ELECTRONIC MAINTAINABILITY

APPLICATION TO MECHANICAL ENGINEERING

BY

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At first sight many readers may feel that this article is hardly connected with the difficulties of marine engineering maintenance in ships. In so far as the adaption of maintainability assessment in design cannot affect existing equipment this is true. But today's difficulties stem from yesterday's decisions. It behoves us, therefore, to minimize tomorrow's problems by ensuring that today's decisions are the very best of which we are capable. Disciplines like reliability and maintainability provide a means of treating these quantities, equally with performance, as design parameters. This treatment has made possible major advances in design in many spheres. It is suggested that the use of these disciplines in marine and other branches of engineering could have an advantageous effect on the quality of today's decisions and hence on tomorrow's maintenance.

> 'I often say that when you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you are scarcely in your thoughts advanced to the state of science, whatever the matter may be.
>
> LORD KELVIN

With the advent of the missile and space age the costs, together with operational and logistical implications, of poor reliability and maintainability become so great (the cost of maintaining an electronic equipment in a warship can be as high as 10 times the purchase price) that considerable effort has been focussed on the improvement of these two qualities.

The point of comparison between reliability and maintainability as a design approach is availability. In common with the other Services of all nationalities the operational availability of weapons and radio systems in H.M. ships is frequently compromised by poor system availability. This is mainly due to the increased complexity, operating environments, and the introduction of components which have not been fully tried in service.

It is often necessary to provide stand-by electronic equipment and redundant systems in order to achieve an acceptable system availability, measures which are not only costly in initial outlay but also in space and upkeep. To combat this state of affairs the results of studies aimed at improving both reliability and maintainability are now being applied with success in the design of electronic equipments.

The subject of reliability has been very fully dealt with in a wide variety of publications, including the last issue of this *Journal* in an article by Commander A. O. F. Venton, 'Availability—A Methodical Approach'. It is therefore sufficient to say that manufacturers of electronic components are now striving more than ever to increase the reliability of their products, publishing the reliabilities achieved under test in their sales literature. These figures, together with figures published periodically by the Royal Radar Establishment at Malvern, are used as a guide by designers of electronic equipment. Such failure rate figures are necessarily based on test results, in which some anticipated service conditions are simulated, backed up by field reports when available. If failure rates of components are available at the stage in design where the equipment composition is known, then the Mean Time Between Failure of the equipment can be assessed. The assessment of likely component failure rates in service can only be as good as the defect reporting and analysing system. Failure rates of new components can only be obtained in time for the designer by laboratory/test shops environmental testing, but such figures, valuable as they are, have deficiencies. Service conditions can neither be completely anticipated nor can they always be completely simulated. So the feed-back of reports of defects and conditions in actual service is required to authenticate and complete the picture. Neither the designer nor the user can by themselves control reliability; it can only be done by both working together through a reporting system. The types, numbers and failure rates of components which might go to make up a typical electronic equipment are listed below. It is important to realize that these failure rates will only apply if the components are operated within their normal working range. Under or over-stressing components in a design will of course result in failure rates below or above the figures quoted.

	Predicted Failure Rate per 10^6 hours	*No. of Components in the equipment*	*Total failures in equipment due to components per 10^6 hours*
Capacitors	0·01	300	3
Diode	0·20	35	7
Joints and Connections	0·008	2,000	16
Potentiometers	0·25	20	5
Resistors	0·25	300	75
Relays	0·05	15	0·75
Transistors	0·50	65	32·5
Valves	10	5	50
Coils	0·01	100	1
Connectors	0·1	20	2
Crystals	0·02	2	0·04
Mechanical Assemblies	0·05	10	0·5
Meters	0·1	1	0·1
Printed Circuit Boards	0·01	12	0·12
Switches	0·05	15	0·75
Thermostats	0·05	2	0·1
Transformers	0·02	6	0·12
			193·98 Failures per 10^6 hours.

Thus the reliability (equipment failure rate) of the electronic equipment is measured, making contractual specification possible.

