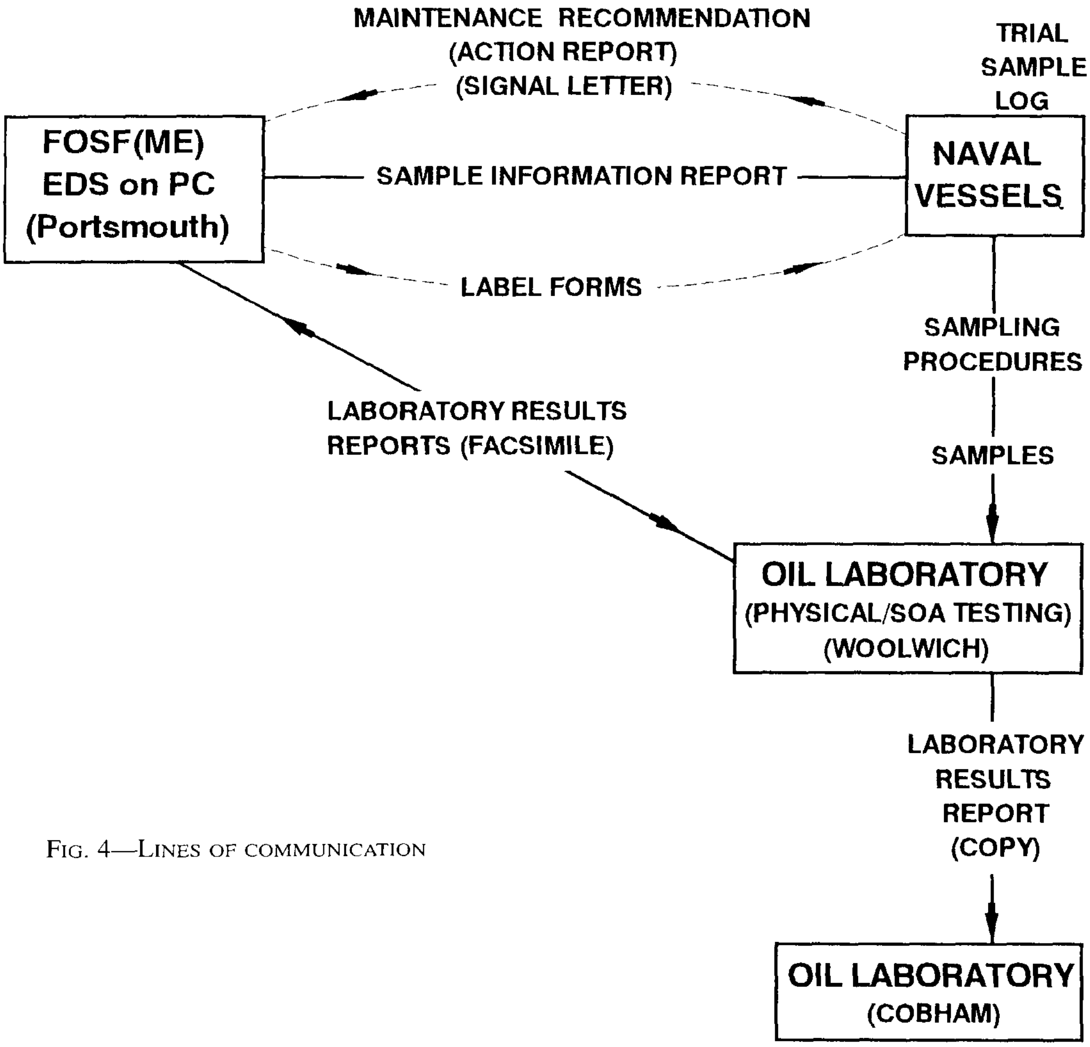

FIG. 4—LINES OF COMMUNICATION

Results

In general terms results were as predicted, particularly for main wear elements. Average readings are shown at Table 1.

