MANAGEMENT AND ASSESSMENT OF AVAILABILITY OF DIESEL ENGINES

BY

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Synopsis

The Royal Navy thinks primarily in terms of availability of systems rather than reliability of equipments alone. In warships, availability is only one factor of many which have to be considered during selection. The required on-board availability of Diesel engines is achieved by shore testing and modification, and optimization of the installation with respect to access for maintenance and removal, together with optimization of overhaul life, and the provision of redundancy, adequate logistic support, and on-board skills. In-service failure rates are reduced by health monitoring, by modification procedure, and by close liaison with the manufacturers.

Although cost is considered at all stages, it is very difficult to assess the value of a military characteristic and the availability of a warship in monetary terms.

Introduction

In the Royal Navy in the past, machinery (and hence ship) availability has been achieved largely by the application of common sense based on experience. The scene is an ever shifting one; personnel, skills, space and capital are at a premium and it is becoming increasingly more important to count the cost of availability. This in turn requires a more scientific approach to reliability and maintainability, which together set the level of availability.

However, the recognition that availability needs to be quantified and costed is a simple step compared with actually doing something about it. This paper describes how this is being tackled in the Royal Navy, dealing with existing procedures and future proposals. The particular equipment considered is the Diesel engine.

Selection

A vast number of Diesel engines exists commercially and when a new naval requirement arises which cannot be met from the standard ranges (see later), it is necessary to carry out a trawl in order to establish which of them is suitable. The obvious parameters such as power, specific fuel consumption, speed, etc. are considered, but in this paper only those having a bearing on availability will be discussed.

Commercial Application

Whenever possible the R.N. likes to use commercially available, well-proven engines, and therefore benefit from the reliability achieved by evolution, and the cheapness achieved by mass production. However, sometimes specific military requirements (for example low magnetic signature, high shock resistance) require custom-built engines. The penalties here are high development and production costs and a long period of teething troubles (unreliability).

Size and Weight

In the context of a particular ship installation these have particular relevance; they can influence accessibility for maintenance as well as tractability to overhaul by replacement.

Declared Overhaul Life

The R.N. is mainly interested in two periodicities—the interval to top overhaul and that to major overhaul—and expects the manufacturer to define and declare these at the outset, together with the periodicities of any other major items of routine maintenance.

Costs

Both capital and life cycle costs are considered at the earliest stages. The former is the most tangible and, until now, has normally been the basis for choice. It is, however, the stated policy to make life-cycle cost the basis for choice, but the problems of putting a value on engine availability, predicting frequency of unscheduled breakdowns and their cost, and all the other uncertainties, combined with the Navy Vote system of annual allocation of money, make life cycle costing at the moment extremely difficult.

Life cycle costing exercises are carried out but currently tend to be of academic interest only, particularly when comparing 'like' equipments. For these assessments a 20-year ship life is normally considered, and fuel, lub-oil, overhaul and manpower costs are estimated.

Testing

A required level of reliability is achieved by good engineering design, and adequate development and testing before putting into service. Testing at prototype and subsequent stages is of prime importance in ensuring reliability; the problem is how much in terms of time and money can the Navy afford to expend at the testing stage?

In the ideal world we would specify the required generator reliability to the manufacturer and, before accepting any production models, we would require the manufacturer to demonstrate to a specified level of confidence that the required reliability had been achieved.

Diesel engine reliability specified by the Navy would be high. This means that the number of engine operating hours which would have to be recorded to demonstrate with reasonable confidence that the specified reliability had been achieved would also be high. TABLE I gives an indication of the sort of test periods required to establish a specified minimum reliability of 2000 hours MTBF, at two different levels of confidence.

The total duration of the test in calendar time could of course be reduced by having several engines on test together, but this would add immensely to the cost. In practice, therefore, we are only able to carry out the following programmes.

If the design incorporates features to meet special military requirements, a prototype engine is built and is type-tested either at the maker's works or at the Admiralty Engineering Laboratory, West Drayton (AEL). The prototype test consists basically of establishing realistic continuous and full-load ratings under tropical conditions and then carrying out an endurance trial against a realistic operating pattern. The aim is to record at least 1000 hours or, if possible,

Table I—*Time required to demonstrate that an MTBF of at least 2000 hours has been achieved.*

Number of failures observed during trial	*Test engine hours required*	
	99 per cent Confidence	*60 per cent Confidence*
0	9,000	1,900
1	12,800	3,900
2	15,500	5,800
3	19,000	7,800
4	22,000	10,200
5	25,000	12,500

4000 hours running free of major defects. In the process inherent faults are revealed and rectified by design modifications, and wear-out lives are predicted. Because of the small population—usually only one—the amount of data produced by the test is inadequate to establish failure or wear-out distributions. The reason for such small test samples is simply lack of money. Not only do the capital costs of the prototype engine and test facilities have to be considered but also the through-costs of fuel, lubricating oil and labour associated with testing.

Another difficulty when type-testing is to predict the service operating pattern; running a Diesel generator at a steady 80 per cent load for a 1000 hours is very different from starting it and stopping it 500 times in the same period, while running it on no-load for 500 hours, full load for 400 hours and 10 per cent overload for 100 hours. A typical type-test operating pattern as used at AEL is shown in Table II.

Table II—*Typical type-test cycle*

Total hrs/week	*Period (hrs)*	*Power*
100	¼	Idling
	2	⅓ full load
	8	full load
	¼	Idling
	14½	⅔ full load

Other hazards which in a military and marine environment will reduce reliability are also considered: these include ship-motion, shock, and the ingestion of salt-water. Although catered for in the design, apart from the shock-testing of small engines and components, they are not simulated currently in the formal type-test.