MAINTAINABILITY

Description

Maintainability can be defined as the ability with which an item can be maintained at a specified standard, at a specified cost of maintenance effort. It is measured in terms of time, men and equipment, that are necessary to achieve a given operational requirement. Thus when maintainability is being considered both corrective maintenance and preventive maintainance must be taken into account, and it is the former which has been the subject of a number of studies during the past eight or so years. In these studies most effort has been concentrated on the reduction of the time necessary to restore a defective equipment to normal working condition. This includes diagnosis, repair, adjustment and test: it excludes delays due to administration and logistics and is called the Active Repair Time (Rp), and in practice it measures the ease with which these actions are carried out and is often referred to as the 'maintainability' of an equipment.

Method of Measuring Maintainability (Active Repair Time)

By carrying out a very large number of observations of defect rectifications at sea on a variety of equipments, and by getting routine reports of repair times with levels of skill employed it is possible to arrive at average times to carry out Active Repairs. When recording Active Repair Times (Rp) it is essential to ascertain the specific functional level (depth of penetration) within the equipment at which the maintenance features, i.e., built-in test equipment, are effective, part, stage, sub-assembly, assembly, etc. From these observations tables of Average Active Repair Times, of which TABLES I and II are examples, can be compiled.

The time required to restore a defective electronic equipment depends mainly upon the facilities available to localize the defect, the method of repair (whether a unit, module, or part is replaced) and the time necessary to adjust and check the equipment after the repair has been carried out. The average

Active Repair Time for an equipment is a measure of the effectiveness of its designed maintenance features; such features being: built-in meters, test points and other visual aids. The average Active Repair Time also depends upon the 'functional level' at which these features are effective, and the 'functional level' at which the repair is carried out.

Functional Levels

Part	One piece, or two or more pieces joined together which are not normally subject to disassembly without destruction of designed use, e.g., valves, resistors.
Stage	A combination of two or more parts—which form a portion of a sub-assembly and is usually not replaceable as a whole, e.g., amplifier stage, detector stage.
Sub-assembly	Two or more parts which form a portion of an assembly or a unit replaceable as a whole, but having parts which are individually replaceable, e.g., terminal board with mounted parts.
Assembly	A number of parts or sub-assemblies or any combination thereof joined together to perform a specified function, e.g., audio-frequency amplifier.
Unit	An assembly or any combination of parts, sub-assemblies, assemblies mounted together normally capable of independent operation, e.g., electronic power supply, radio receiver.
Group	A collection of units, assemblies or sub-assemblies which is a subdivision of a set or system, but is not capable of performing a complete operational function, e.g., aerial group, indicator group.
Equipment (*Set*)	A unit or units and necessary assemblies, sub-assemblies and parts connected or associated together to perform an operational function—e.g., radio receiving set, radar set.
Sub-system	A combination of equipments, groups etc., which perform an operational function within a system. Sub-systems form the major sub-divisions of systems, e.g., radar station, fire control sub-system.
System	A combination of two or more sets, and such other assemblies, etc., necessary to perform an operational function, e.g., surface gunnery system.

The active repair of an electronic equipment consists of a series of tasks which are listed below, and make use of the designed maintenance features.

Active Repair Tasks

Localization—Tracing the defect down to the lowest functional level permitted by the built-in test equipment.	→ Diagnosis
Isolation—Tracing the defect using accessory test equipment at designed test points.	

TABLE I—*Average time in hours to carry out corrective maintenance tas*

FUNCTIONAL LEVELS						
To determine Localization and Isolation time use the column beginn with the Functional Level through which the defect is removed.						
9	8	7	6	5	4	3
SYSTEM NONE	SUBSYSTEM SYSTEM NONE	EQUIPMENT SUBSYSTEM SYSTEM NONE	GROUP EQUIPMENT SUBSYSTEM SYSTEM NONE	UNIT GROUP EQUIPMENT SUBSYSTEM SYSTEM NONE	ASSEMBLY UNIT GROUP EQUIPMENT SUBSYSTEM SYSTEM NONE	SUBASSEM ASSEMBLY UNIT GROUP EQUIPMEN SUBSYSTEN SYSTEM NONE

Note 1 The times given in this table do not include Administrative times, (e.g., attending musters, eating, etc.) or logistic times (e.g., obtaining or waiting for spares).

