The Application of Reliability Engineering Theory to Warship Propulsion Plants with Special Reference to the St. Laurent Class Destroyer Escorts*

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Methods of mathematical analysis are developed for defining and numerically computing the reliability of warship propulsion plants at the design stage and in service.

The reliability of the main propulsion plants of destroyer escorts of the Royal Canadian Navy DDE 205, 206 and 257 Classes is computed, based on failures considered significant, in fourteen ships, over three years of operation.

A requirement is outlined for further development of reliability analysis to improve the effectiveness of the method.

INTRODUCTION

Reliability has always been a primary requirement for warship propulsion plants yet it continues to be one of the naval engineer's most persistent problems. The continuing need to reduce weight and space of propulsion plants and to improve performance and efficiency has resulted in complex, congested installations with highly-stressed machinery and equipment; as a result component failures continue to occur from time to time during the operation of the plants.

Until recently there was no adequate analytical method of computing the reliability of complete installations in terms of the reliability of the many components.

Similar problems became apparent in electronic systems and missiles a few years ago. Elaborate systems containing large numbers of components were required to operate automatically and it was found that reliabilities of systems and sub-assemblies which had hitherto been tolerable were now unacceptable. Mathematical methods were devised for defining and computing reliability and a new theoretical field of engineering developed rapidly, encouraged by the explosive rate of growth of electronics and systems engineering and the urgent requirement for improved reliability in aerospace equipment and missiles. To-day the field of "reliability engineering" is becoming established and text books are appearing (9, 10, 11).

It is considered that reliability engineering can make an important contribution to the engineering of warship propulsion machinery. It offers a precise method of computation and analysis of reliability factors in installations, thus permitting analysis and optimization of possible new plant designs and appraisal of reliabilities achieved in existing propulsion plants. Reliability engineering can relate the reliability of individual items of equipment to the overall reliability of the entire installation. The advantages of being able to cross-connect equipment can be demonstrated mathematically; the advantages of replicating individual items of equipment and the optimum number of replications can be calculated, and in cases where statistical records exist for equipment failures, the probability of plant failure can be computed.

The Basic Principles of Reliability Theory

Studies of data gathered on failures in complex engineering equipment indicate that individual failures in these systems seem to occur in a statistically random fashion and, when many component parts are considered over long periods of time, it is found that the failure rates remain substantially constant with time for a period whose duration depends on the proportion of early wear-out items in the statistical population (8). This pattern of failure has been found to occur in the operating life of a significant proportion of equipments between the initial "debugging" period after construction or overhaul and the time when another overhaul is due when components began to fail due to predictable wear-out. The overall pattern of failure is often depicted in the so-called "bathtub" curve (see Fig. 1).

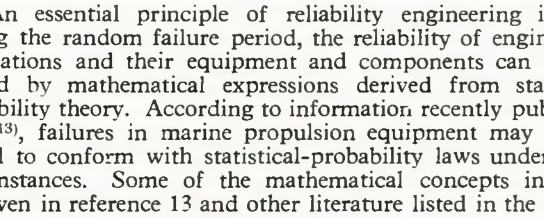

FIG. 1—*"Bathtub" curve—Failure rate versus time*

An essential principle of reliability engineering is that during the random failure period, the reliability of engineering installations and their equipment and components can be described by mathematical expressions derived from statistical probability theory. According to information recently published (5, 8, 13), failures in marine propulsion equipment may be expected to conform with statistical-probability laws under most circumstances. Some of the mathematical concepts involved are given in reference 13 and other literature listed in the bibliography given at the end of the paper.

Summary of Basic Principles

The reliability R of an item of equipment is defined as the probability that it will not fail in a given time. If λ, expressed

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as the number of failures per unit time, is the constant failure rate, then we can write:

$$R = e^{-\lambda t}$$

where e is the natural logarithm base and R will be a number without units and less than 1. Numerical values for $e^{-\lambda t}$ for given values of λ and t may be obtained from tables such as reference (12) where Table X gives values of e^{-x}.

Instead of the failure rate, λ, it is sometimes convenient to use the inverse of λ, called the "mean time to failure" and signified by θ. In this case the expression for R becomes:

$$R = e^{\frac{-t}{\theta}}.$$

This expression for R is called the "hazard function", the hazard in this case being equipment failure.

The foregoing expressions apply where the failure rate is constant; different expressions have been derived for other circumstances, such as failure by old age or wear-out, when failure rate will not be constant but will vary considerably with time.

Consider an engineering system consisting of several pieces of equipment, where every piece of equipment must be operating correctly for the system to function. This situation can be illustrated by the reliability diagram (see Fig. 2).

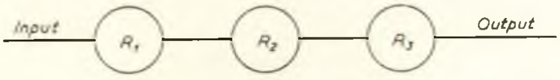


FIG. 2—*Reliability diagram*

If R_1, R_2 and R_3 are the reliabilities of individual items of equipment, the system reliability is the product of individual reliabilities. That is to say:

System reliability $= R_s = R_1 \times R_2 \times R_3 \ldots\ldots R_n$.

Under these circumstances the components are said to have "series" reliability.

Consider the case where multiple components of a given type have been provided in case a breakdown occurs. It is assumed that all components are operating at the same time, but that the output of one is sufficient to ensure satisfactory operation of the system. The reliability diagrams will show a parallel arrangement as shown in Fig. 3; the components are said to have a "parallel-non-switched" redundancy arrangement and the additional components are said to be "redundant".

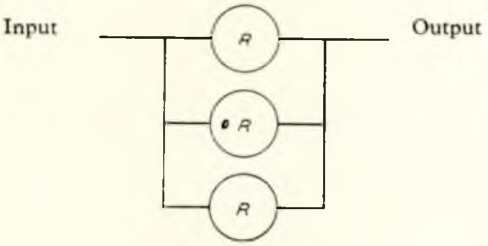


FIG. 3

The provision of redundant components in this way is often called "replication". If there are n replicated components of individual reliability R, the overall reliability R_s is given by:

$$R_s = 1 - (1-R)^n.$$

This is the probability that at least one will continue to operate.

If the redundant components are not operating, but are kept as standby, and the cut-in arrangement is not subject to failure, the overall reliability for n replications is given by:

$$R_s = e^{-\lambda t}\left(1 + \lambda t + \frac{\lambda^n t^n}{n!} + \ldots\ldots \frac{\lambda^2 t^2}{2!}\right).$$

This is called "parallel-switched" redundancy.

However, if first one and then another unit serves as a standby so that operating times are approximately equal, then the parallel-switched standby system reduces to a parallel system (5).

The following cases are also of special interest (8).

Two components of different reliability R_1 and R_2 operating continuously in parallel:

$$R_s = R_1 + R_2 - R_1.R_2.$$

Two components of different reliability R_1 and R_2 in parallel, one operating continuously, the other standby until the first one fails:

$$R_s = R_1 + \frac{\lambda_1}{\lambda_2 - \lambda_1}(R_1 - R_2)$$

where λ_2, λ_1 are the respective failure rates, and R_1 and R_2 are simple exponential functions.

Various other reliability arrangements are possible such as combinations of series and redundant components or two-out-of-three voting systems. The mathematics may also be amplified to allow for more than one mode of failure in components; this is particularly applicable to electronic systems. In general the analysis of marine propulsion machinery reliability can be accomplished with the expressions for series, parallel-non-switched, and parallel-switched redundancy given above.

Note that the foregoing expressions only apply when no repairs are made to failed components during the operating or mission period, t being used for calculating numerical values. It may be shown that the reliability of a replicated system is greatly increased if the individual component parts are repairable, the increase being dependent on the rapidity with which failures can be detected and repairs made.

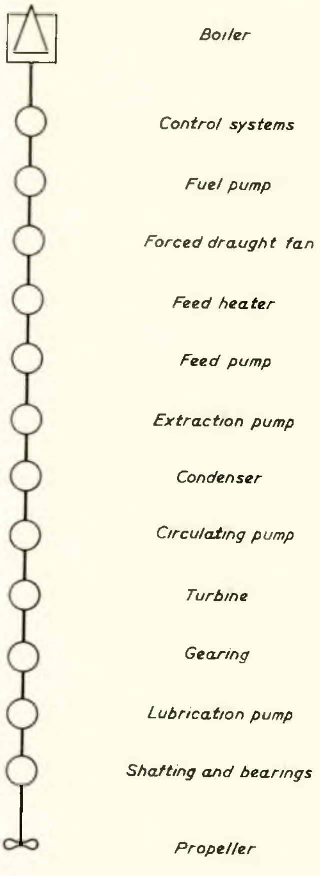


FIG. 4 — *Reliability diagram for simple propulsion plant with no duplication of components*

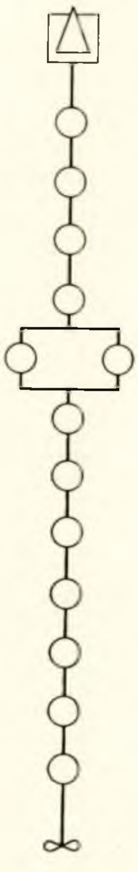


FIG. 5 — *Reliability diagram when a second feed pump is added to the propulsion plant shown in Fig. 4*

APPLICATION TO WARSHIP MAIN PROPULSION MACHINERY

Warship propulsion plants consist of a number of items of machinery which operate together to form a main propulsion system. For example a geared steam turbine plant consists essentially of propellers, shafting and bearings, main gearboxes, turbines, boilers, various items of auxiliary machinery, pipe systems, valves and control equipment. The plant may be considered as a system and the various items of equipment the components of the system (see Fig. 4).

In the simple system shown in Fig. 4, where only vital items of equipment are considered and only one of each type of equipment is provided, failure of one item of equipment will prevent the entire system from performing its function. From the point of view of reliability engineering this system constitutes a "series" arrangement, and if the reliabilities of individual components of the system are R_1, R_2, R_3, etc., the overall reliability R_0 will be given by:

$$R_0 = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_6 \times R_7 \times R_8 \ldots\ldots R_n.$$

Supposing a second feed pump is now added to the propulsion plant shown in Fig. 4, the additional pump is identical to the original feed pump, capable of meeting the needs of the plant at all powers, and connected into the propulsion system in such a way that it can at any time be run interchangeably with the original feed pump. The reliability diagram will now be as shown in Fig. 5; the feed pumps may be said to be "in parallel" and the standby pump is said to be "redundant". The effect of the additional feed pump on reliability can be demonstrated using the expression:

$$R_s = 1 - (1 - R)^n$$

where R_s = the reliability of the feed pump group, R the reliability of individual feed pumps and n the number of replications (the number of feed pumps in parallel). Note that this formula applies only where both feed pumps run either concurrently, or individually with balanced running hours. The effect of replication on reliability can be shown by substituting a numerical value for R in the foregoing equation; if the reliability of one pump is 0·9, the reliability for two replicated pumps will be 0·99 and the reliability of three replicated pumps will be 0·999.

The effect of such replication on the overall reliability of the propulsion plant can be shown as follows:

Let R_{01} be the overall plant reliability before replication.
Let R_{02} be the overall plant reliability after replication.
Let R_6 be the reliability of each feed pump.
Let R_p be the reliability of the group of feed pumps.
Then:

$$R_{01} = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_6 \ldots\ldots R_{12}$$
$$R_{02} = R_1 \times R_2 \times R_3 \times R_4 \times R_5 \times R_p \ldots\ldots R_{12}$$

and
$$\frac{R_{02}}{R_{01}} = \frac{R_1 \times R_2 \times R_3 \ldots\ldots R_p \ldots\ldots R_{12}}{R_1 \times R_2 \times R_3 \ldots\ldots R_6 \ldots\ldots R_{12}} = \frac{R_p}{R_6}$$
$$R_{02} = R_{01} \times \frac{R_p}{R_6}.$$

It can be seen that when additional "redundant" items of equipment are added to the propulsion plant there will be a commensurate change in the reliability of the installation as a whole, and in direct proportion to the change in reliability of the items being replicated.

