
British Standard

Reliability of systems, equipments and components

Part 3. Guide to reliability practices: examples

Fiabilité des systèmes, équipements et composants

Partie 3. Guide pour les pratiques de fiabilité : exemples

Zuverlässigkeit von Systemen, Einrichtungen und Bauteilen

Teil 3. Leitfaden für Vorgehensweisen bei Zuverlässigkeitsuntersuchungen : Beispiele

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Foreword

During the period from 1971 to 1976 BSI published the series of Drafts for Development DD 10 to DD 16, 'Guide on the reliability of engineering equipment and parts'. These were prepared by Committee E/-/6, Engineering reliability, taking into account work carried out by IEC* Technical Committee 56, Reliability and maintainability, and represented the most up-to-date information at that time. The guide was issued in the Draft for Development series of publications to permit its use on a provisional basis so that information and experience of its practical application could be obtained. Those who used the guide were urged to write to BSI giving their experience in putting its principles into practice and giving constructive proposals for improvements. It was the original intention that a British Standard would be published when sufficient knowledge and reaction had been accumulated.

During 1977 the committee was redesignated QMS/2/3, Reliability systems, under the direction of the Quality, Management and Statistics Standards Committee. The committee was charged with the task of converting the Drafts for Development into a British Standard in the light of comments received, improved techniques and other factors, such as new health, safety and product liability legislation. The change in the committee title and reporting structure was influenced by the need to extend the application of reliability to disciplines other than strictly engineering, e.g. building and construction, services, etc.

*International Electrotechnical Commission.

The first decision taken (by QMS/2) was to incorporate the reliability terminology (previously given in DD 12) in the revision of BS 4778, in order (a) to bring together the closely allied disciplines of quality assurance and reliability and (b) provide for a wider readership and appreciation of reliability terms and definitions.

A standardized systematic approach is essential to ensure that statements are consistent and unambiguous in all communications concerning reliability. As well as providing a basis for the preparation of reliability programmes, this standard can be used in preparing documents concerned with the specification of reliability or the reporting of reliability data or tests.

It is vital that reliability be considered in a manner similar to a characteristic of a system, equipment or item from its design conception to the end of its working life, and that the reliability experience of one generation of products, engineers or technology is used by the next. This requires that each factor that affects reliability at any stage in the life of an item be identified and considered in its relationship to the other factors. This procedure can be formalized into a reliability programme. It may be necessary to divide such a programme into two parts, one of which may be the concern of the designer and manufacturer, and the other the concern of the user. It is most important that consideration be given to the reliability of items or parts which are used by one manufacturer but produced by another, i.e. subcontractor evaluation and vendor appraisal (see BS 5750).



Satisfactory reliability has traditionally been achieved by the use of codes of practice or methods of working that have been shown by experience to give good results for established products. However, with the increase in pace of change and performance expectations it is no longer sufficient to consider reliability in purely qualitative terms when its achievement often demands the specification of quantitative acceptance/rejection criteria also. Accordingly the onus should be on all parties (i.e. the designer, supplier, purchaser or any other responsible authority) to specify quantitative requirements wherever possible.

The need to satisfy competing constraints, including stricter health and safety requirements, the advent of new materials and pressure to reduce costs has made people realize that reliability can and should be expressed in quantitative terms if it is to be given its proper weight. For example, an item or product may be required to achieve at least a certain useful life, not to exceed a certain failure rate or to have an extremely high availability. Quantitative statements relating to reliability should then be made which may be accompanied by stipulations that certain codes of practice be followed.

One aspect of quantitative reliability that requires stressing is that often reliability can be predicted even for items or projects of new design and high cost, such as a ship's propulsion system or a new kind of nuclear reactor pressure vessel, but only if there is sufficient knowledge of the processes leading to failure, including data based on statistical observations.