The type-test of an existing design of Diesel engine follows a similar pattern to that prescribed for a prototype, but obviously fewer component failures are expected. Experience has shown, however, that manufacturers are often over-optimistic when rating an engine and, to obtain an acceptable Mean Achieved

Life in naval service, it has had to be down-rated. Part of the cause, particularly for propulsion engines, lies in the various ratings quoted, e.g. sprint, maximum, maximum continuous—Ref. 1; these are qualified by such statements as 'for one hour in any period of 12 hours continuous running'. It is felt that, although the same creep considerations do not apply, the Diesel engine industry might well follow gas-turbine practice and quote a Declared Overhaul Life at life factor 1 for a specified power, together with the life-factors corresponding to higher powers.

As an important part of the type-test we are now instituting maintenance evaluation exercises. Engine availability is a function of both reliability and maintainability. We are vitally concerned, therefore, with reducing the onboard maintenance task to a minimum. This means in practice that maintainability must be carefully considered throughout engine design, and that, when the engine is installed and operating, there will be adequate space for maintenance, job methods will be correctly described, and correct tools, equipment and replacement parts will be available. Before the engine goes into service we attempt to ensure that all these areas are adequately covered by carrying out practical exercises known as maintenance evaluations. These exercises are performed either at the makers works or at the AEL. The manufacturer systematically works through the draft schedules of the on-board preventive and corrective maintenance which has been predicted as necessary for the upkeep of the engine throughout its useful life period. The work is observed, recorded, and in many cases photographed in detail, by a small naval team who produce a composite report which provides the basis for all subsequent maintenance documentation. The results of these exercises have proved extremely valuable in that they:

(*a*) Establish the 'maintenance envelope' which defines the space required for maintenance around the engine when installed.

(*b*) Validate and improve the draft maintenance schedules.

(*c*) Establish the best job methods and provide detailed job instructions for each maintenance action.

(*d*) Provide the detailed lists of tools and stores required to do each job so that adequate on-board support can be supplied.

(*e*) Establish the level of skill and the time required for each job.

(*f*) Provide suggestions for minor but often important modifications to the engine and the installation design to improve maintainability.

The production test is another important aid to in-service reliability. Apart from the flushing of systems and running-in under controlled conditions, the production test can reveal manufacturing defects in the apposite place, i.e. the works rather than the ship. The duration and nature of these tests are the subjects for considerable debate and often the manufacturer and user hold widely differing views. Basically, in a cruelly competitive world, the manufacturer has to assess the cost of testing against that of the equipment breaking down during the guarantee period and do the minimum amount of testing commensurate with ensuring the minimum number of under-guarantee failures. He would be the first to admit that longer production tests would reveal more manufacturing and assembly faults.

The production test is often followed by an examination of selected components to see 'why the engine ran so well'. In the possibly somewhat cynical view of the authors, if the engine has run well it is probably best left alone.