Series/Parallel Operation

Under some circumstances, it is possible for a certain item of equipment to have a parallel arrangement at some plant outputs and a series arrangement at other plant outputs. Consider for example a propulsion plant which has twin identical feed pumps, each capable of meeting 50 per cent of the total requirements of the plant. At plant powers up to 50 per cent, one feed pump can meet the needs of the plant and the second pump is redundant. This is a parallel reliability arrangement. Above 50 per cent power however, both feed pumps will be required to meet the needs of the plant and this is a series reliability arrangement of feed pumps. The reliability diagrams for two pump series—parallel redundancy—are shown in Fig. 6.

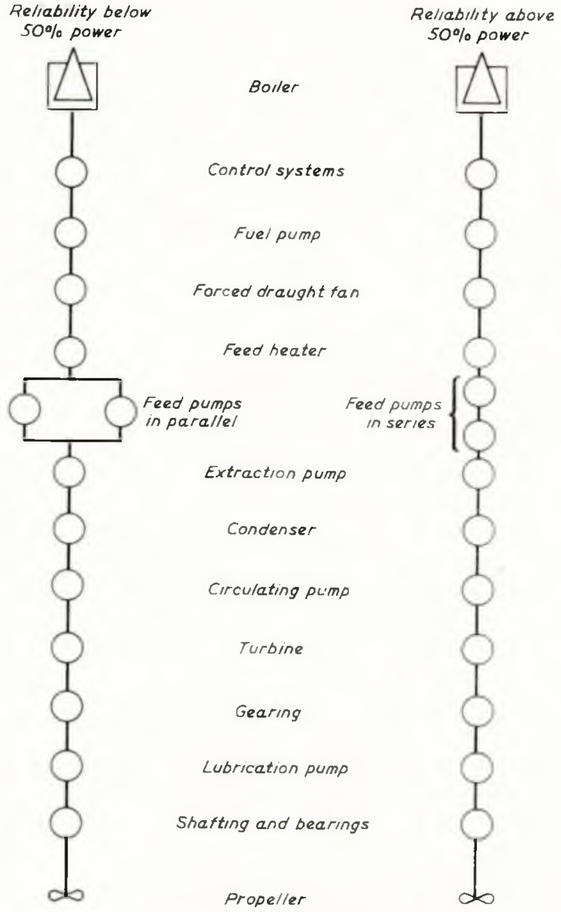


FIG. 6—*Series-parallel operation reliability diagram for plant with twin feed pumps each capable of meeting the needs of the plant at 50 per cent power*

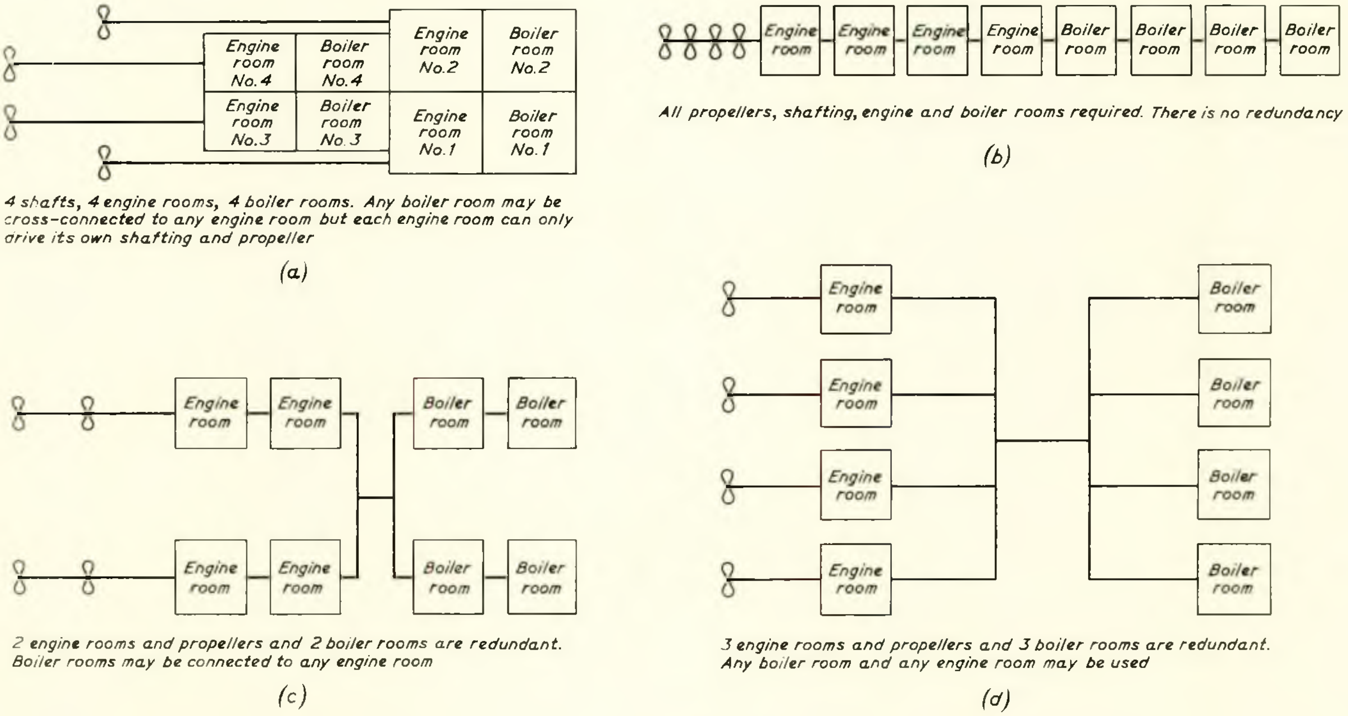
Generally speaking, when series/parallel reliability arrangements are used, the overall group reliability is high at low powers and low at high powers. Some figures for feed pump group reliability with various reliability arrangements are given, for example, in Table I, based on the single-pump reliability of 0·9.

TABLE I

Pump arrangement	Non-switched reliability, percentage plant power		
	25 per cent	50 per cent	100 per cent
Single full-power pump	0·90	0·90	0·90
Twin full-power pumps	0·99	0·99	0·99
Twin 50 per cent power pumps	0·99	0·99	0·81
Four 25 per cent power pumps	0·9999	0·98	0·66

It is apparent, intuitively, that the series/parallel method of replication will increase or reduce the overall plant reliability at various powers, depending on the way it is applied by the designer. Table I shows how reliability analysis can give a meaningful numerical value for the reliability corresponding to a particular machinery arrangement.

This reliability figure for a single component can be converted to a probable "mean time between failures" by using the hazard function, $R_s(t) = e^{-\lambda st}$.



4 shafts, 4 engine rooms, 4 boiler rooms. Any boiler room may be cross-connected to any engine room but each engine room can only drive its own shafting and propeller

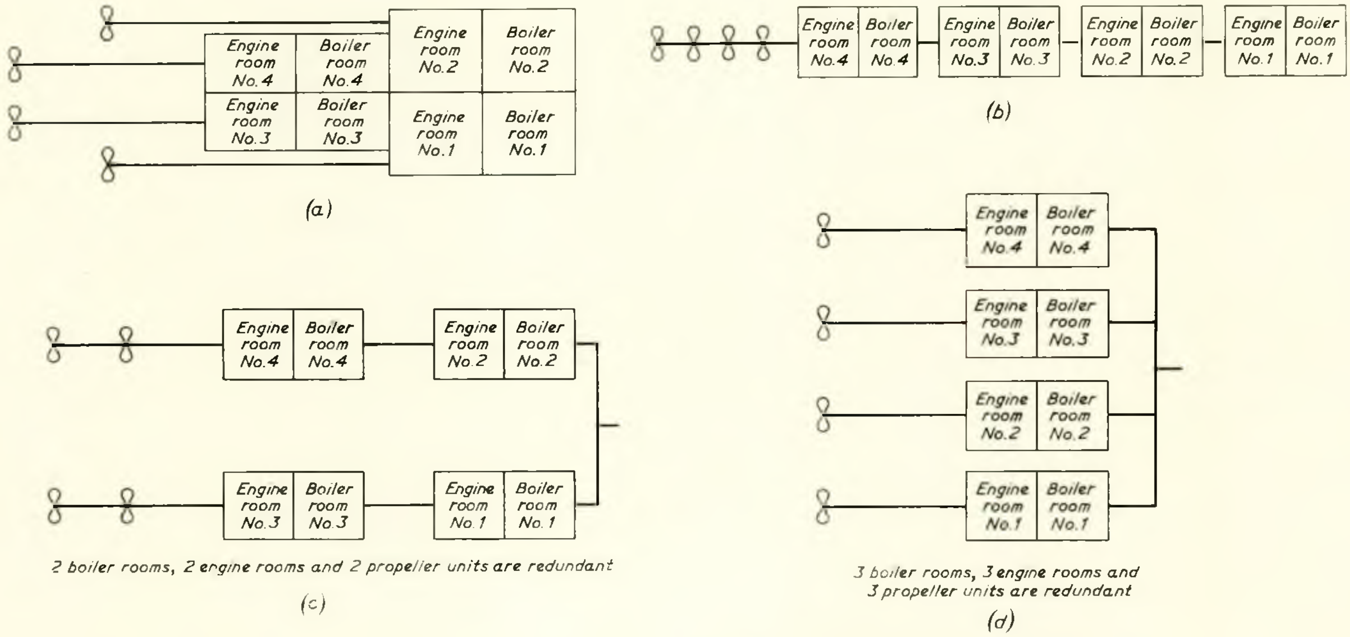
All propellers, shafting, engine and boiler rooms required. There is no redundancy

2 engine rooms and propellers and 2 boiler rooms are redundant. Boiler rooms may be connected to any engine room

3 engine rooms and propellers and 3 boiler rooms are redundant. Any boiler room and any engine room may be used

(a) Unit system being considered.
(b) Redundancy diagram for full power.
(c) Redundancy diagram for 50 per cent power.
(d) Redundancy diagram for 25 per cent power.

FIG. 7—*Reliability diagrams for unitized main propulsion machinery plant—(4 units and 4 shafts)*



2 boiler rooms, 2 engine rooms and 2 propeller units are redundant

3 boiler rooms, 3 engine rooms and 3 propeller units are redundant

(a) Unit system being considered.
(b) Redundancy diagram for full power.
(c) Redundancy diagram for 50 per cent power.
(d) Redundancy diagram for 25 per cent power.

FIG. 8—*Redundancy diagrams for unitized main propulsion machinery plant where boiler rooms cannot be cross-connected but can supply only one engine room*

Similar conversions can also be accomplished for complete systems, although in the case of systems containing redundant components, the foregoing simple expression does not apply and a more elaborate mathematical treatment must be used. Examples of calculations made for the DDE plant are given in Appendix C to this paper.

Effect of Unitization

In many warships, especially larger ones, the "unit" system is used for the propulsion plant. Under this system the ship is provided with multiple main propulsion plants called "machinery units" as a safeguard against action damage.

The replication of main engines and auxiliary equipment which is inherent in "unitizing" has an effect on the overall installation reliability and there will in general be an optimum arrangement.