The designer's or user's confidence that his reliability requirement will be met is dependent not only on the adequacy of the data concerning failure, which should be obtained either from reliability testing, field data, or from a knowledge of the physical processes leading to failure, but also on the application, in the first place, of a disciplined approach to the specification and design of a product or service. It is essential not only that the basic

data be adequate, but also that they be interpreted correctly, in the light of the environmental and other particular factors appropriate to the subject.

Although only three Parts of this standard have been planned at present, further Parts are envisaged in order to give greater emphasis to certain aspects of reliability and to take account of new developments. The first three Parts may be summarized as follows.

Part 1. Guide to reliability programme management.

This Part discusses the essential features of a comprehensive reliability programme for the direction and control of the reliability of systems, equipments and components. Recommendations are given for the drafting of specifications for reliability achievement. The main considerations for the assessment of reliability are reviewed and this is followed by details of the means by which reliability data are transmitted from the point of collection and recording to the point of storage and/or usage.

Part 2. Guide to reliability assessment. This Part recommends general procedures for the assessment of reliability and contains guidance, for the reliability practitioner, on the quantitative and statistical aspects of reliability, such as reliability modelling, the provision of data, and the concepts of redundancy and simulation.

Part 3. Guide to reliability practices : examples. This Part contains authentic practical examples illustrating the principles established in Parts 1 and 2 of BS 5760.

NOTE. This British Standard makes numerous cross-references to BS 4778 'Glossary of terms used in quality assurance (including reliability and maintainability terms)'. The glossary contains definitions relating to reliability concepts applicable to the guide and it is essential that these definitions and concepts be fully understood if this guide is to be interpreted correctly. For this reason it is recommended that BS 4778 be read in conjunction with BS 5760.

British Standard

Reliability of systems, equipments and components

Part 3. Guide to reliability practices : examples

Section one. General

1. Scope

This Part of BS 5760 has been produced to show, by way of examples, how some of the principles described in Parts 1 and 2 are applied in industry. Each is a practical example of the use of reliability techniques, although the names of the organizations have been omitted. Where appropriate, reference is made to the clauses in Parts 1 and 2 of BS 5760 that the examples illustrate.

2. References

The titles of the standards publications referred to in this standard are listed on the inside back cover.

In addition, numbered references are made to the following texts, papers and articles.

- (1) SINGH, C. and BILLINGTON, R. *Systems Reliability, Modelling and Evaluation*. Hutchinson, 1977.
- (2) SHOOMAN, M. L. *Probabilistic Reliability, An Engineering Approach*. McGraw-Hill, 1968.
- (3) HAHN, G. J. and SHAPIRO, S. S. *Statistical Models in Engineering*. John Wiley, 1967.
- (4) DAVIES, O. L. (ed). *Design and analysis of industrial experiments*. ICI Ltd. Oliver and Boyd, London, 2nd ed., 1963.
- (5) LEES, F. P. *Loss prevention in the Process Industries*. Butterworths.
- (6) HARRIS, J. P., AE Electronics (Reliability Division), Warrington. *The Assessment of Hazard Rates for Complex Networks, when demands on the protective system are frequent*. Proceedings of Second National Reliability Conference, sponsored by National

Centre of Systems Reliability, Warrington and Institute of Quality Assurance, London. Birmingham, March 1979.

- (7) OCCHINI, E. *A statistical approach to the discussion of the dielectric strength in electric cables*. IEEE Winter Power Meeting, New York, January 31-February 5, 1971. Paper 71, TP 157-PWR, pp. 2671-2681.
- (8) GLASSER, G. J. Planned Replacement: Some Theory and its Application. *Journal of Quality Technology* 1, 2, 1969, pp. 110-119.
- (9) BARLOW, R. and PROSCHAN, E. *Statistical Theory of Reliability and Life Testing: Probability Models*. Holt. Pinehart and Winston Inc., New York, 1975.
- (10) MANN, N. R., SCHAFER, R. E. and SINGPURWALLA, N. D. *Methods for Statistical Analysis of Reliability and Life Data*. John Wiley, New York, 1974.
- (11) LINDLEY, D. V. and MILLER, J. C. P. *Cambridge Elementary Statistical Tables*. Cambridge University Press, 1952.