Ship Installation

The availability and even the performance of a Diesel engine can often be

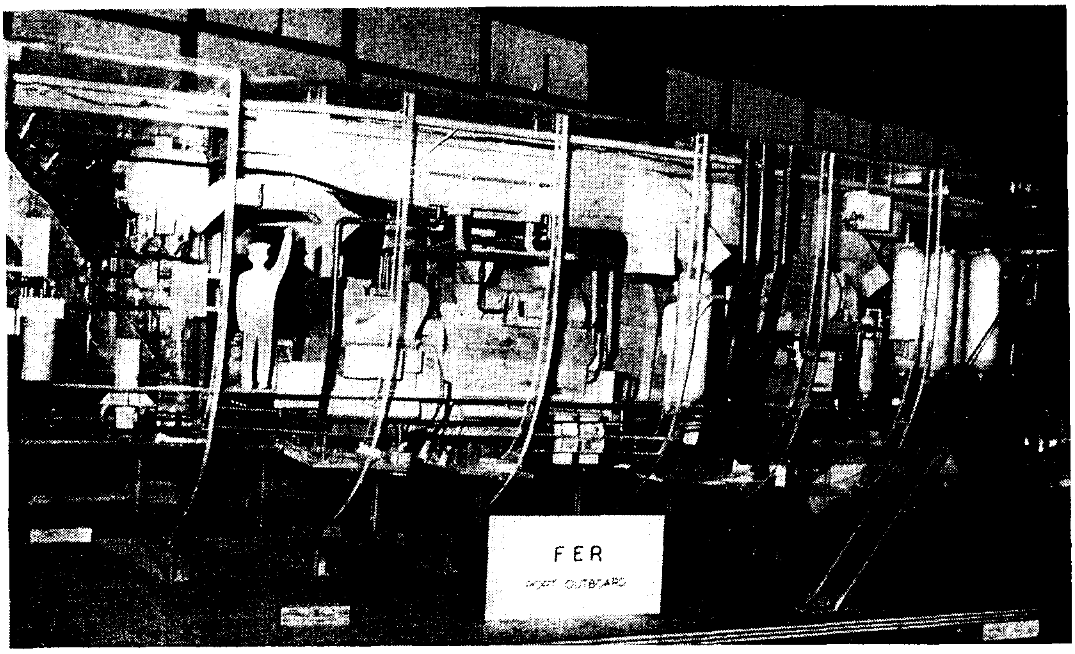


FIG. 1—1/10 SCALE MODEL OF A DESTROYER'S ENGINE ROOM

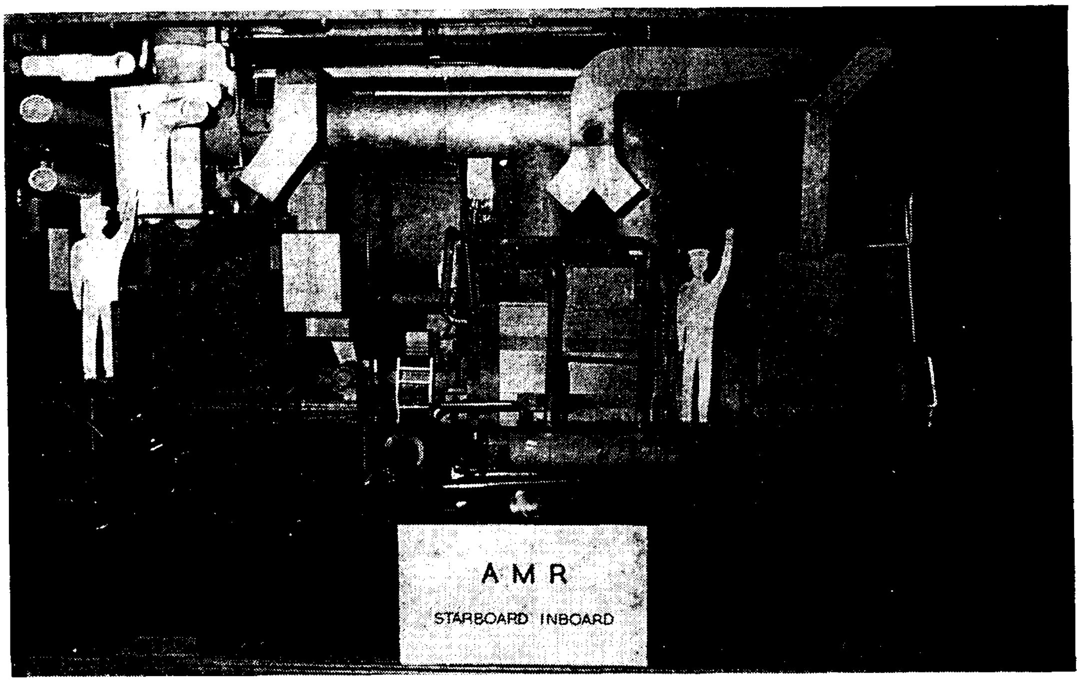


FIG. 2—1/10 SCALE MODEL OF A DESTROYER'S AUXILIARY MACHINERY ROOM

put in jeopardy by insufficient attention to the installation. In general, engine manufacturers specify their terminal points and certain system requirements but otherwise pay scant attention to the installation. In warships, however, we are trying to achieve maximum participation by the engine builder in the system and installation design. During feasibility studies of new machinery layouts, the engine manufacturer is asked to comment on the system design, and, at each stage from preliminary drawings through $\frac{1}{5}$- to $\frac{1}{10}$- scale models of machinery spaces (FIGS. 1 and 2) up to the actual lead ship itself, he is invited to criticize. His vetting includes not only installation features which might affect performance and reliability but also those impinging on access for operation and maintenance.

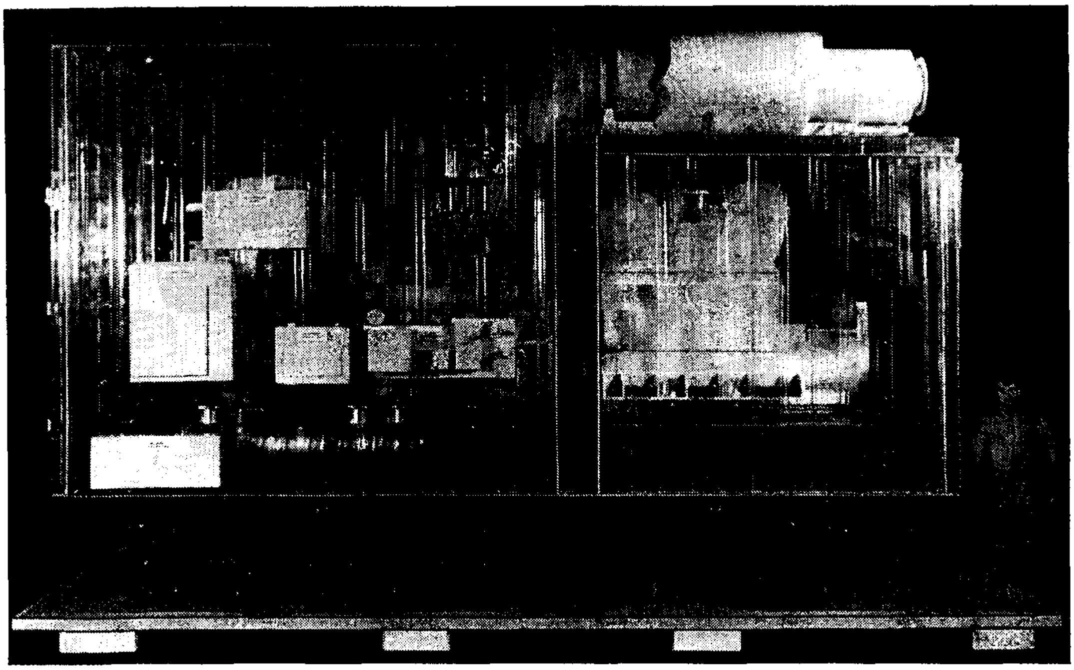


FIG. 3—MODEL OF DIESEL GENERATOR ACOUSTIC MODULE

FIG. 4—DIESEL GENERATOR ACOUSTIC MODULE

We are also increasing the scope of some manufacturers by giving them design and contractual responsibility for Diesel generator modules—See FIGS. 3 and 4. These packages will have an increased system content and will ensure at an early stage considerable optimization with respect to space, access, and performance, i.e. the Diesel generator system will have been optimized but the ship may still be in its feasibility study stages.

Availability of Generating System

The electrical generation and distribution system is probably the most critical system in the ship, the propulsion and weapons systems both being highly dependent on continuity of electrical supply. Ideally the degree of redundancy required would be decided on a basis of reliability. Unfortunately we have not yet achieved the ideal, and in any case there are many other design constraints which must be considered, as well as reliability, when deciding how many generators to fit. The most important of these constraints are:

(*a*) Cost

(*b*) Overall weight of machinery installation

(*c*) Space available

(*d*) Vulnerability—basically at least two generators separated fore and aft by at least two watertight compartments are necessary, even if one perfectly reliable generator could meet all load demands.