The propulsion plant "units" themselves can be considered to comprise a replicated arrangement. Because of the requirements for low weight and space it is normally not feasible to have any redundancy at full power, but at lower powers, one or more of the units may be redundant, and the propulsion plant as a whole has a greater reliability at these powers due to this redundancy. An example is given in Fig. 7 of the redundancy of a four-unit propulsion plant at 100 per cent, 50 per cent and 25 per cent power, assuming that any boiler room can be cross-connected to any engine room. Fig. 8 gives diagrams for a four-unit installation where each boiler room can only be used with its own engine room. Although the reliability of the two installations is the same at the full power condition there is a difference at low powers. Figs. 7(d) and 8(d) for example show the situation at 25 per cent power. If the reliability of an individual engine room is R_a and the reliability of an individual boiler room is R_b then the overall installation reliability at 25 per cent plant power, based on non-switched redundancy is as follows:

a) if boiler rooms can be cross-connected to any engine room:

$$R_{\text{overall}} = [1 - (1 - R_a)^4] \times [1 - (1 - R_b)^4];$$

b) if boiler rooms can be connected only to their own engine rooms:

$$R_{\text{overall}} = 1 - (1 - R_a R_b)^4.$$

Within the individual machinery "units" of course the designer will often use replicated boilers, main engines or auxiliary machinery and equipment to give better reliability.

THE APPLICATION OF RELIABILITY ENGINEERING THEORY TO A DDE MACHINERY INSTALLATION

It is proposed in the following paragraphs, to examine the main propulsion plant of the Royal Canadian Navy DDE 205, 257 class destroyer escorts as an exercise in the application of reliability theory to a warship propulsion plant.

Using several simplifications, expressions are derived for the reliability of the propulsion plant at various powers, based on redundancy. Numerical values are obtained for reliability based on failure statistics in 14 ships over a three-year operating period (except for the fuel pumps which are not the same in the two classes of ship). This is slightly less than the period of 50 ship-years suggested in reference 8 and the statistics will have to be amplified when more experience and more accurate statistics are available.

DDE Main Propulsion Machinery System

The DDE main propulsion machinery system consists of two main boilers supplying steam to two main turbines with power transmission through reduction gearing to twin screws. A criterion for the design of this installation was that the ship should be able to continue steaming at reduced power with either one boiler, one main engine, or one major ancillary out of action. Consequently, as shown later diagrammatically in Fig. 13, the designer has resorted to duplication of most major items of equipment. In a number of cases the method has been to provide two units each capable of sustaining the propulsion system at 50 per cent power. There are exceptions however, for example, each forced lubrication pump can sustain the propulsion system at 100 per cent main engine power and each turboblower can sustain both boilers up to 80 per cent full main engine power. On the other hand, only one main feed pump is provided and this is capable of sustaining the plant at full main engine power; both auxiliary feed pumps operating together in parallel can only supply 40 per cent standby capacity.

Although important units are all fitted in duplicate, it is important to note that several of the duplicate units can only be used with one propulsion system, port or starboard, and cannot be cross-connected. A unit which cannot serve both port and starboard propulsion systems causes a corresponding reduction in overall plant reliability.

Consider for example a DDE which is required to carry out a mission requiring powers up to 50 per cent; if the port extraction pump and the starboard furnace fuel oil pump fail, the duplicate extraction and fuel oil pumps can be cross-connected and the ship is not prevented from completing the mission. If however, the starboard main turbine and the port stern tube bearing fail, the ship is rendered immobile and cannot complete the mission, because the port main turbine cannot be cross-connected to the starboard propulsion system and the starboard stern tube bearing cannot be used with the port propulsion system.

Method of Analysis

The method used was to consider the propulsion plant as a system and the various vital items of equipment such as boilers, turbines, pumps and auxiliary equipment as components of the system. Where more than one component of a particular type is provided, the reliability arrangement was considered as series if all components are required or parallel if some components are redundant. A list of the components considered, and the symbols used to represent their respective reliabilities, is given in Table II.

TABLE II—DDE 205, 257 CLASS MAIN PROPULSION PLANT—LIST OF COMPONENTS AND RELIABILITY SYMBOLS

R_1 : Propeller
R_2 : "A" bracket bearing
R_3 : Stern tube seal
R_4 : Stern tube bearing
R_5 : Plummer block trailing block
R_6 : Bulkhead gland
R_7 : Main gearbox
R_8 : Main turbine
R_9 : Main condenser
R_{10} : Main circulating pump
R_{11} : Closed feed control valve
R_{12} : Motor-driven forced lubricating pump
R_{13} : Turbine-driven forced lubricating pump
R_{14} : Main extraction pump
R_{15} : Main air ejector
R_{24} : Auxiliary feed pumps
R_{16} : Main feed pump
R_{17} : Furnace fuel oil heater
R_{18} : Furnace fuel oil pump
R_{19} : Turboblower
R_{20} : Main boiler
R_{21} : Main boiler water level control system
R_{22} : Main boiler steam temperature control system
R_{23} : Main boiler combustion control system
R_{25} : High pressure air compressor
R_{26} : Low pressure air compressors.

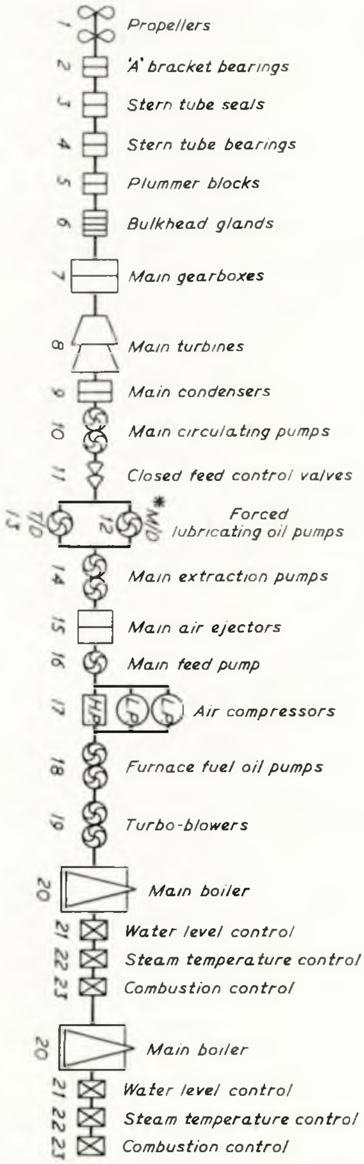
Table III gives a list of vital components which become redundant and indicates the percentage of full plant power at which these components are considered capable of meeting the overall requirements of the plant. The reliability diagrams Figs. 9 to 13 illustrate the redundancy at various powers.

TABLE III—CAPACITY OF AUXILIARIES

The following capacities were assumed for auxiliaries for the purposes of calculation:

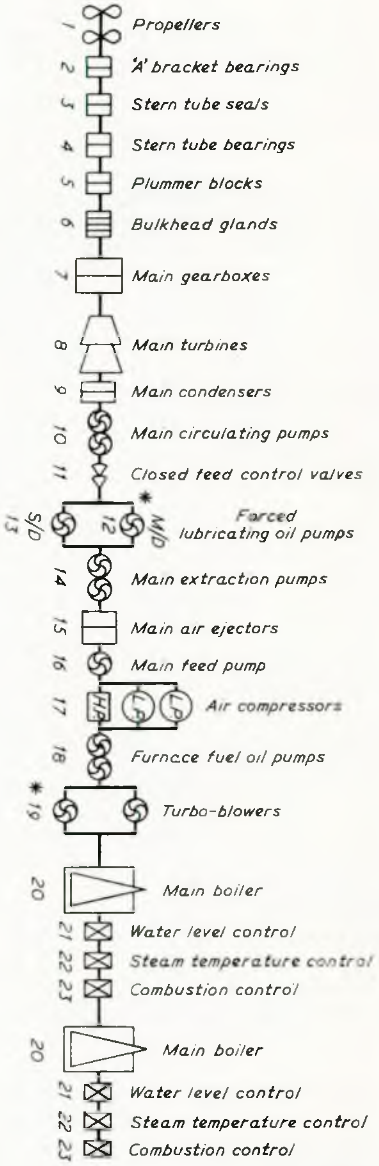
Equipment	*Percentage of full power*
One closed feed control valve	50
One forced lubricating pump	100
One main extraction pump	50
One auxiliary feed pump	20
Two auxiliary feed pumps	40
One main air ejector	50
One furnace fuel oil pump	50
One turboblower	80
One L.P. air compressor	100
Main feed pump	100
H.P. air compressor	100

Note that in some cases the figure assumed is lower than the design output. This reduces the complexity of the mathematics slightly and brings the figures into line with prudent steaming experience.



*Motor-driven forced lubricating oil pump is redundant in addition to the L.P. air compressors

FIG. 9—*Redundancy from 100 to 80 per cent full power*



*One turboblower is now redundant together with two L.P. air compressors and the motor-driven forced lubricating oil pump

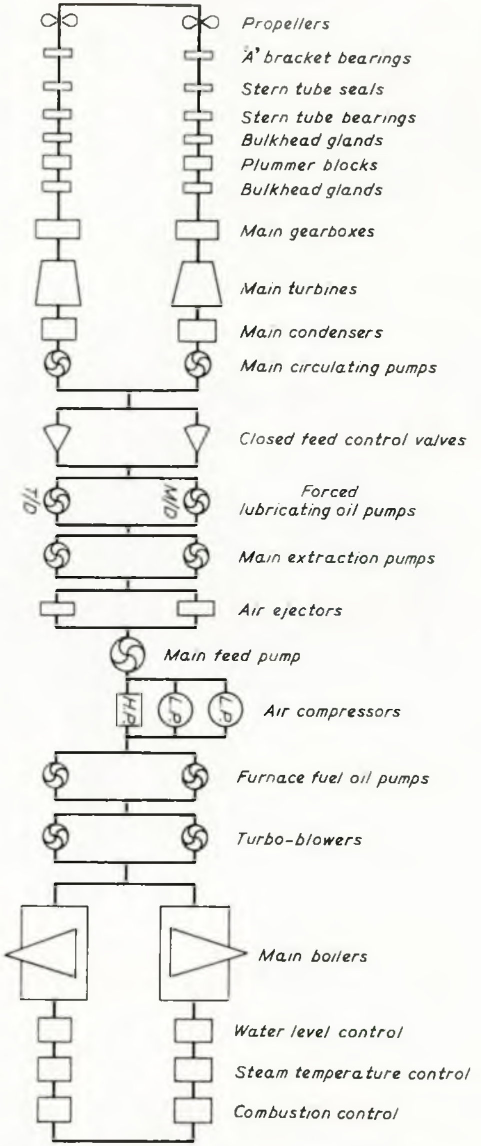
FIG. 10—*Redundancy from 80 to 50 per cent full power*

Equations for Reliability

As a preliminary step, equations were produced to describe the reliability of various groups of similar components in the series and parallel modes. These are given in Table IV. Next, expressions were developed for the overall reliability of the system at various powers. These are summarized in Table V.