TABLE 1—*EDS test data—average readings*

Spectrometric Test Results (ppm)

Cu	Si	Al	Fe	Zn	Mg	Ag	Cr	Ti	Mo
8.5	14.4	6.0	13.9	1100	22.7	0.0	2.3	0.0	0.7

Be	Ni	Pb	W	V	Ca	Ba	P	Na	Sn	Cd
0.0	0.3	11.3	0.6	0.0	3600	0.0	980	22.9	1.7	0.1

Physical Test Results Lubricant

KV	FP	TN	IS	WC	FD
118.3		7.8	0.7	0.0	3.2

Piston assembly wear was entirely as predicted with little actual piston wear (Al 6 ppm) but predominantly ring wear (Fe 13.9 ppm) and a small amount of liner wear (Cr 2.3 ppm). As part of the piston is tin plated the low reading (Sn 1.7 ppm) also suggested little piston wear.

Fork and blade rod bearing wear was also as predicted with lead from the 90/10 Pb/Sn flashing dominating at 11.3 ppm against tin at 1.7 ppm. With any appreciable wear, lead levels would be expected to rise and, once the flashing had worn away, copper levels would also rise as wear of the underlying lead bronze bearing took place.

There was no evidence of main bearing wear as tin levels were low (1.7 ppm) (main bearing composition 80% Al, 20% Sn). Normal copper levels at 8.5 ppm represent a combination of bearing material wear from fork/blades, gudgeon pin, camshaft, thrust, idlers and pump drives.

Additive concentrations (Zn—1200 ppm, Ca—3600 ppm, P—980 ppm) were within the specification for ministry standard detergent oils giving an average Total Base Number of 7.8 mgKOH/g.

Physical test results, on average, were as expected apart from fuel dilution (3.2%) which was not predicted at that level. Some fuel concentrations were considerably higher than this figure and will be discussed in a later section.

The alarm thresholds for each element were contained in a generic table for each engine type. Initial values were arrived at from a combination of factors during the knowledge acquisition process. Once set up, the system was updated by a limits programme (Fig. 5). This analyses all valid readings since the previous update and recommends new limits/trends for subsequent interpretations. Essentially dynamic in nature this process helps to trend against real engines rather than an ideal baseline.

PAXMAN 16YJ																	
ELEMENTS	SN	PB	CU	AL	FE	CR	AG	NI	V	MO	TI	BE	W	SI	NA	CD	MG
PTS READ	552	560	560	560	560	560	513	514	514	514	514	514	514	560	550	513	560
AFTER PASS 2 ...																	
CULL PT	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	Null	86.1	Null	Null
PTS USED	552	560	560	560	560	560	513	514	514	514	514	514	514	560	538	513	560
AVERAGE	1.7	11.2	8.5	5.9	13.8	2.3	0.0	0.3	0.0	0.7	0.0	0.0	0.5	14.4	22.8	0.1	23.0
STD DEV	1.0	10.6	3.4	2.3	5.6	1.6	0.1	0.8	0.0	0.5	0.0	0.0	0.6	7.5	12.4	0.4	10.9
HLA	3.7	32.4	15.3	10.5	25.0	5.5	4.0	1.9	4.0	1.7	4.0	4.0	1.7	29.6	47.6	0.9	44.8
HLR	4.7	43.0	18.7	12.8	30.6	7.1	6.0	2.7	6.0	2.2	6.0	6.0	2.3	37.2	60.0	1.3	55.7
HOC	6.7	64.2	25.5	17.4	41.8	10.3	10.0	4.3	10.0	3.2	10.0	10.0	3.5	52.4	84.8	2.1	77.5
PTS USED	337	279	320	346	301	356	423	385	426	367	424	439	345	257	257	391	334
AVERAGE	.020	.115	.083	.025	.084	.015	.001	.010	.000	.008	.000	.000	.008	.173	.101	.000	.095
STD DEV	.093	.373	.257	.124	.363	.086	.015	.080	.001	.041	.000	.000	.037	.529	.386	.000	.544
NORMAL	.113	.488	.320	.149	.457	.101	.016	.090	Null	.049	Null	Null	.045	.702	.487	Null	.639
MAXIMUM	.206	.861	.577	.273	.820	.187	.031	.170	Null	.090	Null	Null	.082	1.231	.873	Null	1.183

Fig. 5—Limits programme

Comparison between generic table limits from September 1992 to December 1993 showed that, in general, averages have had a downward trend but not markedly so, which would suggest that the original limits were in fact close to the norm. Apart from the normal averaging function, it may also be true that operator awareness of lub oil hygiene had increased due to the programme and therefore conditions would be expected to improve.