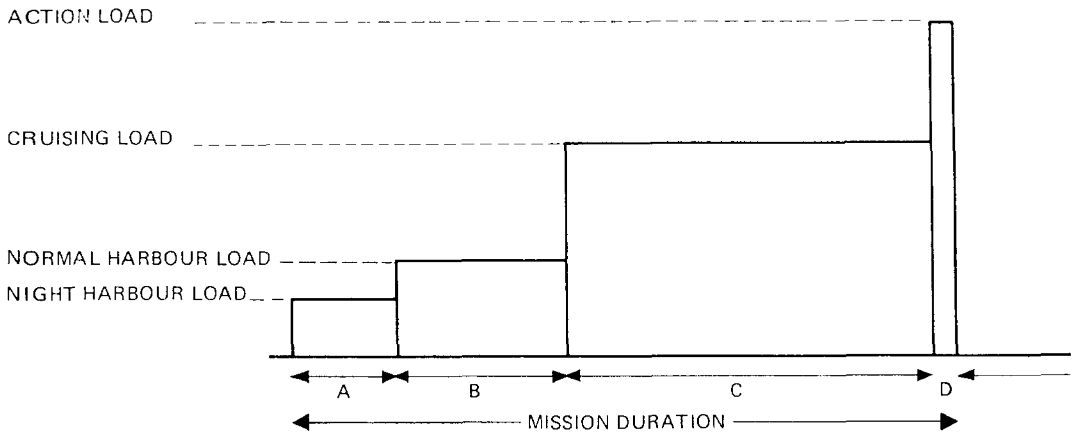
(*e*) The power of available engines. The size chosen will be related to the minimum ship load to ensure that it is not necessary to run generators for long periods at less than 30 per cent full load.

(*f*) The total power demand in various modes of ship operation, e.g. action, cruising, etc.

(*g*) The maintenance load and costs resulting from increasing number of engines fitted.

(*h*) The necessity of ensuring that top overhauls and planned engine changes can be synchronized with ship maintenance and refit periods without, at the expected rate of usage of engine hours, exceeding the declared overhaul life of any engine.

The design of the electrical supply and distribution system will also have various options fixed by constraints similar to the ones mentioned above.



R_A = RELIABILITY DURING PERIODS (TOTAL DURATION A HOURS) AT NIGHT HARBOUR ELECTRICAL LOAD.

R_B = RELIABILITY AT NORMAL HARBOUR LOAD.

R_C = RELIABILITY AT CRUISING LOAD.

R_D = RELIABILITY AT ACTION LOAD.

$R_{MISSION}$ = MEASURE OF MISSION RELIABILITY.

FIG. 5—PERIODS AT POWER LOADS REQUIRED DURING A TYPICAL SHIP MISSION

These options and the number of generators selected are obviously interdependent and must therefore be taken into account when deciding the number of generators.

Consideration of the above constraints and factors, combined with a basic assumption that there should be some minimum degree of redundancy, i.e. at least one engine standby most of the time, enables the possible generator fits and design of the distribution system to be narrowed down to a small number of options each of which will have various advantages and disadvantages.

Reliability Assessment

The problem now is to decide what reliability is acceptable, and which option, when consideration of reliability is included with the other factors already mentioned, is best. A numerical assessment of reliability for each option is thus desirable.

Mission reliability is usually chosen as the measure of system reliability. Mission reliability may be defined as the probability of maintaining the electrical supply at the level required throughout the various phases of the mission of specified length. Thus any failure to meet electrical demand during any phase of the mission because of a generator failure is a mission failure.

The numerical assessment demands:

(*a*) Definition of the phases of the mission, i.e. total times at different power levels corresponding to the various ships states, e.g. action, cruising, and harbour within the duration of the mission. (FIG. 5).

(*b*) Definition of the operating rules of the generator systems—How many generators are normally to be in use in each mission phase? Which generators they are to be? What switching is allowed by the distribution system, i.e. to what extent are generators stand-by to one another?

Reliability dependency diagrams may now be drawn representing the system in each phase of the mission. Reliability for the duration of each mission phase is calculated and a figure representing mission reliability produced from the product of each phase reliability.

$$R_{\text{mission}} = R_A \times R_B \times R_C \times R_D$$

The mission reliability calculated is at best an approximation. However, it is better than nothing, and is used only in a comparative manner, answering the questions:

(*a*) Which option offers best reliability?

(*b*) Which options are acceptable or not acceptable on the basis of reliability?

(*c*) How much extra reliability does one option offer compared to another?

The answers to these questions are now considered together with the advantages and disadvantages already established, before the decision is finally taken. Thus the reliability assessment, although quite crude, at least ensures at this early concept stage of system design that reliability has been considered objectively and is regarded as being of equal importance to other, and possibly at this particular time more pressing, design constraints. Moreover, the analysis of system requirements and operating philosophy necessary before a reliability assessment can be made is itself an extremely useful exercise.

Having made the basic decision, system design is now developed in more detail and progressively refined. The further the design progresses and firms up the less the scope for special reliability activities. However, it is likely that the application of qualitative analysis to identify critical areas and propose modifications to improve reliability of the design as it progresses will become more common in future. Quantitative assessments would be used to check the effect of the proposed modifications.