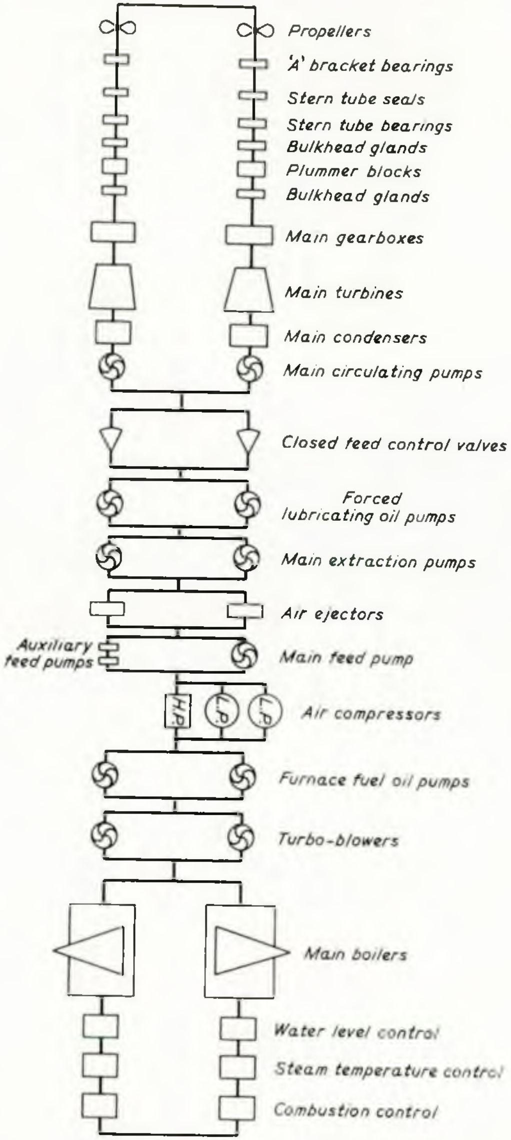
The failure statistics of various components were then reviewed and significant failures were extracted. The decision on whether a failure should be considered significant is often a difficult one which merits further study. The author chose to define as "significant" any failure which would immediately render the component unserviceable.

Failure rates based on the main steaming hours were calculated from the statistics for significant failures and converted into numerical values for reliability (Table VI). The latter were then substituted in the expressions for overall reliability in Table V. This resulted in a numerical figure for the reliability at each power and these are shown graphically in Figs. 14 and 15.



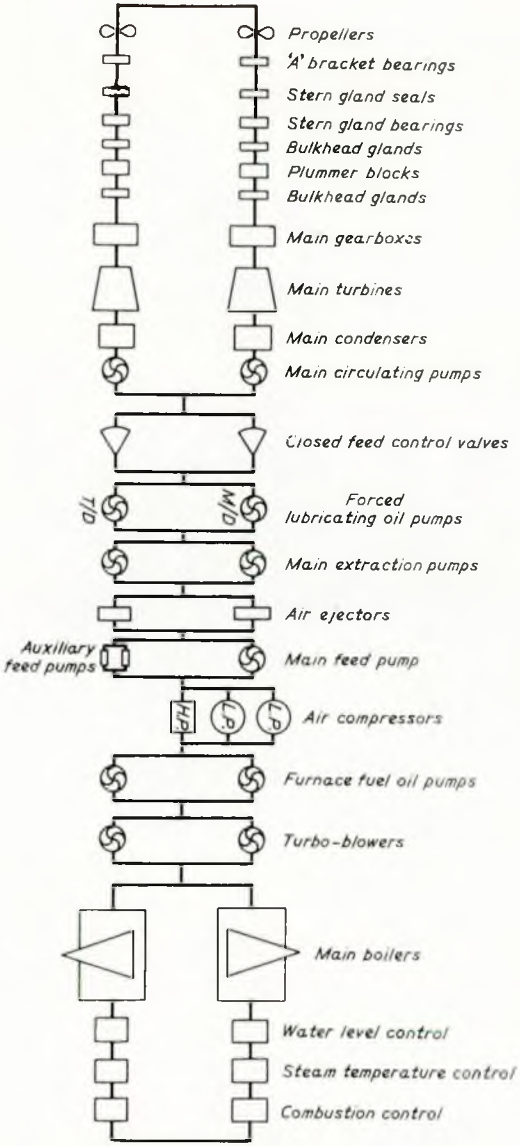
Below 50 per cent full power, one line of main propulsion and associated components are redundant in addition to: one closed feed controller, one main extraction pump, one air ejector, two L.P. air compressors, one furnace fuel oil pump, one main boiler with associated controls, one forced lubricating oil pump and one turboblower

FIG. 11—*Redundancy from 50 to 40 per cent full power*



Below 40 per cent full power, one line of main propulsion and associated components are redundant in addition to: one closed feed controller, one main extraction pump, one air ejector, two L.P. air compressors, one furnace fuel oil pump, one main boiler with associated controls, one forced lubricating oil pump and one turboblower—In this instance the two auxiliary feed pumps now give effective standby for the main feed pump

FIG. 12—*Redundancy from 40 to 20 per cent full power*



Below 20 per cent full power, one line of main propulsion and associated components are redundant in addition to: one closed feed controller, one main extraction pump, one air ejector, two L.P. air compressors, one furnace fuel oil pump, one main boiler with associated controls, one forced lubricating oil pump, one turboblower, the main feed pump and one auxiliary feed pump

FIG. 13—*Redundancy from 20 to 1 per cent full power*

TABLE IV—SUMMARY OF RELIABILITY EXPRESSIONS FOR EQUIPMENT GROUPS

Equipment or assembly	Unit symbol	Series symbol	Series expression	Numerical value	Parallel symbol	Parallel expression	Numerical value
Individual shaft assembly	R_a	R_a	$R_1R_2R_3R_4R_5R_6R_7R_8R_9R_{10}$	0·99490	—	—	—
Shaft pair	R_a	R_b	R_a^2	0·98983	R_b'	$2R_a-R_a^2$	0·99997
Closed feed control valves	R_{11}	R_c	R_{11}^2	0·99908	R_c'	$2R_{11}-R_{11}^2$	>0·99999
Forced lubricating pumps	$R_{12}R_{13}$	R_d	Not required	Not required.	R_d'	$R_{13}+\frac{\lambda_{13}}{\lambda_{12}-\lambda_{13}}(R_{13}-R_{12})$	>0·99999
Main extraction pumps	R_{14}	R_e	R_{14}^2	0·97141	R_e'	$2R_{14}-R_{14}^2$	0·99979
Main air ejectors	R_{15}	R_f	R_{15}^2	0·99722	R_f'	$2R_{15}-R_{15}^2$	>0·99999
Auxiliary feed pumps	R_{24}	R_g	R_{24}^2	0·99814	R_g'	$2R_{24}-R_{24}^2$	>0·99999
Feed pumps, auxiliary in series and parallel	R_{24} R_{16}	R'_h	$R_{16}+\frac{\lambda_{16}}{\lambda_g-\lambda_{16}}(R_{16}-R_g)$	>0·99999	R_h	$R_{16}+\frac{\lambda_{16}}{\lambda'_g-\lambda_{16}}(R_{16}-e^{-\lambda_g' t})$	>0·99999
Furnace fuel oil pumps	R_{18}	R_m	R_{18}^2	0·99409	R_m'	$2R_{18}-R_{18}^2$	0·99999
Turboblowers	R_{19}	R_n	R_{19}^2	0·98244	R_n'	$2R_{19}-R_{19}^2$	0·99992
Individual main boiler assembly	R_o	R_o	$R_{20}R_{21}R_{21}R_{23}$	0·98241	—	—	—
Main boiler pair	R_o	R_p	R_o^2	0·96513	R_p'	$2R_o-R_o^2$	0·99969
Air compressors L.P. only	R_{26}	—	—	—	R_q'	$2R_{26}-R_{26}^2$	0·99987
Air compressors, H.P. and L.P.	R_{25} R_{26}	—	—	—	R_q	$e^{-\lambda_q' t}+\frac{\lambda_q}{\lambda_{25}-\lambda'_q}(e^{-\lambda_q' t}-R_{25})$	>0·99999

Note: The R values shown in this table are for 100 hours main steaming.

TABLE V—SUMMARY OF OVERALL RELIABILITY ANALYSIS

Percentage of power	Symbol	Expression	Equation reference	System reliability	System M.T.B.F. (h)
100–80	R_z	$R_bR_cR_d'R_eR_fR_{16}R_mR_nR_pR_q$	(32)	0·88704	840
80–50	R_y	$R_z\frac{R_n'}{R_n}$	(34)	0·90282	970
50–40	R_x	$R_y\frac{R_b'R_c'R_e'R_f'R_m'R_p'}{R_b\ R_c\ R_e\ R_f\ R_m\ R_p}$	(35)	0·98173	2900
40–20	R_w	$R_x\frac{R_h'}{R_{16}}$	(36)	0·99936	4800
20–1	R_v	$R_w\frac{R_h}{R_h'}$	(37)	>0·99936	5000

Details of the analysis are given in Appendix A of this paper.

Comments on the DDE 205, 206 Class Propulsion Plant Reliability Analysis

Reviewing the chart of reliability, Fig. 14, it can be seen that the reliability based on replication is approximately constant from full plant power to approximately 80 per cent plant power. In this range of power, one forced lubrication pump and the L.P. air compressors are redundant.

At approximately 80 per cent plant power one of the turboblowers becomes redundant, giving a small improvement in reliability at all powers below 80 per cent.

There is a significant improvement in plant reliability and in the mean time between plant failures (M.T.B.F.) below 50 per cent plant power because a number of components becomes redundant at this point and is thus available for standby duty. The effectiveness of this policy is limited however by the lack of a standby main feed pump. Below 40 per cent plant power two auxiliary feed pumps provide standby, giving a major improvement in plant reliability, and there is a further small improvement below 20 per cent power as one of the auxiliary feed pumps becomes redundant.

Fig. 15 shows the effect of replication on the mean time between "propulsion plant failures". In this case the term "plant failure" is defined to mean the inability of the plant to continue operation at the power level being considered.

The M.T.B.F. between full power and 80 per cent power is 840 hours, and when a turboblower becomes redundant at approximately 80 per cent power there is an improvement in probable M.T.B.F. to 970 hours which is maintained down to 50 per cent power. At this point many components become redundant and the probable M.T.B.F. jumps from 970 to 2900, which is maintained down to 40 per cent power. At this point the main feed pump becomes redundant and the M.T.B.F. increases to 4800. It is interesting to note the serious effect of the low M.T.B.F. of the main feed pump. The improvement in plant M.T.B.F. when the main feed pump becomes redundant is 1900 hours. This is of the same order as the improvement at 50 per cent power, which is 1930 hours, brought about by the redundancy of one complete shaft assembly, including gearbox, turbine, condenser and circulating pump, a closed feed control valve, an extraction pump, an air ejector, a furnace fuel oil pump, a main boiler and associated control systems.

The M.T.B.F. of 4800 is maintained down to 20 per cent power, at which point one of the auxiliary feed pumps becomes redundant, giving a probable M.T.B.F. of approximately 5000 hours, an increase of only 200 hours.

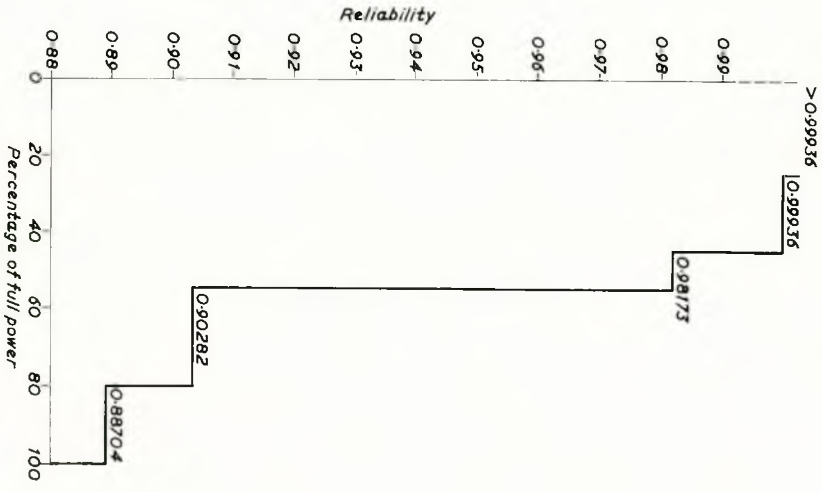
It is apparent that the provision of one redundant feed pump has an important effect on the M.T.B.F. of the propulsion plant, but the provision of a third pump gives a much smaller improvement. Thus triple replication of a component should normally be necessary only when component reliability is extremely low.