For main wear elements, the manufacturer gave warning limits and stated priority action for a rise or rapid rise above that limit. It has been possible to refine those recommendations as EDS operated on more samples. Lead limits were higher than originally recommended and are probably due to greater bearing wear than previously understood. Chromium levels were markedly lower than recommended, both on average and specifically, and figures have been revised accordingly.

It is interesting to note that no firm recommendation was given for magnesium and yet this has been proven to be a good indicator of a sea-water leak when assessed against sodium levels. In general a balance between computer generated recommendations and engineering judgement was developed, particularly in the early stages, until confidence in the system was gained. Other considerations included:

- Maintenance carried out.
- Ship's programme.
- Ease of carrying out recommendation.
- Suspect samples etc.

Examples

Most engines undertaking the programme have been relatively healthy with few problems experienced considering hours run. No inherent material faults were discovered. The main problems were associated with contamination, which EDS highlighted following interpretation of sample data. Higher than normal levels of silicon have been shown to be from the environment e.g. ships transiting the Red Sea ingesting small particles of sand through filtration systems. The 2 main contaminants were found to be water and fuel.

Water

Both sea-water and engine coolant are possible sources of water ingress. Coolant leaks can occur in a number of places, the most common being via liner seals. Sea-water's usual route is via the lub oil cooler or turbocharger intercooler. Experience has shown that testing for water content does not always show a water leak as invariably water was 'flashed off' under normal operation, usually venting through the crankcase breather. Sodium sebacate from the coolant inhibitor, however, remains in the system and normally shows as a rising level of sodium. This has been detected on a number of occasions by EDS and ships were alerted to check for leaks which may not have been readily apparent. Levels above 90 ppm have, however, been successfully detected by ship's operators.

Whilst a coolant leak is relatively straightforward, sea-water has more far reaching effects, leading to accelerated bearing wear if not detected quickly. One ship operating abroad showed excessive levels of sodium and magnesium as shown at point D of (FIG. 6).

A leaking intercooler was diagnosed, confirmed by EDS and a defective tube plugged. EDS also recommended an oil change. Levels of lead at this stage were rising but only just above normal alert limits. The next sample (point E) showed further increases in lead levels even though sodium and magnesium levels were reducing. Copper, Aluminium and Chromium were also rising. EDS recommended an inspection of large end bearings, 2 were found to have worn part of the lead flashing and were replaced. The oil system was drained, flushed and recharged on completion. Subsequent samples have been normal. This example illustrates how quickly wear can take place if undetected and where EDS has proved to be an invaluable tool.