Note 2 When built-in test facilities enable localization to the functional level through which failure is being removed (the top row of functional level columns), do not use the value shown in the isolation column at this functional level; instead use ·000 hours.

Note 3 To determine the time for the disassembly, reassembly, alignment and checking tasks, only use Column 1 of functional levels in the appropriate row at which the task is performed.

Note 4 To determine the checking time, enter Column 1 at the functional at which the check out is being made and multiply by the number of operating modes affected by the replaced functional level.

Note 5 A separate Table is required for valves.

Disassembly—Making the defective part or module accessible for removal.

Interchange—Removal of the defective part or module and the fitting of the replacement part or module.

Reassembly—Retracing the steps taken in disassembly.

} ——→Replacement

Alignment

Check

} ——→Test

Use of the Active Repair Time Tables During Design

By reference to such tables as I and II it is possible, as design progresses, to establish a probable Mean Time To Restore for the equipment under design. This involves:—

(*a*) The composition and layout of the equipment

(*b*) The extent of built-in test equipment

(*c*) The number and location of test points

(*d*) The functional levels at which the built-in test equipment and test points are effective

(*e*) The functional levels at which repair or replacement are carried out.

ing malfunctions caused by part failure other than valves or front panels

		CORRECTIVE MAINTENANCE TASKS					
		Diagnosis		*Replacement* (See also TABLE II)		*Test*	
2	1	*Localization*	*Isolation*	*Disassembly*	*Reassembly*	*Alignment*	*Check*
:	PART	·021	·772	1·281	1·334	·156	·175
SEMBLY	STAGE	·039	1·179	·328	·561	·077	·167
IBLY	SUBASSEMBLY	·056	1·417	·165	·262	·045	·158
	ASSEMBLY	·073	1·569	·122	·191	·030	·149
P	UNIT	·089	1·700	·094	·134	·021	·138
MENT	GROUP	·106	1·821	·071	·090	·015	·124
STEM	EQUIPMENT	·121	1·924	·049	·061	·010	·108
M	SUBSYSTEM	·136	2·022	·032	·037	·007	·091
	SYSTEM	·150	2·100	·016	·017	·003	·062
	NONE	·165	2·172	·000	·000	·000	·000

TABLE II—*Interchange times for parts other than valves and fuses*

Type of Part	*Average Time*
Parts with 2 wires or 2 tags to be soldered	0·081
Parts with more than 2 cables or 2 tags to be soldered—with clamp	0·081 + 0·034 per wire over 2. Add 0·027
Parts attached with screws, nuts and washers	Add 0·022 for each screw, nut and washer combination
Note: For connections which do not conform to the above type, e.g., pins, wrapping, screws, etc., a separate Table is provided	

The method of using the tables can best be shown by an example. Suppose a grid leak resistor, which is a part in a preselector assembly, fails. It has been decided that the preselector assembly will be a replaceable module, and therefore any defect resulting from a failed part (excluding valves) within the preselector will be corrected by replacement of the preselector assembly.

Localization

By using built-in test equipment, i.e. input and output meters, the defect can only be localized to the EQUIPMENT level. The average localization time of 0·073 hours is obtained from the intersection of the EQUIPMENT column (Column 4 of the functional levels, since equipment failure is being removed through the replacement of the preselector *assembly*) and the LOCALIZATION column.

Isolation

By using accessory test equipment at designed test points the part that has failed within the preselector assembly can be traced to the preselector assembly. This is isolation at the Assembly level. The isolation time of 0·772 hours is determined from the interesection of the ASSEMBLY row (Column 4 of functional levels) and the ISOLATION column.

Disassembly

The equipment must be opened, and the chassis unfastened and slid out to gain access to the preselector assembly. This is disassembly at the equipment level. The disassembly time at the equipment level is the same whether parts, sub-assemblies, or assemblies, etc., are being replaced (see Note 1 of TABLE I). Therefore only Column 1 (beginning with PART) of functional levels should be used. The disassembly time of 0·049 hours is obtained from the intersection of the EQUIPMENT row (Column 1 of functional levels) and the DISASSEMBLY column.