"Availability" and "Confidence Limits"

It is possible to take a reliability analysis further than the

TABLE VI—FAILURE STATISTICS AND CALCULATION OF INDIVIDUAL EQUIPMENT RELIABILITIES

	Equipment name	Total failures	Significant failures (N_f)	Number fitted per ship (n)	Main steaming hours (S)	M.T.B.F. $\theta = \frac{S \times n}{N_f}$	Failure rate Per cent/1000 h		Reliability $R = \exp(-\lambda t)$ $t = 100$ h
R_1	Propeller	0	0	2	107 654	$>10^7$	$<0·01$	R_1	$>0·99999$
R_2	"A" bracket bearings	2	1	2	107 654	215 308	0·46445	R_2	0·99954
R_3	Stern tube seal	14	0	2	107 654	$>10^7$	$<0·01$	R_3	$>0·99999$
R_4	Stern tube bearing	5	5	2	107 654	43 062	2·3222	R_4	0·99768
R_5	Plummer block/trailing block	4	2	2	107 654	107 654	0·92890	R_5	0·99907
R_6	Bulkhead gland	1	0	4	107 654	$>10^7$	$<0·01$	R_6	$>0·99999$
R_7	Main gearbox	11	1	2	107 654	215 308	0·46445	R_7	0·99954
R_8	Main turbine	19	1	2	107 654	215 308	0·46445	R_8	0·99954
R_9	Main condenser	3	0	2	107 654	$>10^7$	$<0·01$	R_9	$>0·99999$
R_{10}	Main circulating pump	15	1	2	107 654	215 308	0·46445	R_{10}	0·99954
R_{11}	Closed feed control valve	1	1	2	107 654	215 308	0·46445	R_{11}	0·99954
R_{12}	M.D. forced lubricating pump	1	1	1	107 654	107 654	0·92890	R_{12}	0·99907
R_{13}	T.D. forced lubricating pump	24	8	1	107 654	13 457	7·4311	R_{13}	0·99237
R_{14}	Main extraction pump	62	31	2	107 654	6945	14·399	R_{14}	0·98560
R_{15}	Main air ejector	3	3	2	107 654	71 769	1·3934	R_{15}	0·99861
R_{24}	Auxiliary feed pump	20	2	2	107 654	107 654	0·92890	R_{24}	0·99907
R_{16}	Main feed pump	37	19	1	107 654	5666	17·649	R_{16}	0·98235
R_{18}	F.F.O. pump (reciprocating)	6	3	2	50 724	33 816	2·9572	R_{18}	0·99704
R_{19}	Turboblower	44	19	2	107 654	11 332	8·8245	R_{19}	0·99118
R_{20}	Main boiler	114	28	2	107 654	7690	13·004	R_{20}	0·98700
R_{21}	Main boiler W.L. control	8	8	2	107 654	26 914	3·7155	R_{21}	0·99628
R_{22}	Main boiler S.T. control	4	1	2	107 654	215 308	0·46445	R_{22}	0·99954
R_{23}	Main boiler combustion control	5	1	2	107 654	215 308	0·46445	R_{23}	0·99954
R_{25}	H.P. air compressor	8	3	1	107 654	35 885	2·7867	R_{25}	0·99721
R_{26}	L.P. air compressor	31	25	2	107 654	8620	11·601	R_{26}	0·98840



The reliability figure indicates the proportion of propulsion plants which would be able to maintain the specified power after 100 hours main steaming *without repairs.*—For example, in a group of 100 ships, 11 ships would probably be unable to continue at 80-100 per cent full power—Two ships would be unable to continue after 100 hours at 50-40 per cent full power (without repairs)

FIG. 14—*Reliability of DDE 205 class propulsion plant—For time period 100 hours main steaming*

author has done in the preceding example. For instance, if suitable statistics were available to indicate the average time that components remained unserviceable after a failure and to indicate the time required for planned preventive maintenance it would be possible to compute the probable "availability" of the propulsion system over a given number of hours using the values previously calculated for M.T.B.F.

Another concept which can be introduced into reliability analysis is that of "confidence limits". It is apparent that any statistical predictions based on observation of a small number of components for a short time are likely to be less accurate than predictions based on observations of a large group of components for a long period of time. A numerical value can be calculated to describe the probable variations of observed results from the precise figure for, say, system reliability, obtained by reliability calculations; the numerical value is derived using the concept of "confidence level". However the concepts are among the more sophisticated aspects of reliability analysis which are beyond the scope of this paper.

DISCUSSION

Using the methods outlined in this paper it was possible to develop expressions for the reliability of a DDE propulsion plant at various powers. This analysis is regarded as a tentative and experimental one as there are several factors affecting reliability which require further investigation.

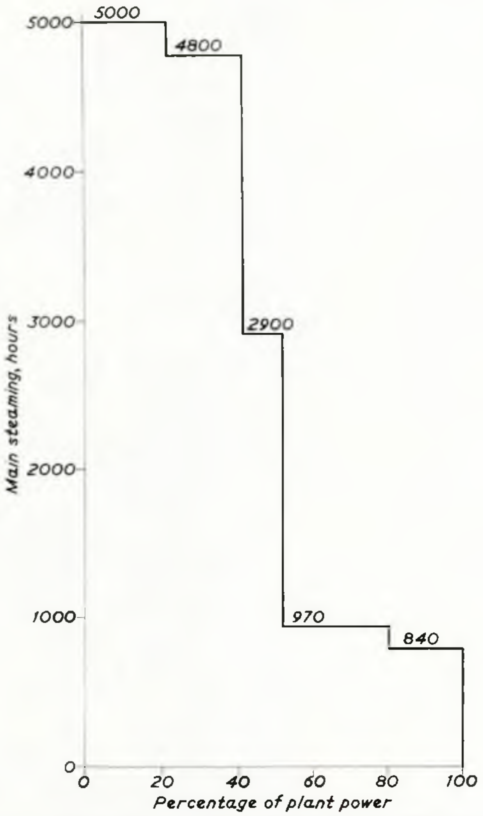


FIG. 15—*Probable mean time between propulsion plant failures in DDE 205, 206 class*

Note that in this case, the term "plant failure" means that the ship cannot proceed at the power specified

The following are some of the areas which require attention:

Statistical Records of Failures

The statistics available at present are not sufficiently comprehensive to give an accurate figure for frequency of failure. For example a check of *Engineering Quarterly Letters* revealed significant failures which had not been reported in "Material Failure Reports".

Components Considered

The components included in the analysis are those which have been known to cause, or are likely to cause, propulsion plant "failures" in DDEs. Certain components such as heat exchangers, evaporators, Diesel and turbo-alternators, de-aerating systems, valves and piping have been omitted from this analysis, but could be included in a more sophisticated one. Similar arguments apply to crude hand control arrangements provided as standby to certain automatic components and to automatic cut-in devices.

Assumption of Failure Rate

The assumption of random failure has been verified for various propulsion plant components and results are given in the literature(8). There are many contributory factors to machinery unreliability which may change as the equipment gets older and as modifications are eventually introduced to alleviate failure patterns. There is a requirement for more information on the failure rates experienced in warships to achieve an understanding of how failure rates change over the ships' 20 year design lives. There is also a need to investigate the effect of different types of usage—intermittent operation, effect of shut-down time, effect of component power output, etc.

Steaming Hours—Basis for Calculation of Failure Rates

A fundamental requirement for the successful application of reliability theory is to relate the failure rates of individual components to the main steaming hours of the complete plant. There are two obvious alternatives. The first is to calculate the individual component failure rates based on the running hours of each component, then to try and relate these running hours to main steaming hours. This involves establishing the standby time and running time of each component and relating them to main steaming hours for various steaming conditions from auxiliary steaming to full power. It is a complex problem for the DDE because of the way auxiliaries are started or shut down as the main engine power changes.

The second alternative is to calculate component failure rates in terms of elapsed time or "main steaming" hours. This simplifies the analysis considerably, but future projections of reliability made on this basis are only valid if the pattern of steaming and maintenance does not change significantly for the period being considered. For this paper, "main steaming hours" was used as the basis for calculating failure rates of both the components and the propulsion plant as a whole because this was the most practicable method.

The problems just outlined, and others, place a limitation on the effectiveness of reliability analysis at the present time. It is nevertheless considered that the calculated results give an interesting illustration of the reliability of warship propulsion plants and of the effect of replication. It is apparent that the probability of propulsion plant failure can be taken into consideration when assigning warships for operational missions, and this becomes accurate when large numbers of warships are involved.

The ability to determine the effects of replication on plant reliability, together with past experience of component failure rates should be a useful aid to propulsion plant designers.

CONCLUSIONS

It is concluded that reliability analysis will make a worthwhile contribution to the engineering of warship propulsion plants. Further investigation and development of the method will lead to better understanding of reliability and permit improvements to be made in future ship designs.

It should be possible to develop a comprehensive method encompassing maintenance and overhaul frequency and various operating factors which affect reliability, and to include the additional dimension of "probable availability". This will make it possible to choose the optimum frequency and scale of overhauls by achieving a balance between reliability and maintenance cost.

At the design stage it will be helpful in determining the optimum compromise between reliability, weight/space, and capital cost. It should be possible to compare reliability and availability statistics on various types of boilers, engines and critical auxiliaries such as feed pumps and turboblowers so that cost-effectiveness can be emphasized and subjective factors kept to a minimum in the selection of equipment.

In the inter-naval field, if standard methods of compiling statistics for comparison can be evolved under the A-B-C (American-British-Canadian) tripartite naval agreements, the results can only be of benefit, economically and operationally, to all concerned.

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APPENDIX A

METHOD OF CALCULATION OF RELIABILITY OF DDE MAIN PROPULSION SYSTEM

Basic Equations Used for Computing Reliability

Let the reliability of system component "p" be R_p;
Let the reliability of system component "q" be R_q;
Let the reliability of system component "r" be R_r;
Let the reliability of system component "n" be R_n.
Then if the "n" components are in series, the overall reliability R_s is given by:

$$R_s = R_p.R_q.R_r \;.\;.\;.\;.\;.\; R_n \qquad (1)$$

If two elements are in parallel with switched redundancy, the overall reliability R_o is given by:

$$R_o = R_p + \frac{\lambda_p}{\lambda_q - \lambda_p} \cdot (R_p - R_q) \qquad (2)$$

where λ_p and λ_q are the respective failure rates. If two elements R_p and R_q are in parallel with non-switched redundancy, then:

$$R_o = R_p + R_q - R_p.R_q \qquad (3)$$

For pairs of identical parallel elements in series:

$R_{o1} = (2R_p - R_p^2)$ for the first pair,
$R_{o2} = (2R_q - R_q^2)$ for the second pair,

and the reliability of the two pairs in series is given by:

$$R_s = R_{o1}.R_{o2} = (2R_p - R_p^2)\,(2R_q - R_q^2) \qquad (4)$$

Note that some units can be operated with either switched or non-switched redundancy. When alternate running of units to keep running hours balanced is a common practice, the expression for non-switched redundancy has been used in the calculation.