3. Definitions

For the purposes of this Part of BS 5760 the definitions given in BS 4778 apply.

4. Arrangement/structure

The examples given in clauses 5 to 26 are arranged in the order of the phases of a project as described in table 1 of BS 5760 : Part 1 : 1979. The phases and the industries to which the examples relate are given in table 1. Appendix A illustrates the use of the various basic mathematical techniques used in reliability assessment.

Table 1. Catalogue linking the examples with the product/industry concerned and the type of technique used

	Project phase	Clause	Product/industry	Type of technique
SECTION 2	Definition	5	Electronic components	Reliability requirements in a target specification
		6	Marine engineering	Reliability and maintainability specification
		7	Automobile engineering	Reliability programme
		8	Guided weapon	Reliability and maintainability plan
SECTION 3	Design and development	9	Aeronautical components	Non-parametric reliability estimates
		10	Aircraft components	Non-parametric reliability estimates
		11	Power generation	Reliability prediction for alternative designs
		12	Compressed air system	System availability
		13	Telephone exchange equipment	Reliability improvement programme/design review
		14	Automobile engineering	Failure mode, effect and criticality analysis
		15	Chemical plant	Reliability and plant safety protection
		16	Chemical plant	Fault tree analysis
SECTION 4	Production	17	Electric cable	Physics of failure
		18	Telecommunications	Compliance testing for qualification
		19	Aircraft system	Production reliability demonstration
		20	Electronic equipment	Collection of field failure data
SECTION 5	Function and maintenance	21	Domestic appliances	Ranking of field failure data
		22	Aircraft components	Weibull analysis of field failure data
		23	Food processing	Weibull analysis of a failure mechanism
		24	Scientific instruments	Failure data collection and analysis
		25	Paper manufacture	Use of reliability data for maintenance planning
		26	Machine tools	Modelling of failure time distribution

Section two. Definition phase

5. Example of the reliability statement in the target specification for a group of transistors

5.1 Introduction. The 'target specification' (or design brief) describes the primary purpose of an item in general terms and includes performance, conditions of use and reliability. This example shows how the reliability requirements may be presented for a group of transistors in a single installation (or system or equipment).

5.2 Function of the item. The item acts as a switching element in complex electronic equipments such as mechanically static electronic telephone exchanges.

5.3 Criteria for failure

Defined upper limit of leakage current
Defined lower limit of gain
(and other characteristics as appropriate).

5.4 Electrical conditions in use

Cut off V_{CEX} 60 V (70 V peak)
On state I_C 0.55 A, V_{CE} 1.0 V

5.5 Environmental conditions in use

Ambient temperature 0 °C to +65 °C
Maximum humidity 95 % r.h.

5.6 Duration requirements

Annual operating time 8760 h
Equipment duration 20 years
Transistor useful life = 8760 h/year × 20 years
= 175 200 h

5.7 Failure rate requirements

Observed failure rate: not greater than 2000 failures in time (FITS) at maximum junction temperature at any point in the 20 year life.

Extrapolated failure rate: not greater than 100 failures in time (FITS) at a junction temperature of 100 °C at any point in the 20 year life.

NOTE 1. For any particular case the method of extrapolation should be declared.

NOTE 2. A FIT is the unit of failure experienced in 10^9 h.

6. Example of a target reliability and maintainability specification for the main gearing for a marine system

6.1 Introduction. This example illustrates the way in which the reliability clauses for a specification for marine main gearing are drawn up in accordance with the principles outlined in BS 5760 : Part 1.

6.2 The function of the item. The main propulsion gearing, torque tubes and flexible couplings transmit power from the ship's engines to the propeller. The nature of the item will be as defined by the relevant clauses of the general specification for the item, of which this target reliability and maintainability specification forms a part.

Approved arrangements of interlocks are to be provided in order to minimize any risk of damage to the main propulsion machinery in consequence of failures.