Data

The biggest problem limiting the application of quantitative reliability techniques at both the early concept or later stages is the lack of good quality failure and repair data to use in the calculations. If the engine to be fitted is already in service, data will have been collected but probably will not be in a form readily usable in reliability assessments. In the long term the Navy is improving its data collection and processing by setting up the Ship Upkeep Information System. SUIS will collect failure, defect, and repair data on all equipments in service in the fleet which will enable the distributions of time-to failure to be established and used in the system design calculations. Data from SUIS will also, it is hoped, enable total cost of ownership to be considered more fully, for both equipment selection and in system design. However, forward design studies will often include new equipment for which no data is available. To meet this situation it is necessary to devise methods whereby predictions of reliability for new engines may be based on historical data gathered on engines in service. These predictions should take account of all relevant information on existing and new equipments.

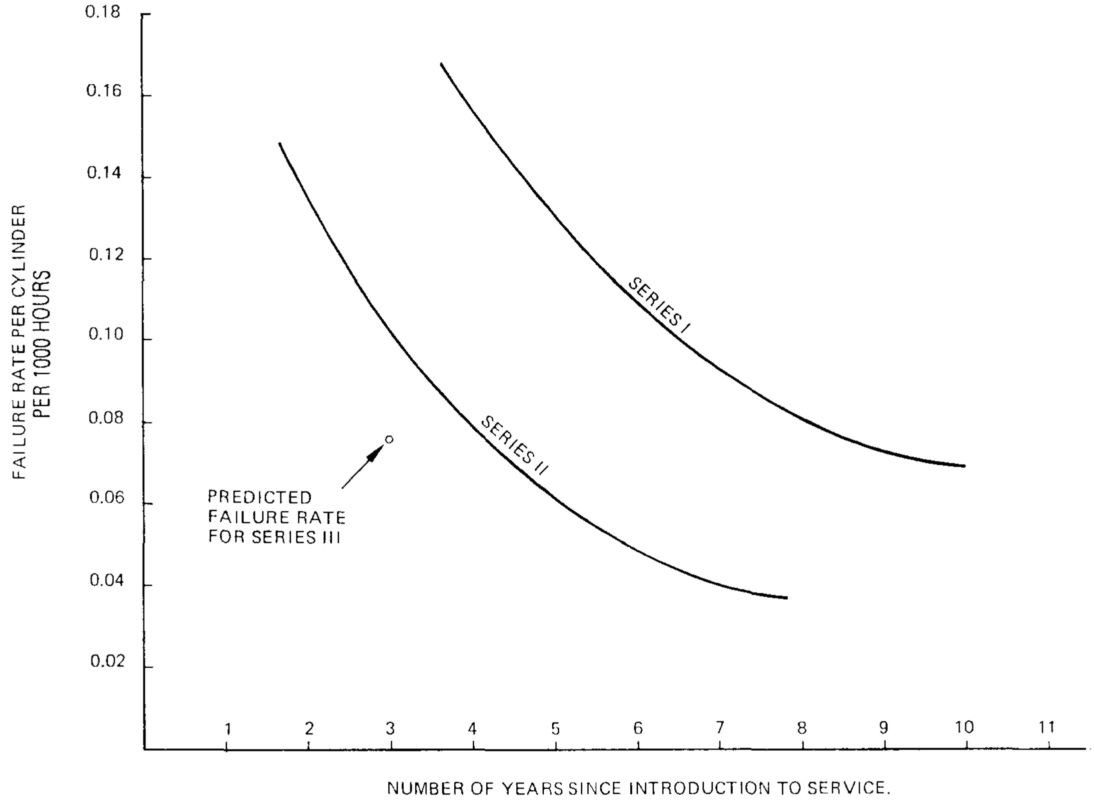


FIG. 6—TRENDS IN RELIABILITY

Several approaches are possible and are now under investigation:

(*a*) The first approach, when the new equipment is considered sufficiently similar to equipment already in service, is to read across from historical data on the old equipment.

(*b*) The second approach is to use statistical methods to attempt to find a relationship between failure rate and various physical characteristics of those engines on which data is available, and use this relationship to forecast the failure rate of a new engine from its own physical characteristics. FIG. 6 shows curves relating 'failure rate' to 'years since introduction into service' for two separate but related families of engines from limited data collected over a two year period. There is good correlation between these two variables and, as one might expect, the trend shows that failure rate of a particular engine type decreases with increasing time in service because of a continuing development programme. The fact that the Series II curve is of similar form to the Series I, but with lower failure rates, indicates that an improved design standard was achieved with the Series II engines.

A second regression analysis involving all the engines in the two families produced an expression linking failure rate with the following engine parameters as independent variables:

Number of cylinders
Operating r.p.m.
b.h.p. per cylinder
Years since introduction into service
Specific weight, lb/b.h.p.

Specific fuel consumption and b.m.e.p. characteristics were discarded as insignificant. This regression expression was then used to establish the failure rate (3 years after introduction into service) for a new series engine from the same design stable by substituting the Series III engine characteristics into the expression (FIG. 6). This illustrates an approach only. More work on further data is required, and the method must be validated by comparison of the predictions with what happens in practice.

(*c*) The final approach to the problem is via synthesis. Here failure of engine component parts would be estimated using historical data and examination of the various failure modes of the components. The component failure rates would then be summated to predict an overall engine failure rate. This approach is used commonly in electronic work but its application to mechanical equipments needs further investigation.

On-board Trials

On-board trials make an important contribution to in-service reliability; initially these comprise setting-to-work of the generators by the manufacturers for the shipbuilder and finally they comprise a formal MOD acceptance trial.

Setting-to-work is concerned primarily with steady-state and dynamic performance. Although this has already been demonstrated at the maker's works, this is the first time that the Diesel generator has been connected into the ship's systems. Performance obviously can be affected by system characteristics (e.g. an excessive intake suction depression can reduce the weight of air induced, leading to a reduction in engine power and at the same time increase the specific fuel consumption), which themselves can also affect availability. Examples of installation aspects which should be checked during the setting-to-work and shipboard trials period include compartment ventilation, starting arrangements, circulating water system, etc.