Reliability of Units in Series and in Parallel

Shaft Assembly

The assembly consists of a propeller, "A" bracket bearing, stern gland seal, stern gland bearings, bulkhead glands, plummer and trailing block, main gearbox, main turbine, main condenser and main circulating pump. From the reliability standpoint the components are arranged in series, as there are no standbys, if one item fails the whole shaft assembly is affected. Let the reliability of the single shaft assembly be R_a. Using the reliability symbols given in Table II, and the expression for series reliability, equation (1):

$$R_a = R_1.R_2.R_3R_4R_5R_6R_7R_8R_9R_{10} \qquad (5)$$

Pair of Shaft Assemblies in Series

Let R_b be the reliability of two shaft assemblies in series. From equation (1):

$$R_b = R_a.R_a = R_a^2 \qquad (6)$$

Pair of Shaft Assemblies in Parallel

Let R_b' be the reliability of a pair of shaft assemblies in parallel. From equation (3):

$$R_b' = 2R_a - R_a^2 \qquad (7)$$

Closed Feed Control Valves

Let the reliability of the closed feed control valves in series be R_c; then from equation (1) and Table II:

$$R_c = R_{11}.R_{11} = R_{11}^2 \qquad (8)$$

Let the reliability of the closed feed control valves in parallel be R_c'. Then from equation (3) and Table II:

$$R_c' = 2R_{11} - R_{11}^2 \qquad (9)$$

Forced Lubricating Oil Pumps

Let the reliability of the forced lubricating pumps in series be R_d. Then from equation (1) and Table II:

$$R_d = R_{12}.R_{13} \qquad (10)$$

Note that in this case the reliability of the turbo-pump is different from that of the motor-driven pump. Should it be desired to show the reliability of the electrical cut-in device separately, the motor-driven pump and cut-in can be treated as a pair of components in series.

Let the reliability of the lubricating oil pumps in parallel be R_d'. Then from equation (2) and Table II:

$$R_d' = R_{13} + \frac{\lambda_{13}}{\lambda_{12} - \lambda_{13}} (R_{13} - R_{12}) \qquad (11)$$

Main Extraction Pumps

Let the reliability of the main extraction pumps in series be R_e. Then from equation (1) and Table II:

$$R_e = R_{14}.R_{14} = R_{14}^2 \qquad (12)$$

Let the reliability of the main extraction pumps in parallel be R_e'. Then from equation (3) and Table II:

$$R_e' = 2R_{14} - R_{14}^2 \qquad (13)$$

Main Air Ejectors

Let the reliability of the main air ejectors in series be R_f. Then from equation (1) and Table II:

$$R_f = R_{15}.R_{15} = R_{15}^2 \qquad (14)$$

Let the reliability of the main air ejectors in parallel be R_f'. Then from equation (3) and Table II

$$R_f' = 2R_{15} - R_{15}^2 \qquad (16)$$

Feed Pumps

Let the reliability of the two auxiliary feed pumps in series be R_g. Then from equation (1) and Table II:

$$R_g = R_{24}.R_{24} \qquad (17)$$

Let the reliability of the two auxiliary feed pumps in parallel be R_g'. Then from equation (3) and Table II:

$$R_g' = 2R_{24} - 2R_{24}^2 \qquad (18)$$

The main and auxiliary feed pumps can be considered as a parallel group in two ways. At main engine powers below

20 per cent one auxiliary feed pump constitutes an effective standby for the main feed pump. Under these circumstances there are in effect three pumps in parallel (see Fig. 13). Let the reliability under these circumstances be R_h. Then from equations (2) and (18) and Table II:

$$R_h = R_{16} + \frac{\lambda_{16}}{\lambda_g' - \lambda_{16}} (R_{16} - R_g') \qquad (19)$$

At main engine powers between 20 per cent and 40 per cent the auxiliary feed pumps must both operate concurrently to provide an adequate standby for the main feed pump. Under these circumstances there is in effect a parallel pair of auxiliary feed pumps in series (see Fig. 12). Let the reliability under these circumstances be R_h'. Then from equations (2) and (17) and Table II:

$$R_h' = R_{16} + \frac{\lambda_{16}}{\lambda_g - \lambda_{16}} (R_{16} - R_g) \qquad (20)$$

Air Compressors

The air compressors are considered to be a vital auxiliary because they supply the automatic boiler controls. Two low pressure compressor installations and one high pressure compressor installation are provided and each of these can meet the needs of the plant at any power.

Let the reliability of the L.P. compressors only, be R_q'. Then, considering them as a parallel pair, from Table II and equation (3):

$$R_q' = 2R_{26} - R_{26}^2 \qquad (21)$$

Let the reliability of L.P. and H.P. compressors be R_q. Then, considering them as a replicated group of three, from Table II and equation (2):

$$R_q = e^{-\lambda_q' t} + \frac{\lambda_q'}{\lambda_{25} - \lambda_q'} (e^{-\lambda_q' t} - R_{25}) \qquad (22)$$

Furnace Fuel Oil Pumps

Let the reliability of the two furnace fuel oil pumps in series be R_m. Then from equation (1) and Table II:

$$R_m = R_{18}.R_{18} = R_{18}^2 \qquad (25)$$

Let the reliability of the two furnace fuel oil pumps in parallel be R_m'. Then from equation (3) and Table II:

$$R_m' = 2R_{18} - 2R_{18}^2 \qquad (26)$$

Turboblowers

Let the reliability of the two turboblowers in series be R_n. Then from equation (1) and Table II:

$$R_n = R_{19}.R_{19} = R_{19}^2 \qquad (27)$$

Let the reliability of the two turboblowers in parallel be R_n'. Then from equation (3) and Table II:

$$R_n' = 2R_{19} - R_{19}^2 \qquad (28)$$

Main Boilers

One main boiler and its associated water level control, steam temperature control and combustion air/oil indicators can be considered as a series system. Let the reliability of this series system be R_o. Then from equation (1) and Table II:

$$R_o = R_{20}.R_{21}.R_{22}.R_{23} \qquad (29)$$

If greater rigour is required in the analysis, the reliability of standby arrangements can be included. For the water level there is the secondary arrangement of a thermo-hydraulic water level control and the tertiary arrangement of hand control. For the steam temperature there is hand control. The boilers can be steamed without combustion indicators if necessary.

Let the reliability of the boilers and associated controls in series be given R_p. Then from equations (1) and (29) and Table II:

$$R_p = R_o.R_o = R_o^2 \qquad (30)$$

Let the reliability of the boilers and associated controls in parallel be given by R_p'. Then from equations (3) and (29) and Table II:

$$R_p' = 2R_o - R_o^2 \qquad (31)$$

The reliabilities of pairs, groups and assemblies are summarized in Table IV.

Overall Reliability of the Main Propulsion System at Various Powers

100 to 80 per cent Full Power

In the range 100 per cent to 80 per cent full power, all main and ancillary machinery is required, except for the motor-driven forced lubricating pump and L.P. air compressors. The arrangement from the reliability standpoint is given in Fig. 9. All equipment is in series except for the air compressors which form a replicated group of three, and the two forced lubricating pumps which form a replicated group of two, but these groups are in series with the rest of the system.

Let the overall reliability of the plant be R_z. Then from equation (1) and Table IV:

$$R_z = R_b.R_c.R_d.R_e.R_f.R_{16}.R_m.R_n.R_p.R_q \qquad (32)$$

80 to 50 per cent Full Power

Below 80 per cent main engine power one turboblower can sustain both boilers. For reliability purposes the second blower can therefore be considered redundant. The arrangement is now as in Fig. 10, the forced lubricating pumps and the turboblowers being parallel pairs in series with the rest of the system.

Let the overall reliability be R_y. Then from equation (1) and Table IV:

$$R_y = R_b.R_c.R_d{}^1.R_e.R_f.R_{16}.R_i.R_m.R_n'.R_p.R_q \qquad (33)$$

Note that this differs from the expression for R_z given in equation (32) only in the turboblower term, i.e.

$$R_y = \frac{R_z}{R_n} . R_n' \qquad (34)$$

50 to 40 per cent Full Power

Below 50 per cent full power, a number of ancillaries, one shaft assembly and one main boiler become redundant, as shown in Fig. 11. Let the overall reliability be R_x. Then from equation (34) and Table IV:

$$R_x = R_y \frac{R_b'}{R_b} \frac{R_c'}{R_c} \frac{R_e'}{R_e} \frac{R_f'}{R_f} \frac{R_m'}{R_m} \frac{R_p'}{R_p} \qquad (35)$$

40 to 20 per cent Full Power

Below 40 per cent full power two auxiliary feed pumps in series give an adequate standby for the main feed pump. The arrangement is shown in Fig. 12. Let R_w be the overall reliability. From equation (35) and Table IV:

$$R_w = R_x \frac{R_h'}{R_{16}} \qquad (36)$$

20 to 1 per cent Full Power

Below 20 per cent full power one auxiliary feed pump gives adequate standby for the main feed pump.

For reliability purposes the three feed pumps in parallel can be considered as shown in Fig. 13.

Let the overall reliability be R_v. From equation (36) and Table IV:

$$R_v = R_w . \frac{R_h}{R_h'} \qquad (37)$$

A summary of overall reliability is given in Table V.

APPENDIX B

SIMPLIFYING ASSUMPTIONS

Among the engineering considerations used to simplify the presentation are the following:

1) *Main Circulating Pump*

The analysis assumes that the circulating pumps are essential to the operation of the main engines. This is true when manœuvring, proceeding astern, and in certain ahead conditions, but the pumps are not essential for all ahead steaming due to "scoop effect" in the main circulating system.

2) *Shaft Trailing*

Should one main engine/gearing/shafting system become unserviceable, the ship can continue at reduced power. If circumstances are such that the tailshaft coupling can be "broken", the trailing arrangements permit the ship to proceed at powers up to 50 per cent (the circumstances assumed in the analysis). If the tailshaft coupling cannot be separated, the ship may continue at powers below about 39 per cent with the defective shaft locked.

3) *De-aerator Feed Heater*

The DDE is provided with a full-flow de-aerating system with an associated extraction pump, vent condenser, and various valves, systems and automatic devices, but this has been left out of the analysis to simplify the presentation. Failure of the de-aerating system would limit plant power to approximately 90 per cent of the normal full power figure (the failure reports used for this paper did not include any instance of a ship being disabled due to a de-aerator failure, but a recent report indicated one such failure in a DDE).

4) *Electrical Power*

The DDE machinery plant is so designed that some propulsive power can be maintained in the event of a temporary failure of electrical power. Because of this, and a five-fold replication of alternators, the latter has been omitted from the analysis.

The foregoing simplifications and others which will be apparent to engineers familiar with the equipment and patterns of equipment utilization in a DDE, emphasize the complexity of the reliability problem and indicate the need for a standard, systematic method of analysis to augment traditional methods of plant design. They also emphasize the difficulties faced by plant designers attempting to estimate the reliability of warship propulsion plants by intuitive methods.

APPENDIX C

THE CALCULATION OF SYSTEM M.T.B.F.