Approved arrangements are to be provided to accept and transmit control signals and actuation inputs as required by the main propulsion control systems. The manufacturer will be advised of the detailed requirements by the customer.

NOTE. 'Approved arrangements' means arrangements that are to the approval of the customer.

6.3 Criteria for failure. Failure is defined as being either an event that causes an immediate reduction of 20 % or more in any of the specified power output capabilities, or a condition that requires more than 4 h to repair, or both.

6.4 Choice and value of the reliability characteristic.

A figure of 100 000 h mean time between failures (MTBF) throughout the operating life of the equipment is to be the aim. Routine preventive servicing and maintenance will be permitted in order to assist in the achievement of this aim, such maintenance to be only at intervals that are compatible with the ship's refitting and maintenance cycle.

6.5 Operating regime. The expected mode of operation of the gearbox is as follows:

- (a) operating hours between refits h

Operating modes between refits are as follows:

- (b) ahead on each engine singly h
- (c) ahead on both engines together h
- (d) manoeuvring on each engine singly h
- (e) manoeuvring on both engines together h

Refits are to take place at intervals of years

The expected life of the ship is refitting cycles.
Lubrication oil will be maintained at a pressure between and
over temperature range to

- (f) the main gearing has to be capable of operating satisfactorily for at least h when the gearing room is flooded to the deckhead.

6.6 Reliability assurances and programme. A reliability evaluation and assurance programme is to be prepared and submitted to cover the following:

- (a) the organization and methods used during the design, development and production of the equipment in order to achieve the reliability target;
- (b) modes of possible component and system failure and the identification of critical areas;
- (c) the apportionment of failure rates to subassemblies and components within the equipment consistent with the overall target reliabilities, stating the basis for the apportionment;
- (d) a theoretical evaluation of the equipment to assess its ability to meet its reliability target or to highlight problem areas and suggest alternative designs;
- (e) proposals on methods of verifying that the target failure rates will be achieved, appropriate to each stage of development and production. These should include the identification of critical subassemblies and/or components that may require reliability verification by testing to an adequate confidence level;
- (f) an assessment of the cost in terms of time and money required to achieve reliability targets, including any test programmes necessary;
- (g) the provision of a means of determining the progress of the reliability and assurance programme in relation to the overall time scale for the equipment.

6.7 Maintainability. In parallel with the reliability programme, the maintenance requirements are to be established and a maintainability evaluation carried out which should include the following:

- (a) the identification of any short life items that have to be used in the design and proposals for making them readily accessible and easy to remove;
- (b) the justification of any 'special to type' tools required for maintenance;
- (c) provision for a demonstration of accessibility and ease of maintenance;
- (d) provision of a preliminary maintenance schedule (PMS) with estimates of manhours and time for each item and suggested range and scale of spare parts; (The basis of the PMS should be the estimated reliability of the parts, and this should be declared, so that the PMS adjustment can be based on data collected under the initial schedule.)
- (e) provision of a comprehensive handbook describing and illustrating the system and all conceivable maintenance repair procedures;
- (f) provision of accurate drawings for manufacture, installation and maintenance together with suitable procedures for their amendment;
- (g) provision of a comprehensive illustrated list, for the identification and ordering of spare parts.

7. Example of an automobile reliability programme

7.1 Introduction. The example describes the reliability activity in one section of the automobile industry. It consists of a reliability programme chart and some details of parts of this programme. The whole example is a formalized and simplified version of the actual situation and is as seen by the reliability analysis group of the company, a group whose main concerns are to establish objectives and to collate and analyse field data.

7.2 The reliability programme

7.2.1 General. The activities of the reliability analysis group occur during all phases of the life cycle of the product, as shown in figure 1. These phases are

- definition
- design and development
- production
- operation.

It should be noted that some activities occur during more than one phase; for example, the product verification specification* defines test objectives but also incorporates the checklist needed in the design and development stage. It is also interesting that the feedback from the customer is handled by the manufacturer. This is because the product is generally sold to non-technical customers.