Interchange

To remove and replace the defective preselector it is assumed that 13 cables and 21 screws must be removed. From TABLE II, and other tables not reproduced here, the interchange time is made up as follows:—

2 cables	0·081
11 additional cables	0·374
21 screws	0·391
Handling	0·005
Interchange time	0·851 hours

Reassembly

Following the replacement of the preselector assembly the chassis must be slid back, refastened, and the equipment closed. This is reassembly at the equipment level. As for disassembly, the reassembly at the equipment level is the same whether parts, sub-assemblies, etc., are being replaced. Therefore only Column 1 (beginning with PART) of functional levels should be used. The reassembly time of 0·061 hours is determined from the intersection of the EQUIPMENT row (Column 1 of the functional levels) and the REASSEMBLY column.

Alignment

The tuning capacitor shafts must be aligned on the assembly of the preselector. This is alignment at the assembly level, and again only Column 1 of functional levels should be used. The alignment time of 0·030 is found from the intersection of the ASSEMBLY row (Column 1 of functional levels) and the ALIGNMENT column.

Check

An equipment performance check is required at the equipment level. Again only Column 1 of the functional levels is used. The checking time is determined from the intersection of the EQUIPMENT row (Column 1 of functional levels) and the CHECK column. Since this equipment is assumed to have only one mode of operation the checking time is therefore 0·108 hours (See Note 4).

The Active Repair Time (Rp) for the preselector is therefore

$$0{\cdot}073 + 0{\cdot}772 + 0{\cdot}049 + 0{\cdot}851 + 0{\cdot}061 + 0{\cdot}030 + 0{\cdot}108 = 1{\cdot}944 \text{ hours.}$$

If the preselector has a failure rate of 0·01279 failures per 1,000 hours, then

$$\text{the Maintenance Rate (Mcp)} = \frac{0{\cdot}01279}{1000} \times 1{\cdot}944$$

$$= 0{\cdot}02489 \text{ Active Repair Hours per 1,000 hours.}$$

In this way a Part Maintenance Rate can be established for each part or replaceable module within an equipment or system. A system with an Mcp of 20 hours per 1,000 hours will require

$$\frac{20 \times 100 \times 24}{1000} = 48$$ hours of Active Repair time during an operation period of 100 days.

Specifying Maintainability (Active Repair Time)

A specification should contain a clear and accurate description of the technical requirements for an equipment, and the procedure by which it can be proved that the requirements have been met. Provided that a purchaser has been able to compile Active Repair Time Tables and the failure rates of components can be assessed for the conditions of service he has in mind for a project, he would be able to specify a required maintainability realistically. Without this data a required maintainability can, of course, be specified, but not realistically. The procedure is as follows. An Equipment Repair Time (ERT) is specified and it is required that the design of the equipment shall be such that the geometric mean of all active repair times shall not exceed the specified ERT. Compliance with this requirement is proved in the final design stage, and in the pre-production and production stages. In the final design stage the contractor must produce theoretical worksheets using agreed failure rates and active repair times for the replacement of every part or module of the equipment. From these worksheets the calculated Geometric Mean Time To Restore should not exceed the specified ERT. (Because of the distribution of repair times the Geometric Mean is usually adopted). At the pre-production stage the contractor will be considered to have met the required maintainability if, by a trial with the pre-production model in which selective repairs are carried out, the Mean Time To Restore ($MTTR_G$) is found to be such that

$$\text{Log}\,(MTTR_G) = \log\,(ERT) + 0{\cdot}397\,(S)$$

where S is the standard deviation.

(Standard deviation is the root-mean-square deviation of the observed active repair times from their average, i.e.

$$S = \frac{\sqrt{\sum\ i\,(xi - \bar{x})^2}}{N}$$

where xi = The value of one measurement of the sample

$\bar{x}$ = The sample or measured mean

N = The sample size).

$$\text{Log}\ MTTR_G = \frac{\sum_{i=1}^{20} (\log Rpi)}{20}$$

where Log $MTTR_G$ = the log of Geometric Mean Time to Restore.