When it is assumed that individual equipments have exponential failure distributions, then the system which uses these equipments, and in which some of the latter are redundant, will not have an exponential failure distribution, and the statement:

System reliability $= R_s = e^{-\lambda_s t} = e^{-\frac{t}{\theta s}}$

will not be true. This expression, solved for $1/\lambda_s$ gives a good approximation of the system M.T.B.F. only when the contribution to the system failure rate of the redundant equipment is small compared to the contribution of the non-redundant equipments. This is the case in the DDE analysis only for the higher power levels, 100 to 80 per cent, and 80 to 50 per cent full power. For the remaining power levels, it is necessary to integrate the system reliability function from zero to infinity. The derivations of the expressions for θ_x, θ_v, and θ_w, are shown in the following notes:

50 to 40 per cent Full Power

$$\begin{aligned} R_x(t) &= R_b{}'R_c{}'R_d{}'R_e{}'R_f{}'R_{16}R_m{}'R_n{}'R_p{}'R_q \\ &= R_d{}'R_q{}' \exp(-\lambda_{16}t)\,[2\exp(-\lambda_a t) - \exp(-2\lambda_a t)] \\ &\times [2\exp(-\lambda_o t) - \exp(-2\lambda_o t)]\,[2\exp(-\lambda_{11}t) - \exp(-2\lambda_{11}t)] \\ &\times [2\exp(-\lambda_{14}t) - \exp(-2\lambda_{14}t)]\,[2\exp(-\lambda_{15}t) - \exp(-2\lambda_{15}t)] \\ &\times [2\exp(-\lambda_{18}t) - \exp(-2\lambda_{18}t)]\,[2\exp(-\lambda_{19}t) - \exp(-2\lambda_{19}t)]. \end{aligned} \tag{i}$$

To simplify notation, let $A\exp(-B\lambda_C - D\lambda_E) = A\,(B.C.D.E.)$. (ii)

Then:

$$\begin{aligned} R_x(t) &= R'_d R_q\,(16)\,[2(a) - (2.a)]\;[2(o) - (2.o)] \\ &\times [2(11) - (2.11)]\;[2(14) - (2.14)]\;[2(15) - (2.15)] \\ &\times [2(18) - (2.18)]\;[2(19) - (2.19)]. \end{aligned} \tag{iii}$$

Define the operator p with the following properties:

$$\text{a)}\quad p(x, y, z, \ldots\ldots) = (2.x, y, z, \ldots\ldots) + (x, 2.y, z, \ldots\ldots) + (x, y, 2.z, \ldots\ldots) + \ldots\ldots \tag{iv}$$

$$\text{b)}\quad p(x, y, [z], \ldots\ldots) = p(x, y, z, \ldots\ldots) - (x, y, 2.z, \ldots\ldots). \tag{v}$$

$$\begin{aligned}\text{c)}\quad p^2(x, y, z, \ldots\ldots) &= (2.x, 2.y, z, \ldots\ldots) \\ &+ (2.x, y, 2.z, \ldots\ldots) \\ &+ \ldots\ldots \\ &+ (x, 2.y, 2.z, \ldots\ldots) \\ &+ \ldots\ldots \end{aligned} \tag{vi}$$

$$\begin{aligned}\text{d)}\quad pf(x+y+z+\ldots\ldots) &= f(2x+y+z+\ldots\ldots) \\ &+ f(x+2y+z+\ldots\ldots) \\ &+ f(x+y+2z+\ldots\ldots) \\ &+ \ldots\ldots \end{aligned} \tag{vii}$$

$$\begin{aligned}\text{e)}\quad pf(x+y+[z]+\ldots\ldots) &= pf(x+y+z+\ldots\ldots) \\ &- f(x+y+2z=\ldots\ldots). \end{aligned} \tag{viii}$$

Then:

$$\begin{aligned} R_x(t) &= R_d{}'R_q{}'\;128(a, o, 11, 14, 15, [16], 18, 19) \\ &- 64p\,(a, o, 11, 14, 15, [16], 18, 19) \\ &+ 32p^2(a, o, 11, 14, 15, [16], 18, 19) \\ &- 16p^3(a, o, 11, 14, 15, [16], 18, 19) \\ &+ 8p^4(a, o, 11, 14, 15, [16], 18, 19) \\ &- 4p^5(a, o, 11, 14, 15, [16], 18, 19) \\ &+ 2p^6(a, o, 11, 14, 15, [16], 18, 19) \\ &- p^7(a, o, 11, 14, 15, [16], 18, 19) \\ &= R_d{}'R_q\,\phi\,(16). \end{aligned} \tag{ix}$$

The number of terms in the expansion is:

$$7C0+7C1+7C2+7C3+7C4+7C5+7C6+7C7 = 2^7 = 128.$$

To find $\theta_x = \int_0^\infty R_x(t)dt$, the integral of the function (α) $R_d{}'R_q$ must be defined.

$$(\alpha)R^1{}_d R_q = (\alpha)\left[(13) + \frac{\lambda_{13}}{\lambda_{13} - \lambda_{12}}\{(12) - (13)\}\right]$$

$$\times\ \Big[(2/3.26) + \frac{2\lambda_{26}/3}{2\lambda_{26}/3 - \lambda_{25}}$$
$$\{(25) - (2/3.26)\}\Big]$$
$$= (\alpha)\ \Big[(13,\ 2/3.26) + \frac{\lambda_{13}}{\lambda_{13} - \lambda_{12}}$$
$$\{(12,\ 2/3.26) - (13,\ 2/3.26)\}$$
$$+ \frac{2\lambda_{26}/3}{2\lambda_{26}/3 - \lambda_{25}}$$
$$\{(13,\ 25) - (13,\ 2/3.26)\}$$
$$+ \frac{2\lambda_{26}\lambda_{13}/3}{(\lambda_{13} - \lambda_{12})\ (2\lambda_{26}/3 - \lambda_{25})}$$
$$\{(12,\ 25) - (13,\ 25)$$
$$- (12,\ 2/3.26) + (13.2/3.26)\}\Big] \tag{x}$$

Define the function,

$$\psi(\lambda_\alpha) = \int_0^\infty (\alpha)\ R_d' R_q dt = \frac{1}{\lambda_\alpha + \lambda_{13} + 2\lambda_{26}/3}$$
$$+ \frac{2\lambda_{26}/3}{2\lambda_{26}/3 - \lambda_{25}} \left[\frac{1}{\lambda_\alpha + \lambda_{13} + \lambda_{25}} - \frac{1}{\lambda_\alpha + \lambda_{13} + 2\lambda_{26}/3}\right]$$
$$+ \frac{\lambda_{13}}{\lambda_{13} - \lambda_{12}} \left[\frac{1}{\lambda_\alpha + \lambda_{12} + 2\lambda_{26}/3} - \frac{1}{\lambda_\alpha + \lambda_{13} + 2\lambda_{26}/3}\right]$$
$$+ \frac{2\lambda_{26}\lambda_{13}/3}{(\lambda_{13} - \lambda_{12})(2\lambda_{26}/3 - \lambda_{25})}$$
$$\left[\frac{1}{\lambda_\alpha + \lambda_{13} + 2\lambda_{26}/3} + \frac{1}{\lambda_\alpha + \lambda_{12} + \lambda_{25}} - \frac{1}{\lambda_\alpha + \lambda_{12} + 2\lambda_{26}/3} - \frac{1}{\lambda_\alpha + \lambda_{13} + \lambda_{25}}\right]. \tag{xi}$$

$\lambda_{12} = 10^{-5} \times 0{\cdot}93$
$\lambda_{13} = 10^{-5} \times 7{\cdot}43$
$\lambda_{25} = 10^{-5} \times 2{\cdot}79$
$2\lambda_{26}/3 = 10^{-5} \times 7{\cdot}73$

The factor 10^{-5} will be left out in the calculations below. All failure rates are thus expressed in per cent failures per 1 000 hours.

$$\psi(x) = \frac{1}{x + 15{\cdot}16} + 1{\cdot}56\left[\frac{1}{x + 10{\cdot}22} - \frac{1}{x + 15{\cdot}16}\right]$$
$$+ 1{\cdot}14\left[\frac{1}{x + 8{\cdot}66} - \frac{1}{x + 15{\cdot}16}\right]$$
$$+ 1{\cdot}79\left[\frac{1}{x + 15{\cdot}16} + \frac{1}{x + 3{\cdot}72} - \frac{1}{x + 8{\cdot}66} - \frac{1}{x + 10{\cdot}22}\right]. \tag{xii}$$

Hence:

$$\theta_x = \int_0^\infty R_x(t)dt$$
$$\begin{aligned}
&= 128\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + \lambda_{16} + \lambda_{18} + \lambda_{19})\\
&- 64p\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + [\lambda_{16}] + \lambda_{18} + \lambda_{19})\\
&+ 32p^2\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + [\lambda_{16}] + \lambda_{18} + \lambda_{19})\\
&- 16p^3\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + [\lambda_{16}] + \lambda_{18} + \lambda_{19})\\
&+ 8p^4\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + [\lambda_{16}] + \lambda_{18} + \lambda_{19})\\
&- 4p^5\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + [\lambda_{16}] + \lambda_{18} + \lambda_{19})\\
&+ 2p^6\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + [\lambda_{16}] + \lambda_{18} + \lambda_{19})\\
&- p^7\ \psi(\lambda_a + \lambda_o + \lambda_{11} + \lambda_{14} + \lambda_{15} + [\lambda_{16}] + \lambda_{18} + \lambda_{19}).
\end{aligned} \tag{xiii}$$

40 to 20 per cent Full Power

$$R_v(t) = R_x R_h'/R_{16}$$
$$= R_x\left[\frac{\lambda_g}{\lambda_g - \lambda_{16}} - \frac{\lambda_{16} R_g}{(\lambda_g - \lambda_{16})\ R_{16}}\right]. \tag{xiv}$$

Both terms of expression (xiv) may be found using expression (ix).

$$R_v(t) = \frac{\lambda_g}{\lambda_g - \lambda_{16}}\ R_x - \frac{\lambda_{16}}{\lambda_g - \lambda_{16}}\ R_d' R_u\ \phi\ (g)$$

$$\int_0^\infty R_v(t)dt = \frac{\lambda_g}{\lambda_g - \lambda_{16}}\ \theta_x - \frac{\lambda_{16}}{\lambda_g - \lambda_{16}} \sum_{n=0}^{7} (-1)^{n+1}\ 2^n$$
$$p^{7-n}\ \psi(\lambda_a + \lambda_o + [\lambda_g] + \lambda_{11} + \lambda_{14} + \lambda_{15} + \lambda_{18} + \lambda_{19}) \tag{xv}$$

The term on the right of expression (xv) may be found using expression (xiii) and substituting λ_g for λ_{16}.

20 to 1 per cent Full Power

A derivation similar to that of Note 5 gives:

$$\int_0^\infty R_w(t)dt = \frac{\lambda_g}{\lambda'_g - \lambda_{16}}\ \theta_x - \frac{\lambda_{16}}{\lambda'_g - \lambda_{16}} \sum_{n=0}^{7} (-1)^{n+1}\ 2^n$$
$$p^{7-n}\ \psi(\lambda_a + \lambda_o + [\lambda'_g] + \lambda_{11} + \lambda_{14} + \lambda_{15} + \lambda_{18} + \lambda_{19}). \tag{xvi}$$

Estimation of System M.T.B.F. for Lower Power Levels

Since it is difficult to calculate the numerical values of expressions (xiii), (xv) and (xvi), and since the error introduced by using the expression:

$$\theta_s = -t/ln\ R_s(t) \tag{xvii}$$

is not known, (i.e., the relationship between $-t/ln\ R_s(t)$ and $\int_0^\infty R_s(t)dt$ is not known) a third method of estimating the system M.T.B.F. will be used, so that a comparison of the three methods may be made.

The true system M.T.B.F. will be greater than the inverse of the system failure rate calculated as the sum of the equipment failure rates where $2\lambda/3$ is used as the failure rate for an operational redundant group of two equipments, and $\lambda_1\lambda_2/(\lambda_1 + \lambda_2)$ is used as the failure rate of a standby redundant group of two equipments with individual failure rates λ_1 and λ_2. Thus:

$$\lambda_x < 2\lambda_a/3 + 2\lambda_{11}/3 + \frac{\lambda_{12}\lambda_{13}}{\lambda_{12} + \lambda_{13}} + 2\lambda_{14}/3$$
$$+ 2\lambda_{15}/3 + \lambda_{16} + 2\lambda_{18}/3 + 2\lambda_{19}/3$$
$$+ 2\lambda_o/3 + \frac{2\lambda_{25}\ \lambda_{26}/3}{\lambda_{25} + 2\lambda_{26}/3}$$
$$= 54{\cdot}414 \tag{xviii}$$

hence $\theta_x > 1840$ hours.