For a new product the starting point for the programme would be the design concept. However, it should be noted that the process is circular in that the entire programme may be retraced several times during production of a particular model, a characteristic of any living programme. Each time the programme is begun again, there will of course be a modified design concept, so perhaps a spiral is a more illustrative model than the circle.

7.2.2 Establishing reliability objectives for service.

The reliability objectives are expressed as two maximum percentile lives (usually distances) L_1 and L_2 . L_1 is set as the end of the warranty period that may apply and hence controls early failures. L_2 relates to the total distance the vehicle has travelled when sold by the second owner, thus controlling the failure percentage at high distances. The procedure used to arrive at these percentages ensures that they relate to the effects of failure on mobility, safety, legality, customer loyalty and the cost of repair (labour and parts cost). Figure 2 shows how reliability objectives are tabulated. The ratings are mostly related to objective facts. The weightings are empirical as is the function used to translate the total score into the maximum allowable failure incidences.

7.2.3 Product verification specification (PVS)*. This document (figure 3) defines all the testing to be performed during the design, development and production stages, which will include reliability tests. A similar document is used to summarize the results from the testing at any time in the programme. These are compared directly with the objectives so that any short-fall can be identified.

The term 'reliability' in 'reliability acceptance criteria' (RAC) is loosely used; it relates to the level of pass needed on any test and often refers to performance parameters other than reliability in the strict sense. However, note that BS 4778 states that reliability characteristics are quantities used to express reliability in numerical terms, e.g. mean life.

7.2.4 Field data collection: vehicle description. A large number of vehicles are monitored whilst in the hands of the customers. On acceptance into the sample a vehicle description is taken; the details are shown in figure 4 (type I data sheet). This information is coded and fed to the computer; it allows subsamples of vehicles with particular specifications to be analysed.

7.2.5 Field data collection: vehicle repair history. A set of type II data sheets (figure 5) describes the complete repair and service history of a vehicle from sale date. The coded information is fed to the computer and linked to the type I information. This allows reliability calculations to be made for individual items, or groups of items, for particular types of failure mode (described in the event code) within any groups defined by the type I data.

7.2.6 Field data collection: reliability report. The information described in 7.2 is analysed using a computerized Weibull analysis routine. The results are published in the reliability analysis report (figure 6). This contains all the necessary information for the recipient to know the basis of analysis. It summarizes the Weibull analysis by quoting failure percentages at two standard distances. The acceptability of the current performance is determined by whether or not it meets the service reliability objective (figure 2).

7.3 Comments

7.3.1 This example could give more information if it included data on sales of spares, and results from extended trials by normal use by selected company servants.

7.3.2 The computerized Weibull analysis routine (see 7.2.6) should be one that produces a graph with limits and the original points, as well as the line and the estimates of the parameters.

*Product verification specification (PVS) is the term used in this example, but this type of work may also be covered by 'test specification' and 'acceptance specification'. See BS 4778.