Support

This comprises handbooks, drawings, training, maintenance schedules, spare gear, special tools, and depot spare equipments.

Handbooks

These cover the design, operation, and maintenance of the Diesel engines and are important both as training aids and books of reference. They make a vital contribution to availability because they prevent operator-induced failures and facilitate preventive and breakdown maintenance.

Drawings

Unless the engine is of MOD design, the Royal Navy does not hold design and production drawings of Diesel engines because of the heavy work-load of up-dating. At headquarters there is rapid access to the makers for any particular detailed drawing; otherwise reduced size general arrangement drawings of each installation, selected assembly drawings, and a number of detailed drawings of major components such as pistons, connecting-rods, cylinder heads, are relied upon.

In ships, only general arrangement and selected assembly drawings are carried because of the limited space available, but in future this range may be extended using microfilm. It is appreciated, however, that drawings can be of great assistance for rapid and accurate fault diagnosis and hence availability; the long-term aim should be to carry the minimum number of drawings compatible with the maximum availability.

Training

This makes an important contribution to equipment availability for reasons similar to those mentioned under the heading 'Handbooks'. It has been found that there is no substitute for 'hardware' and therefore in H.M.S. *Sultan* at Gosport there is a comprehensive range of the Diesel engines used in the Royal Navy. These are started, stopped, and stripped by ratings undergoing equipment and ship courses and, coupled with static exhibits and excellent lectures from experienced engine-room personnel, make a major contribution to Diesel engine availability in warships.

Maintenance Schedules

These are based on our chosen upkeep policy for the engine, the maker's recommendations, and our operating experience; the maintenance actions required are validated during the maintenance evaluation exercise. The usual upkeep policy is one of exhange, i.e. periodicities, expressed in engine running-hours, are set for preventive maintenance actions such as top overhaul and complete engine major overhaul, and the sub-assemblies or complete engine as appropriate are exchanged for new or reconditioned parts. These periodicities are set largely on a rather *ad hoc* basis based on makers recommendation and type-test, and modified as operating experience is gained and engine development progresses. Considering an engine whose upkeep policy is replacement by a new or reconditioned engine at the end of its planned life, if life is set too short unnecessary expense will be incurred due to changing engines before they need to be overhauled, but the ship downtime involved is scheduled; if planned life is set too long the frequency of unscheduled breakdowns will be greater and with them the amount of unscheduled ship downtime, but the overall number of engines required in the pool and number of overhauls arising will be less. Clearly there is an optimum length of life before planned replacement, at which the total life cost (including a measure of value of ship availability) of a fleet of engines is minimised (see also sub-paragraph headed Depot Spares).

The first step in estimating the optimum life is to establish the cost of scheduled and unscheduled downtime of the actual system. In the absence of true costs, an agreed ratio, e.g. downtime due to unscheduled changes is agreed to be, say, twice as expensive as scheduled downtime, may be good enough.

The second part of the problem involves statistical analysis of engine failure data to establish the distribution of failure. Weibull plotting is generally an adequate way of doing this. This is a useful technique whereby failure data (running hours to failures which necessitate engine change) can be fitted to the Weibull distribution, which has the handy property of being able to cope with increasing, constant, or decreasing failure rates. A Weibull plot enables identification to be made of the life in operating hours at which the risk of engine failure starts to increase with time, i.e. wear-out failure starts to occur. There is no point in making an engine replacement before the wear out phase is either imminent or has been entered. This plot also allows the cumulative probability of failure up to achievement of any chosen engine life to be read off.

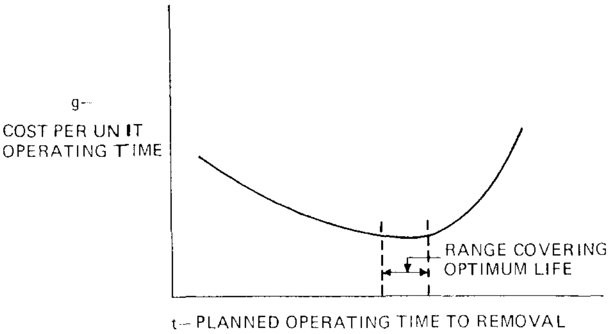


FIG. 7—OPTIMIZATION OF PLANNED LIFE WITH RESPECT TO OVERHAUL COSTS

The object is to minimise the cost per unit operating time, so if:

C_p = Cost of planned exchange

C_f = Cost of unplanned exchange

$$\left.\begin{array}{l} S(t) = 1\text{-}F(t) \text{ probability of survival to planned life } t \\ F(t) = \text{probability of failure before planned life } t \end{array}\right\} \begin{array}{l}\text{Read straight} \\ \text{from Weibull} \\ \text{plot}\end{array}$$

$$\text{MAL} = \text{Mean achieved life} = \int_0^t S(t).dt.$$

g = Cost per unit operating time

$$\text{thus } g = \frac{C_pS(t) + C_fF(t)}{\text{MAL}}$$

g can now be plotted for different values of planned life (FIG. 7), and the value, or range of values of t at which g is a minimum gives the optimum planned life for the equipment. Ref. 3 gives details of the method and other replacement models.

Spare Gear

This comprises spare parts carried on board to enable in-situ maintenance and repair to be carried out. The initial outfit is based on the maker's recommendations but this is modified in the light of operating experience. Depleted stocks are replenished from a distribution centre (SPDC) in UK and air freight enables rapid supply. The great problem is to know how large a stock to carry at the distribution centre and in individual ships; in the end the value of ship availability must be balanced against the value of stock carried. A slightly easier teaser is to decide whether it is cheaper to scrap defective components or repair them; a problem which, however, becomes insoluble if the repair process is more expensive but quicker than buying new.