Using expression (xvii):

$\theta_x > 5000$ hours.

Using expression (xviii):

$\theta_x \doteq 2900$ hours

$$\lambda_v < \lambda_x - 17{\cdot}649 + \frac{\lambda_{16}\lambda_g}{\lambda_{16} + \lambda_g} \tag{xix}$$
$$= 54{\cdot}414 - 17{\cdot}649 + 1{\cdot}681$$
$$= 38{\cdot}446$$

$\theta_v > 2600$ hours.

Using expression (xvii):

$\theta_v > 100\,000$ hours.

Using expression (xv):

$\theta_v \doteq 4800$ hours

$$\lambda_w < \lambda_x - 17{\cdot}649 + \frac{\lambda_{16}\lambda'_g}{\lambda_{16} + \lambda'_g} \tag{xx}$$
$$= 54{\cdot}414 - 17{\cdot}649 + 0{\cdot}596$$
$$= 37{\cdot}361$$

$\theta_w > 2680$ hours.

Using expression (xvii):

$\theta_v >> 100\,000$ hours.

Using expression (xvi):

$\theta_v \doteq 5000$

Discussion

Mr. D. K. Nicholson (Associate Member) said that whether or not the analytical study of factors which influenced reliability did indeed warrant the grandeur of recognition as a fully-fledged field of engineering, a distinction not uncommonly accorded these days to many fields of endeavour in applied logic, Lieutenant-Commander Benn was to be complimented for making an interesting presentation on this new subject and its application to marine engineering. Commander Benn had for many years been associated with the design development, the operation, and the maintenance of DDE machinery. His views on the application of reliability engineering theory to warship propulsion was therefore of particular interest.

In advocating the application of reliability engineering to the design and development of marine machinery installations, it was noted that the author had confined his paper to system reliability as influenced by the replication of components. The replication of components was determined by component reliability which in turn was determined on the basis of operational experience. While Commander Benn explained how system reliability was determined once a ship was in operation, he did not indicate how reliability engineering theory might be applied at the system development stage when there might be no comparable operating experience with the required components.

It was suggested that reliability engineering might be defined as the art of getting good mileage out of unreliable equipment, using the device of replication. A replication factor of two had long been applied to naval machinery installations and was also clearly recognized in the make-up of most living species. The use of replication in nature and in naval engineering was similar since, in both cases, the object might be said to retain mobility and usefulness, at some level short of full power, after the loss of one component such as a boiler, an extraction pump, a limb or a kidney. Replication in these cases, it would be noted, did not exceed two. It had, in fact, been established in naval engineering practice to provide sufficient equipment to meet full power without replication, but to include not less than two boilers and two fuel, feed, extraction and lubricating oil pumps. If the reliability of any one of these components was assessed or known at the design stage to be incompatible with the operating requirements of the ship, then necessary design change action would be expected to produce the required level of reliability. The replication solution, which was to fit additional units until it was certain that there would always be at least one of them working at all times, seemed to be more applicable to electronic circuitry than marine power plants.

Commander Benn rightly drew attention to the relation between reliability engineering, cost effectiveness and planned maintenance. He perhaps had not emphasized that replication beyond the minimum acceptable number of units could rapidly increase planned maintenance time and thereby increase the overall ship cost per operational day. Reliability engineering was seen primarily as the means or basis of revising planned maintenance periods to achieve an acceptable failure rate or M.T.B.F.

Although Commander Benn had warned of the need for making a clear distinction between significant failures and insignificant failures in applying reliability engineering theory, it was questionable whether this had been properly considered in compiling the data given in Table IV. This table gave numerical values of reliability for twelve R.C.N. DDE machinery systems. On the basis of failures described as significant, the propeller shafting systems were generally recognized as being among the most reliable systems in any ship installation, the validity of the information from which the reliability ratings shown in Table IV were derived was highly questionable, particularly since it appeared that bulkhead gland failures were a substantial contributing factor.

Lieutenant K. Davies, R.C.N. (Associate Member) stated that in any endeavour where the end product was not useful in an infinite time scale—and most engineering effort fell well in this category—peripheral studies which could not be applied to improving the next generation product served no useful purpose.

If reliability engineering was to be applied to improve the design of marine installations and not merely to provide a rather interesting statistical exercise condemning or praising past effort, then a much more general philosophy must be accepted than had been implied, incorporating the following points.

Components in a propulsion system were not pumps and turbines and boilers but gear teeth, seals, shafts and bearings and so on.

The fact that a certain pump had a reliability of 0·99997 was of little value to the designer when faced with the design of a new pump. What he must know, if a reliability level was to be achieved, was the reliability of an EN37 pinion meshing with EN37 wheels with a K factor of 400 and a loading factor of 1·25 and so on.

Thus, statistical data based on actual components *not* subsystem reliability must be compiled if any real benefit was to be achieved from reliability engineering.

This was by no means simple in mechanical fields, since the following factors would affect each component's reliability:

1) peak transient loading factor
2) design safety factor
3) service (continuous, continual or intermittent)
4) materials.

The assumption, however, that this had not been done was invalid, on the contrary much work *had* been done, and manufacturers and designers alike worked to rules which would give satisfactory reliability in service compared with K factor limitations for gearing, loading factors for bearings, etc., and service factors for many items of equipment. Engineering design was full of rules of thumb for achieving reliability. The thing that had not been defined had been what level would be achieved and the deluded designer had always replied: "One?"

Resultant systems' reliability merely confirmed the designer's competence and confidence to design the next generation of equipment.

Lieutenant J. R. McFarlane, R.C.N. felt that the methods outlined in the paper could be used to advantage when predicting the overall reliability of a system. It also provided a useful method of determining what improvement could be obtained in a system by inserting a more reliable component or more redundancy.

For commercial vessels the results of the reliability analysis could probably be applied directly and redundancy and cost could be kept to a minimum. In warships the reliability analysis should be treated with some caution. There might be a need for greater redundancy than was shown to be useful by the analysis.

This was not because of reliability considerations but because there was a need for dispersal of components so that the ship would have greater probability of survival in action. Lieutenant McFarlane wished to thank the author for a most interesting and stimulating paper.

MR. A. W. RUSSELL pointed out that, since the introduction of "planned maintenance" in the Royal Canadian Navy, many facts relating to reliability of equipment and components were, or could be made, readily available to the designers, but that this information was not used to its fullest advantage.

Mr. Russell agreed that, for new equipment, stated reliability standards should be laid down by the designer at the design stage, as had been pointed out at the meeting. However, many of the defects and failures experienced in the past regarding existing equipment, had been greatly reduced, and in some cases eliminated, due to proper maintenance planning, which in turn accentuated the overall reliability concept, whether it was a single line system or duplicate line system.

This accumulated knowledge and the data derived from the information feed-back from ships in the R.C.N. would be most beneficial when setting out reliability criteria for improved or new equipment.

It was strongly recommended that the overall potential of D.P.M. (Director of Planned Maintenance) be realized and brought to the attention of all concerned and the knowledge used to a more profitable advantage than was now being experienced.

Author's Reply

The author thanked the contributors for their comments. Mr. Nicholson had expressed doubts that reliability should be considered a field of engineering. This development had been brought about by the urgent needs of missiles, electronics and systems engineering mentioned in the introduction to the paper. The reliability problems which confronted engineers in these fields were critical and it had been necessary to devise new techniques of testing, analysis, and computation. These techniques rapidly grew into a field of technology involving a considerable degree of specialization and mathematical background, as a scrutiny of the contents of the references would indicate.

The author took the view that the availability of analytical approach in depth to reliability problems fulfilled a long overdue requirement; there were few engineering fields where the need for improvement and a scientific approach was greater than in the field of reliability. As naval engineers at sea had emphasized in recent years, reductions in weight and space and improvement in machinery efficiency had in many cases been accompanied by a deterioration in reliability and availability.

The method outlined in the paper was, of course, only one part of the final reliability analysis; it provided an extra dimension to existing methods. Its main significance was to impose a methodical and disciplined approach on the plant designer and it permitted the use of meaningful numbers as a measure of effectiveness. Just as critical path scheduling necessitated a very logical and thorough examination of a project plan and required the planner to consider the exact significance of each phase in the overall project, so reliability analysis would permit a logical presentation of a propulsion plant design, requiring an objective explanation and understanding of the contribution of each component to the overall reliability of the plant.

In reviewing specifications for new propulsion equipment the author had always thought it remarkable that much effort had been expended by engineers to define efficiency and performance with precise figures which could be contractually enforced, but in such vital aspects as reliability and maintainability, loose statements had been permitted such as, "the reliability is to be as high as possible", or, "all equipment is to be reliable and easy to maintain". Such statements were of little use contractually.

There was a need to encourage suppliers of equipment to produce statistical evidence of satisfactory reliability in terms of availability and mean time between failures, and some progress had been made in this regard in the current R.C.N. destroyer programme.

The ultimate objective of reliability analysis was, of course, to determine the optimum replication of components, to eliminate excessive replication (for minimum maintenance and capital cost) but to provide enough replication of components to ensure satisfactory propulsion plant availability and guarantee the safety of the ship. There would obviously be a trade-off between the cost through the ship's life of extra components and the probable unavailability of, say, a $40 million ship.

The author would, however, agree with Lieutenant McFarlane's observation that in a warship, the requirements of damage control might have an overriding effect on the degree of replication of certain components. Extra components might be used to achieve dispersal of vital equipment.

Regarding Mr. Nicholson's comment on the significance of failures the author felt that selection of significant failures was not easy and, in the paper, he had pointed out a requirement for an agreed definition of a "failure" which had been arbitrarily defined on page 536 of the paper as "any failure which would immediately render the component unserviceable".

Referring to Table VI, the total failures figure was given for each component, followed by the number of significant failures for that component. This had been done to indicate to the reader the degree of selection. On the main boilers, for example, 114 failures had been reported but only 28 had met the author's definition of "significant". The decision to consider the failure significant had been made by three experienced seagoing engineers with reference to other engineers with DDE experience as necessary.

In considering bulkhead gland failures, Mr. Nicholson might have been considering the "total failures" column of Table VI; reference to the "significant failures" column showed that no bulkhead gland failures were considered significant and a figure of zero failures had been used in the calculations, giving a reliability greater than 0·99999.

With regard to Lieutenant Davies' comments the author believed that the customer had been remiss in not specifying a required figure for reliability and availability in the past. On the other hand, suppliers were sometimes reluctant to discuss the number and duration of failures experienced in service and they could rarely supply statistics of M.T.B.F. Manufacturers of gas turbines were an exception, however, as representatives of companies active in the aircraft field were accustomed to providing M.T.B.F. figures and would often supply statistics of unscheduled shut-downs, unscheduled engine changes etc.

It was encouraging to hear that in the requirements for the DDH 280 class, reliability target figures had been provided for the COGOG propulsion plant and that reliability analyses were included in the plant design work.

With regard to Mr. Russell's comments on the utilization of planned maintenance information the author would confirm that the reliability analysis in the paper was made possible by the existence of material failure report procedures, associated with the planned maintenance system. It was possible that as a reliability analysis became established some changes might be recommended in the information to be reported. Ultimately it was to be hoped that the relationship between maintenance, reliability and frequency of overhaul would be more clearly established. Some work had already been done on this aspect of maintenance.

In conclusion, the author expressed his appreciation to Mr. MacDonald of the R.C.A. company for his help in preparing the paper, Commander J. L. Cohrs, R.C.N., and Lieutenant-Commander G. F. Smith, R.C.N., for many helpful discussions, and to Mr. A. Gowling for his work on the diagrams.