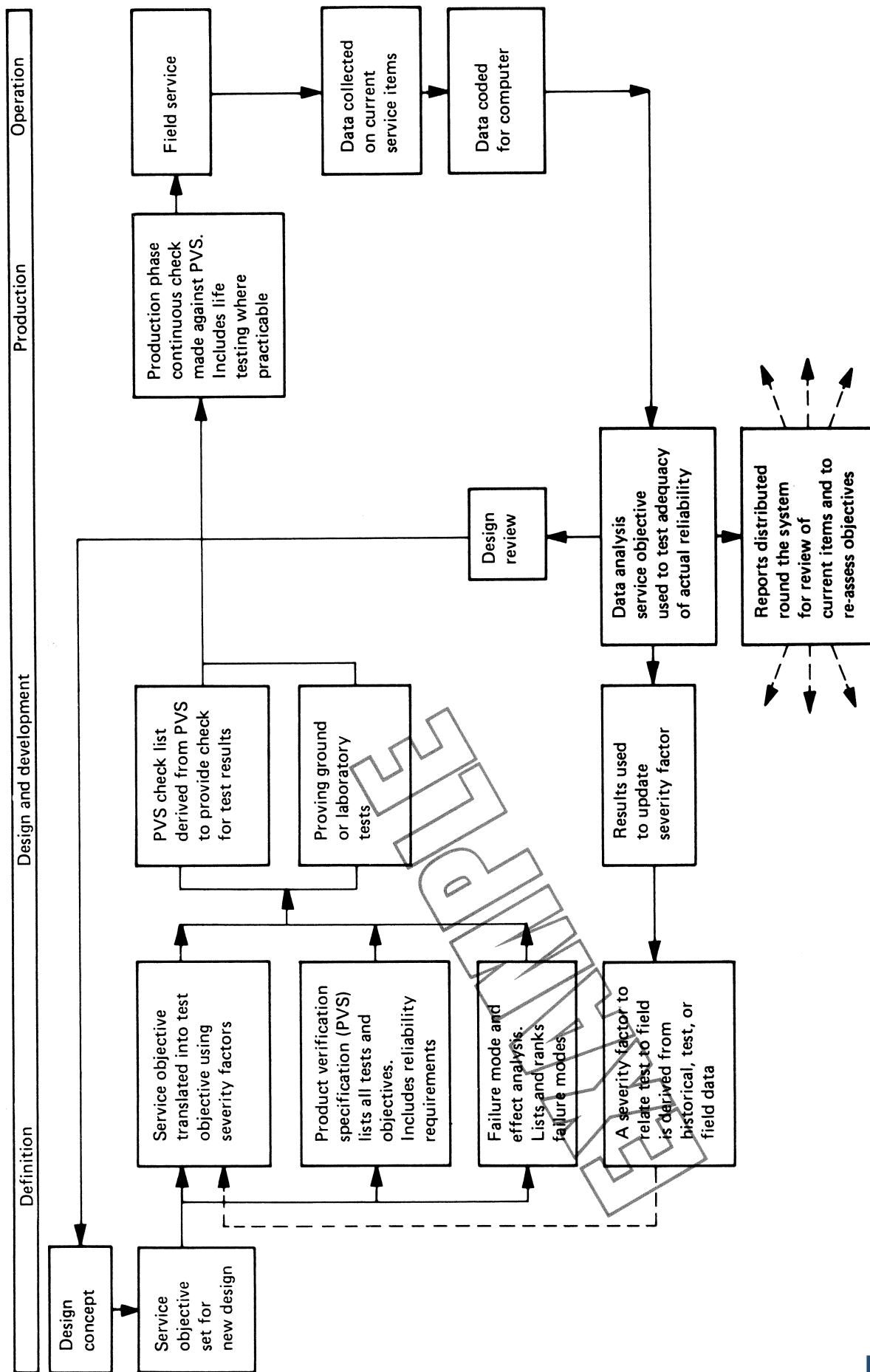


Figure 1. Reliability programme

Reliability Objective				No.	
				Date	
Component			Part No.		
Failure mode					
Failure effect					
Service results					
Data source: Failure incidence at:					
L_1 L_2					
Factor	Actual	Rating	Weighting factor	Score	Rating justification
Cost of material					
Labour repair time					
Effect on mobility					
Effect on potential loyalty					
Effect on vehicle safety					
Effect on vehicle legality					
Total score					
Reliability objective	Failure incidence at:			Remarks	
	L_1 (km)		L_2 (km)		
Prepared by			Concurred		

Figure 2. Reliability objective

PRODUCT VERIFICATION SPECIFICATION Full component description given here	Remarks	
	Timing	Indicates the length of time required to perform the tests
	RAC	Reliability acceptance criteria Specifies the standards to be achieved with a stated confidence level
	Sample size	Derived from the reliability acceptance criteria as given in the next column
	Usage	IP In process —Production checks
		PV Product verification —Final design stage
		DV Design verification —Initial design stage
	Source of test	Full description of the test procedure may be contained in another document. This will be referenced here
	Accept / Fail criteria	Definition of what constitutes a failure or an acceptable level of pass
	Description	Description of the test procedure
	Test name	Descriptive title of the test procedure