Depot Spares

These are complete spare equipments and assemblies held in a few machinery depots in the United Kingdom. They provide an insurance against catastrophic failures in service and also the pool from which to draw new or overhauled equipments and assemblies when a ship comes in for programmed maintenance or refit. In both instances the availability of these depot spares can reduce the down-time of a ship but it can also represent a large capital investment. This is discussed fully in Ref. 2 in which the author demonstrates that provided a monetary value can be put on the availability of a ship the depot spare holding can be optimized. Unfortunately costing the value of warship availability is extremely difficult. Optimum depot spare stock holdings can only be determined if consistent ship operating patterns are applied and there is a high population of the particular equipment under consideration. In practice neither of these applies: the Navy operates in peace but must plan for war, and as equipment complexity increases so numbers in use fall. However, by applying a rigid procedure of equipment standardization and modification it is hoped to counteract this latter tendency.

Standardization

Standardization is an obvious and vital adjunct to the achievement of high availability, presupposing, of course, that the best equipment on which to standardize has been selected initially.

At the end of the last war, there were over 300 different types of Diesel engine in use in the Royal Navy and its auxiliary services; now there are less than 80. This has reduced the diversity and cost of the elements of support already discussed, and has resulted in improved reliability by giving a higher population of similar engines from which to gather reliability data. On the debit side, however, a deliberate policy of standardization can result in an over- (or under-) powered installation, design stagnation and total reliance on a few manufacturers.

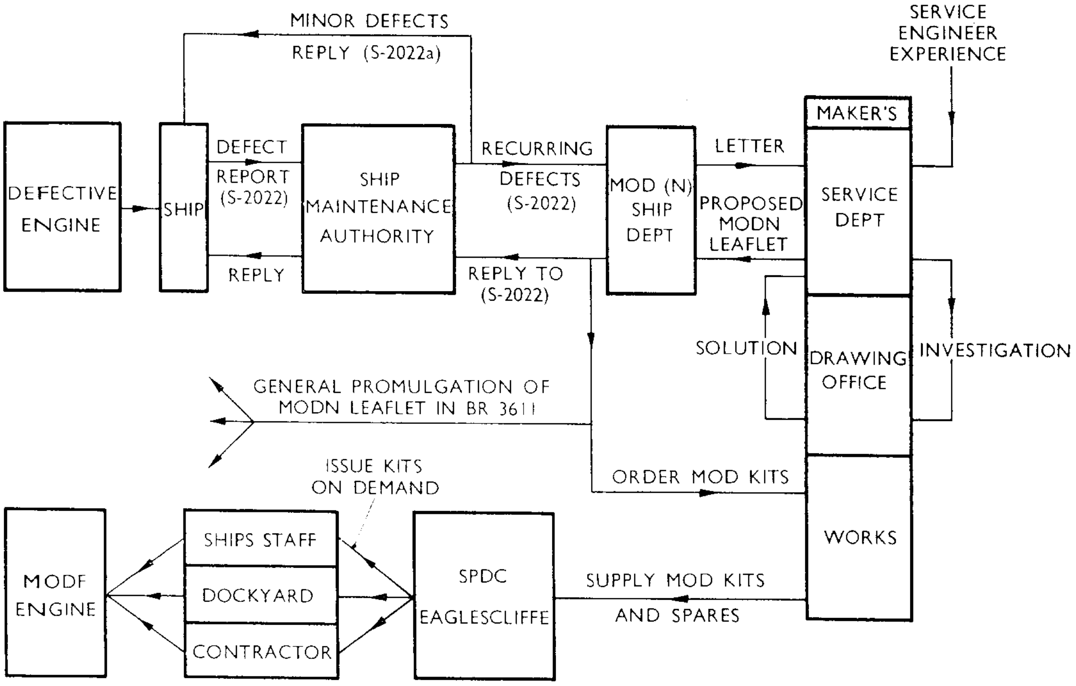


FIG. 8—MODIFICATION PROCEDURE

Modification Procedure

Although prototype and production testing and on-board setting-to-work will reveal a large number of Diesel engine design deficiencies, the acid test of reliability is in-service running. Defects reported from sea are analysed by the MOD and if there appears to be a design deficiency or repeated failure the manufacturers are told. The manufacturer also has his own feed-back from commercial equipments via his service engineers. The information from these two data sources enables him to propose the introduction of modifications to overcome any shortcomings in the design. If approved, the modification is then processed by a well defined but fairly complex procedure.

This procedure must be applied with great care; considerable experience and knowledge of the equipment is necessary to maintain standardization and reliability of equipment throughout the fleet while keeping the capital expenditure on modification kits and the labour cost of carrying out the modifications to a minimum. The procedure followed by the R.N. is illustrated in FIG. 8.

This system is complex but is considered essential to keep things under control. Like all complex systems, however, it has a number of drawbacks, the most important being the tie-up with new production. Because the system is so detailed the time-lag between the approval of a modification, and the issue of information to the Fleet can be considerable (up to 5 years) but for new production the introduction of a modification is often a simple matter. This can result in new equipments entering service with a modification state in advance of handbooks and documentation. If a modified component then fails, the replacement demanded and supplied may well be of an unmodified type which either will not fit or, when fitted, demodifies the equipment. Ways of overcoming this deficiency are being examined.

Other Aids to the Achievement of High Availability

Exchange Upkeep Policy

For Diesel engines fitted in new construction warships, the normal upkeep policy will be to exchange the engine at the end of its achieved life for a new or reconditioned engine. To minimize the exchange time, special removal trunks or portable plates clear of other fittings are built into the ship. Having parted the engine from its generator and prime systems, it can be lifted out using special gear and a dockside crane and be replaced by a new or overhauled engine. The bogey time for the complete operation, including any setting-to-work trials, is 48 hours, but it is confidently expected that this can be bettered. Currently it is intended to follow this procedure only for major overhauls and repairs, but if the interval between top overhauls can be increased to 6000 hours it is hoped to remove the engines for these as well.