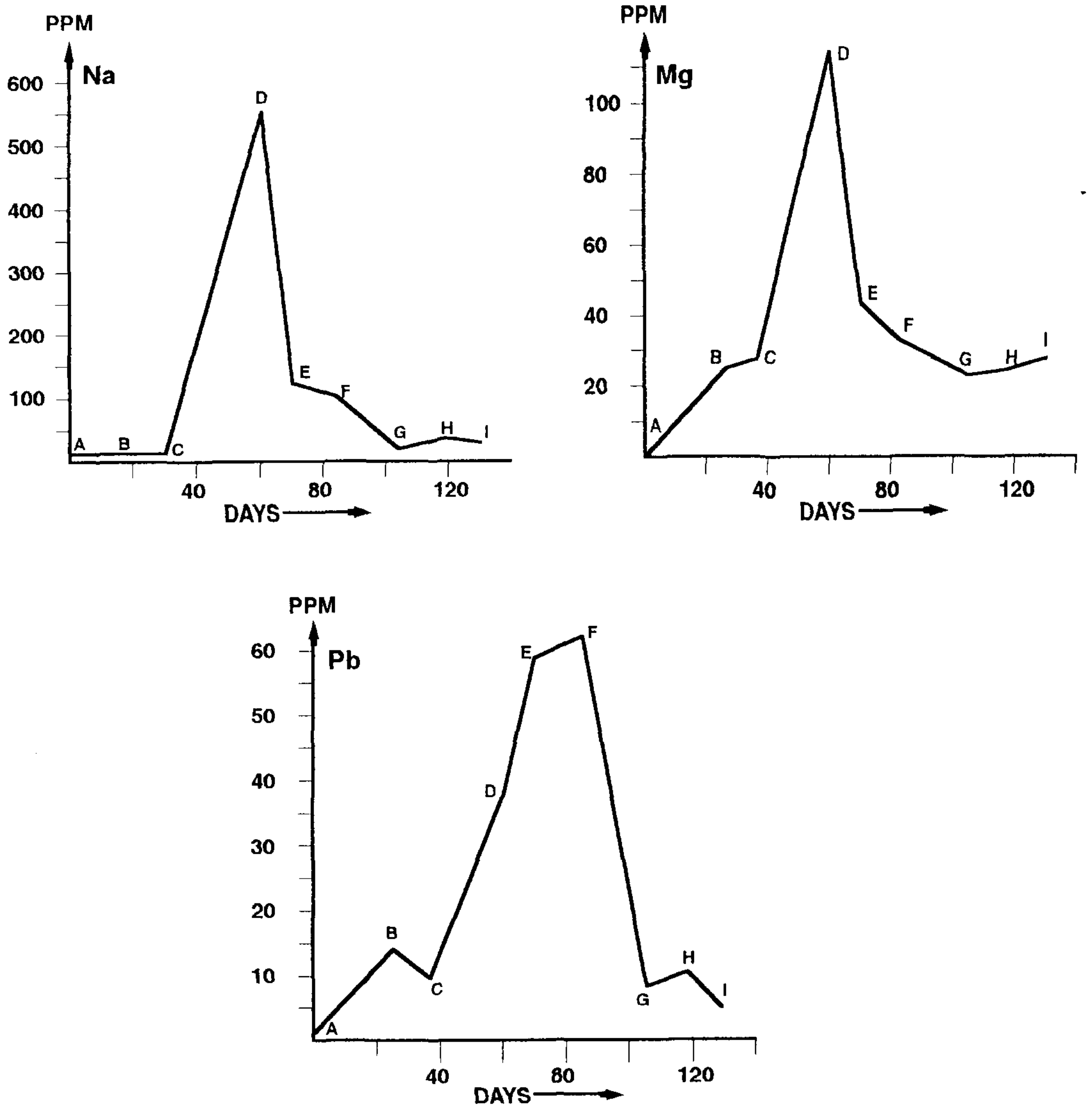

FIG. 6—EFFECTS OF SEA WATER LEAK

Fuel

Fuel dilution is a common feature of many diesel engines. Apart from the obvious risk of explosion if concentrations become too high, it has a harmful effect on oil performance and this increases the likelihood of accelerated wear. Ships routinely check for fuel dilution using a simple viscosity cup comparator. One laboratory sample showed over 10% of fuel dilution. The ship had not spotted the problem because their reference oil sample had been made up incorrectly. A defective fuel pump was diagnosed and replaced.

Laboratories are able to specify the ratio of burnt to neat fuel. In most cases it is approximately 50:50. A number of injection equipment faults have been pinpointed using the system. Underlying fuel dilution has been found to be caused by the oil lubricated fuel pumps.

Developments

Despite logistic delays it has been possible, as illustrated in the previous section, to predict failure with EDS in a timescale which enables preventative action to be taken. Engines approaching normal overhaul periods have had running hours extended by some 25% on the strength of EDS recommendations, performance, Vibration analysis and oil consumption.

Additional benefits have been developed and more experience gained. New engine types have been added using the existing knowledge base. Single element faults have a common logic whatever the engine type. Research into bearing materials etc. was necessary to ensure that combination rules still applied or new combinations considered. In the long term full knowledge acquisition techniques would be needed.