Figure 3. Product verification specification

Owner: _____

Regn. No. _____

2				6				10			
---	--	--	--	---	--	--	--	----	--	--	--

Reliability Analysis Vehicle Identity Number

Chassis No. _____

Date of sale to owner

15			18			21		
----	--	--	----	--	--	----	--	--

		Column	Circle Nos. Required										Column 25
Number of Doors	Including Estate and Van Doors	25	0	1	2	3	4	5	6	7	8	9	
Movable Front ¼ Vents	0 = No 1 = Yes	26	0	1	2	3	4	5	6	7	8	9	
Movable Rear ¼ Vents	0 = No 1 = Yes	27	0	1	2	3	4	5	6	7	8	9	
Type of Seat	0 = Bucket non reclining 2 = Bench non reclining 8 = Bucket reclining 9 = Bench reclining	28	0	1	2	3	4	5	6	7	8	9	
Gear Change System	0 = Manual 4spd floor 2 = Manual 4spd column 6 = Automatic 3spd	29	0	1	2	3	4	5	6	7	8	9	
Axle Ratio	Enter the first two significant digits of the axle ratio e.g. for 3.99 enter 39	30	0	1	2	3	4	5	6	7	8	9	
Paint Type	0 = Not known 1 = Non metallic 2 = Metallic	31	0	1	2	3	4	5	6	7	8	9	
Trim Type	0 = PVC or Vinyl 1 = Cloth 2 = Hide	32	0	1	2	3	4	5	6	7	8	9	
Dual Line Brake System	0 = No 1 = Yes	33	0	1	2	3	4	5	6	7	8	9	
Type of Brake System	0 = All drum 2 = Disc front drum rear 3 = All disc	34	0	1	2	3	4	5	6	7	8	9	
Servo Fitted	0 = No 1 = Yes	35	0	1	2	3	4	5	6	7	8	9	
Power Assisted Steering	0 = No 1 = Yes	36	0	1	2	3	4	5	6	7	8	9	
Damped Steering	0 = No 1 = Yes	37	0	1	2	3	4	5	6	7	8	9	
Starter Type	0 = Not known 1 = Pre-engaged 9 = Inertia	38	0	1	2	3	4	5	6	7	8	9	
Electrical Power Supply	0 = Not known 2 = 12V gen 9 = 12V alt	39	0	1	2	3	4	5	6	7	8	9	
Wheel Type	0 = Standard 8 = Increased dia 9 = Increased width	40	0	1	2	3	4	5	6	7	8	9	
Date of Production	1968 1969 1970 1971 1972 1973 1974 1975	41	0	1	2	3	4	5	6	7	8	9	
January	61 73 85 01 13 25 37 49	42	0	1	2	3	4	5	6	7	8	9	
February	62 74 86 02 14 26 38 50	43	0	1	2	3	4	5	6	7	8	9	
March	63 75 87 03 15 27 39 51												
April	64 76 88 04 16 28 40 52												
May	65 77 89 05 17 29 41 53												
June	66 78 90 06 18 30 42 54												
July	67 79 91 07 19 31 43 55												
August	68 80 92 08 20 32 44 56												
September	69 81 93 09 21 33 45 57												
October	70 82 94 10 22 34 46 58												
November	71 83 95 11 23 35 47 59												
December	72 84 96 12 24 36 48 60												
Manufacturing Plant		44	0	1	2	3	4	5	6	7	8	9	
		45	0	1	2	3	4	5	6	7	8	9	
Body Type	0 = Saloon 1 = Estate 2 = Van 3 = Coupe	46	0	1	2	3	4	5	6	7	8	9	
Vehicle Type	0 = Base/Deluxe 1 = Standard	47	0	1	2	3	4	5	6	7	8	9	
'L' Pack Fitted	0 = No 1 = Yes	48	0	1	2	3	4	5	6	7	8	9	
'X' Pack Fitted	0 = No 1 = Yes	49	0	1	2	3	4	5	6	7	8	9	
'G' or 'R' Pack Fitted	0 = No 1 = Yes	50	0	1	2	3	4	5	6	7	8	9	
Sun Roof Fitted	0 = No 1 = Yes	51	0	1	2	3	4	5	6	7	8	9	
Heated Backlite Fitted	0 = No 1 = Yes	52	0	1	2	3	4	5	6	7	8	9	52