Apart from increased ship availability, the exchange policy gives the additional benefits of a smaller, less skilled engine-room staff and better environmental conditions for overhaul (in turn leading to higher reliability). The disadvantages are the need for a bigger holding of depot spare engines, the increased dependence of the ship on base support, and the necessity for complete interchangeability between engines.

Line Overhaul

The exchange policy is supported by line overhaul of the engines withdrawn from the ships. Overhaul lines for the Navy's Diesel engines exist at some of the home dockyards and at the maker's works. These enable the engines to be overhauled by specialists in good working conditions, with proper spares, tools and test facilities. It is during overhaul that the majority of approved modifications are incorporated.

Service Contracts

To support the Fleet's resources the MOD has service contracts with some of its equipment suppliers. This allows manufacturers' service engineers, at very short notice, to visit ships which are in trouble—sometimes on the other side of the world. Although the Navy likes to be as self-sufficient as possible, sometimes it is necessary to call in a specialist who may have many years experience of a certain engine. These visits can improve availability in two ways; an on-board defect can be rectified quickly and valuable field data can be fed straight back into the firm, the latter provided the design and service departments speak to each other.

Health Monitoring

Currently this is confined to monitoring the lubricating oil, although possibly vibration analysis techniques will one day be extended to the Navy's Diesel engines. We monitor the lubricating oil for two reasons:

(*a*) For its continuing suitability to remain in service.

(*b*) For debris from the wearing parts.

The techniques used for (*a*) are well known and will not be discussed but those used for (*b*) are fairly recent innovations. The Navy is employing two techniques; one in current use for maintenance and the other under trial. The former uses magnetic chip detectors; these are easily removable magnets placed in the lubricating oil system and inspected at regular intervals, usually daily, to see what debris has been caught. The technique depends on the fact that debris originating from a particular source will always have a unique shape which, once identified, can be related to that source whenever found. In the Royal Navy the main use of this technique is in machines fitted with rolling type bearings, e.g. gas turbines, small gearboxes, and superchargers.

The technique under trial is spectrometric oil analysis. This trial is to last three years and is being conducted on the propulsion Diesel engines fitted in a class of survey ships. Although spectrometric oil analysis is a viable technique, there are problems connected with ships' diesel engines:

(*a*) The high rate of oil make up caused by consumption and leakage, and changes due to fuel dilution. This can amount to 2 to 3 times the sump capacity per week.

(*b*) The need for extreme discipline in recording any upkeep actions between sampling which might subsequently affect the next analysis.

(*c*) The problem of getting samples from a ship at sea to a laboratory for analysis in good time.

The present trial, which has been in hand for one year, is intended to find a relationship between oil analysis trends and actual engine events.

Improving the Situation

It is the stated MOD policy to concentrate design and development effort, as far as possible, onto a limited range of makes and models. Engines will be replaced in this range only when it is essential and cost effective to do so, thus enabling us to take full advantage of reliability growth through design modification over a long period, i.e. evolution not revolution.

The manufacturer must be made fully aware of our requirements and we must ensure that he pays specific attention to reliability and maintainability. This will necessitate better specifications and some additional contractual requirements.

The improved specification must include:

(*a*) The expected engine operating profile

(*b*) The expected environmental conditions

(*c*) The preferred upkeep policy

(*d*) The required overhaul cycle

(*e*) The target reliability required on acceptance into service, and the ultimate reliability aimed for after development.

(*f*) The target maintainability required, expressed as 'times to perform specified maintenance tasks'.

It would be advantageous to take contractual action to require the manufacturer to:

(*a*) Nominate a suitably qualified engineer as Reliability Engineer for the project.

(*b*) Draw up a reliability programme for the project in conjunction with the MOD.

(*c*) Conduct a review of the equipment specification to ensure that full account is taken of reliability at the earliest stage and that no requirement of the specification is liable to jeopardize the achievement of the reliability target.

(*d*) Conduct reliability and maintainability design reviews as the design develops, including consideration of possible modes of failure and the effect of such failures both on the equipment, and if possible on the system in which the equipment is likely to be fitted, and, where weaknesses are revealed, either to implement design changes or to make proposals to the MOD for design modifications.

(*e*) Tabulate technological innovations and their expected effect on the reliability and maintainability of the equipment compared with similar older equipments.

(*f*) Draw up outline preventive maintenance and servicing schedules as foreseen to be required to achieve target reliability between planned overhaul periods of the equipment.

(*g*) Make an assessment of equipment reliability based on all available data and compare it with the reliability target.

(*h*) Make proposals for the environmental and reliability test programme and, where considered practical, for demonstration testing.

Although it is probably uneconomic to demand full reliability demonstration testing of the engine, the above requirements would ensure that full attention is paid to reliability and maintainability at the design stage. By requiring the manufacturer to orientate himself towards and tackle the problem of reliability in a more formal manner, it will, in the long term, pay dividends in improved availability and lower support costs. In the even longer term, perhaps a form of contract acceptable both to ourselves and the manufacturer will be found in which reliability will be both specified and subsequently demonstrated by operating data collected from the fleet; this contract would contain penalties for missing the target and bonuses for exceeding it.

Conclusion

We are now in an era of planned obsolescence. However, this should not be allowed to rub off onto the Diesel engine industry. Particular characteristics of Diesel engines, compared with all other prime movers apart from steam engines, have always been their general long life and reliability. These must not be sacrificed on the altars of high speed and low specific weight; when new Diesel engines are designed reliability and maintainability must receive their fair share of development effort. This can only come about if the customer demands, and is prepared to pay for, high standards, and makes it clear to manufacturers that when making his choice of engine he is interested in reliability, maintainability, and total costs of ownership at least as much as, if not more than, any of the other engine characteristics.

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