Log Rpi = the log of the active repair time for the i th repair.

20 = Number of repairs carried out.

The expression Log $MTTR_G \leq \log ERT + 0{\cdot}397\,(S)$ assures a probability of 0·95 of accepting an equipment as a result of one test where the true $MTTR_G$ is equal to the specified ERT. At this, the pre-production stage, where a pre-production model is available for trial, 20 or perhaps 50 failures are separately introduced into the equipment on the basis of the failure rate of each type of part (valves, fixed resistors, paper capacitors, etc.) to the tota equipment failure rate. Thus if 60 per cent of the equipment failure rate is due to valves, then 12 (if 20 failures are being introduced) of the introduced failures must be valve failures. The Active Repair Time for each of the failures is noted and, as the Active Repair Time for each failure will depend upon the knowledge and experience of the technician carrying out the repair, each result must be multiplied by a factor (K), the ability rating of the technician. If the test is not taking place under conditions similar to those that will be experienced when the equipment is in service account must also be taken of this.

The contractor is considered to have met the specification for production models if no design changes or modifications are introduced following acceptance of the pre-production model; or if the maintainability of the equipment has not been reduced below the specified ERT by the introduction of design changes or modifications.

There is some evidence which suggests that the distribution of Active Repair Times may not always be log normal.

Clearly the distribution will depend upon the construction of the equipment and the fault isolation features, etc.

The technician carrying out the acceptance trial should be as familiar with the equipment as the technician who will be responsible for its maintenance in service. If the technician is not fully familiar with the equipment at the start of the tests it will be found that his Active Repair Times will decrease towards the end of the trial as he becomes more familiar with the equipment. Obviously an agreed standard of familiarity must be reached by the technician, and this might be that standard which would be expected of a rating after successfully completing a Pre-Commissioning course.

Application to Mechanical Systems

It is considered that this approach might well be used with mechanical systems. The stages for investigation would be as follows. First a functional level breakdown is required as in TABLE 1. Parts that would be replaced simultaneously should be treated as a single assembly. Where different modes of failure would cause a difference in the way of carrying out the repair they should be treated as separate parts. For each Unit the length of time necessary to perform each repair must be estimated. The normal steps being:

(*a*) Diagnosis of the trouble (localization)

(*b*) Isolation and cooling (isolation)

(*c*) Removal of parts causing an obstruction to access (access)

(*d*) Disassembly (access)

(*e*) Repair of replaced parts, including fitting, alignment, balance, etc. (replace)

(*f*) Reassembly (access)

(*g*) Replacement of parts which caused an obstruction to access (access)

(*h*) Restore to normal (clean, etc.) (align)

(*i*) Test.

Prediction of active repair times could be initiated as soon as the general arrangement drawing is available. In many cases this work would lead to design improvements, which at this stage could be made relatively cheaply. The alternative, to build a prototype and establish maintainability purely by testing is much less satisfactory. This is because productive commitments in programme time and material are bound in such cases to hamper changes. At such a stage they are usually heavily restricted by their effects on delay or costs. On the other hand while the design is still on the drawing board changes are relatively cheap, hence the attractions of the 'drawing board' assessment.

Mechanical Maintainability Assessment, particularly in the system field, is already in use in this country. The British Aircraft Corporation for instance are carrying out complete Reliability and Maintainability Assessments of the whole 'Concord' design to establish operating costs. They are employing ex-maintenance technicians from the Royal Air Force and Civil Airlines to analyse the maintainability of every major component of the aircraft. A sequential diagram is used and a time estimate is made for all maintenance actions. From estimated, calculated or established failure rates plus scheduled maintenance routines the upkeep costs can be arrived at, and so the upkeep costs per flying hour. These costs are examined for peaks, and re-design action initiated where necessary.

It is appreciated that in marine engineering surrounding obstructions often contribute substantially to the length of Active Repair Time. Nevertheless it is considered that the Active Repair Time of most individual machines could be improved by the adoption of a discipline such as the one described here.