In parallel with the SOA/EDS system programme, work was carried out in identifying an up to date means of assessing physical oil condition on board ship. The main drawback of the original kit was that the viscosity test could mask incipient problems in engines operating under light load running conditions; fuel dilution tending to reduce viscosity whilst levels of insolubles and oxidation increasing the same. Although the new kit gave an actual measurement of both viscosity and insolubles, no correlation of them could be made against fuel dilution. Using the data from EDS a graph of expected readings was produced which provided some guideline to follow.

It has been possible to effectively monitor the running in process and overhauler's standards at overhaul, using EDS as shown at (FIG. 7). Dominant features were lead flashing wear from bearings and iron/chromium from piston rings bedding into liners.

Rules were modified to suit operational requirements. In some cases it was not always possible to act upon a recommendation immediately and certain element concentrations would remain high but stabilize. As configured the system would not flag up sufficient priority or recommend actions in this case. Rules were modified to include a high but stable category for essential wear elements.

Automatic scheduling and labelling is being developed as identification of samples and transmission of results data is a potentially weak area. Certainly as more engines are added the volume of data necessitates a modem link type transfer from laboratory to the EDS system.

Benefits

The main benefits of the system can be summarized as follows:

1. Failure prediction (subject to logistic chain timescales and nature of fault).
2. Oil change on condition.
3. Monitoring overhaul standards.
4. Monitoring new oil standards.
5. Enhanced awareness of engine health.
6. Extended engine life.

In terms of overall health assessment both the operator and CM managers can benefit from an enhanced awareness and appreciation of what is actually happening inside their machinery. Although most conditions are inferred from other sources they are, nonetheless, extremely useful.

Cost effectiveness

In the world of maritime defence, as in many other areas, an inevitable balance has to be struck between effectiveness and financial cost. This is even more important now as defence budgets continue to reduce in real terms and organiza-

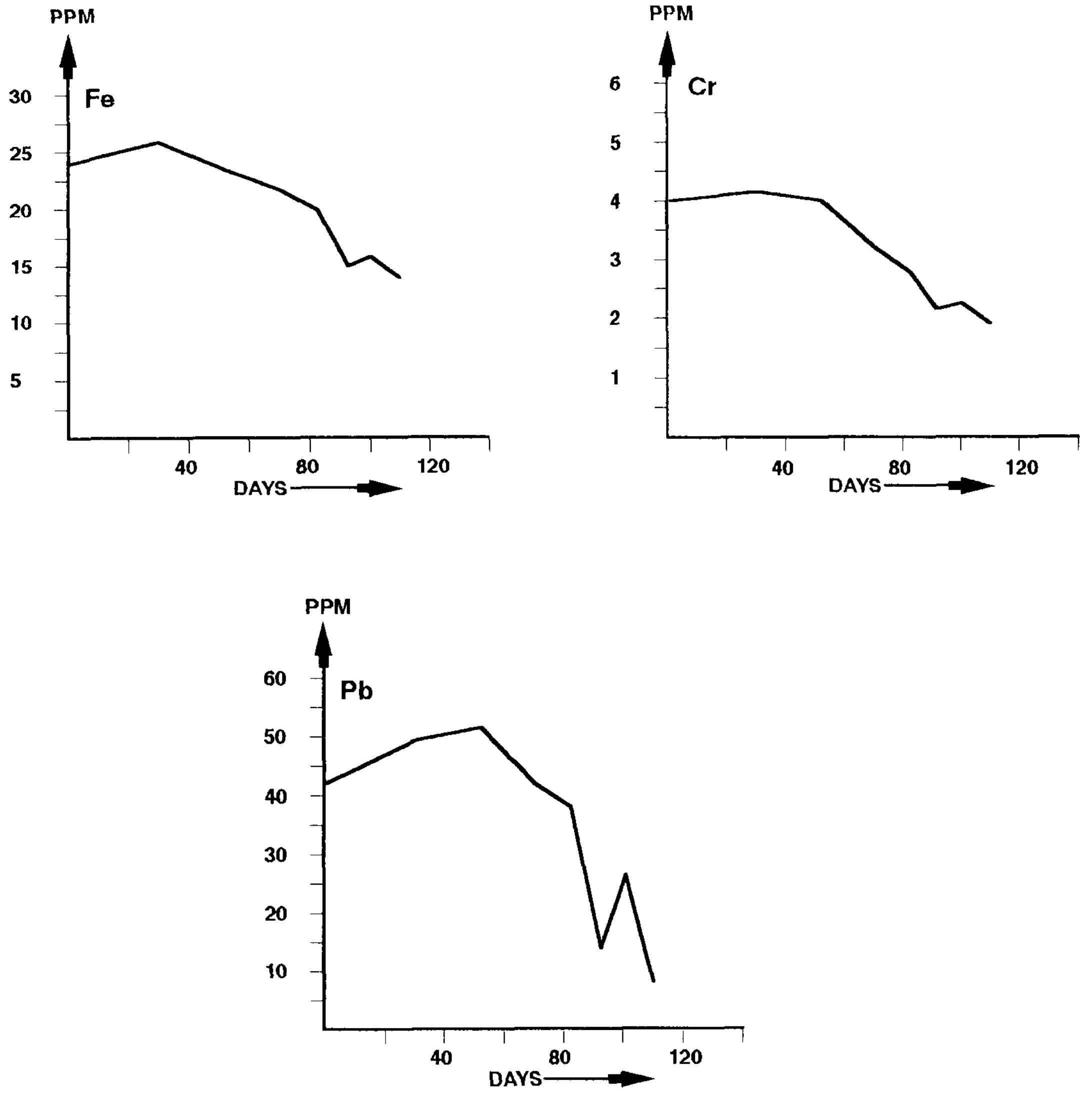

FIG. 7—RUNNING IN PERIOD

tions strive to achieve value for money. It is possible to allocate additional resources to a specific area and maintain an ultra reliable operating environment as, say, in the world of nuclear submarines. This option is clearly not affordable for all and therefore compromises have to be made. The loss of a ship's availability, for even an hour, is difficult to put a price on; during peacetime it may be a minor inconvenience but at war it could be incalculable.

Any initiative which costs relatively little in financial terms but can realise true savings and help overall reliability is cost effective in its broadest sense. In its first year EDS made effective savings, even after deduction of initial setting up, hardware and laboratory costs. That trend has continued, potential failures have been averted, hours between overhauls extended and confidence in reliability improved.

Way ahead

The RN's own programme for diesel engines should continue to expand. Once the planned automatic scheduling and labelling module is installed, additional engines and new types can realistically be added. Intelligent interpretation of data in its many forms, coupled with more reliable data acquisition processes, is believed to be part of the way forward. No single CM technique tells the whole story; an integration of techniques suitable for each application to give the operator/engineering manager/designer a more reasoned picture of health, will result in more reliable machinery and greater flexibility in operation/maintenance.

For diesel engines it is envisaged that 3 techniques, all controlled by one EDS, could be integrated:

- Operating parameters.
- Wear debris oil analysis.
- Vibration analysis.

For example a faulty fuel injector could be diagnosed by high exhaust temperatures, corroborated through vibration analysis indicating a combustion defect and oil analysis showing fuel dilution, and ring/piston wear in extreme cases.

Conclusions

Health assessment of diesel engines is complicated as most facets of condition have to be inferred from different sources. Traditional methods have been utilized successfully for a number of years and are as important today.

EDS systems can be a powerful addition to the decision maker's arsenal; having the ability to emulate much of the human expert's reasoning processes and automatically make sense of far more information than a single expert could ever hope to achieve. The RN's diesel engine health assessment programme has successfully achieved that aim, whilst being careful to maintain a balance between the roles of the expert system, other CM techniques and—the final arbiter—the person actually taking the decision.

It is clear that expert systems can help make maritime defence more cost effective, and more importantly, have the ability to do so now. Full integration with other suitable CM techniques is seen as offering the most potential for the future. There is also enormous potential for assessing the health of a whole range of machinery types using similar techniques.

Acknowledgements

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