Figure 4. Type I data sheet

Reliability Analysis Vehicle Identity Number:

[illegible]

Figure 5. Type II data sheet

Reliability Analysis Report

CONFIDENTIAL

Ref. no.
Date
Page of

Subject:	Component/Model Description
Object:	Usually to determine life characteristics
Foreword:	Specifies the sample on which estimates are based
Conclusions:	Includes statement on the acceptability of the life estimated by the sample in relation to the reliability objective
Results:	Presented in the following tabular form
	Failure percentage at
	L_1 L_2
Country and/or manufacturing plant	

Reliability objective (see figure 2)

Figure 6. Reliability analysis report

8. Example of a reliability and maintainability plan for a guided weapon

8.1 Introduction. This example (from a reliability specification) shows how a defence contractor was instructed on the planning of his reliability and maintainability plan for a conventional guided weapon. Note the attention to management aspects as well as to the content of the plan.

NOTE. The references have been omitted since they are not crucial to the illustration.

8.2 Reliability and maintainability plan

8.2.1 General. The contractor is to prepare reliability and maintainability plans based on reference A.

8.2.2 Reliability plan

8.2.2.1 Subject headings for individual tasks are:

(a) Organization

- (1) definition of management structure
- (2) subcontractor evaluation
- (3) integration of reliability and other parameters
- (4) programme monitoring and documentation
- (5) configuration control

(b) Components

- (1) component standardization
- (2) component selection and supplier quality control

(c) Analysis

- (1) reliability design principles and predictions
- (2) reliability modelling
- (3) design reviews
- (4) failure mode, effect and criticality analysis
- (5) thermal and stress analysis

(d) Tests

- (1) programme and plans
- (2) development tests
- (3) durability and packaging tests
- (4) qualification tests
- (5) reliability tracking, growth and demonstration tests

(6) maintainability tests

(7) production acceptance tests

(8) failure reporting procedures

8.2.2.2 In carrying out reliability prediction, an agreed failure rate list should be used. MIL Handbook 217C gives this information.

8.2.2.3 Reliability tracking and growth tests are to be carried out during the design and development phases. The contractor should have an agreed reporting system.

8.2.2.4 Reliability demonstration tests should be achieved by thermal cycling or continuous running at maximum stress subjected to whole systems of agreed subsystems.

8.2.2.5 Failure mode and effects analysis is to be undertaken and statements are expected concerning the level to which this analysis will be carried out.

8.2.3 Maintainability plan. Reference B provides information on the essential tasks of the maintainability programme plan. These are:

- (a) testing philosophy
- (b) maintainability analysis
- (c) upkeep plan
- (d) maintainability prediction
- (e) collection and recording of all maintainability data
- (f) maintainability status reports and demonstration
- (g) maintainability design criteria
- (h) design trade-offs (Whenever these are considered, the effect on maintainability and the implications have to be taken into account.)
- (i) maintainability standards for all subcontract and embodiment supply items

8.3 List of references

- A. Customer's own guide to preparation of reliability and maintainability programme plans.
- B. Customer's own information on the essential tasks of the maintainability programme plan.
- C. Full reference to MIL Handbook 217C.

Section three. Design and development phase

9. Example of the use of non-parametric reliability technique

9.1 Introduction. Given some form of test data, statistical methods used in the prediction of reliability frequently assume the exponential, or some other known, failure frequency distribution for both mission and operational life reliability. These assumptions are not always justified, and can lead to significant variations particularly where the accumulated data are small or limited.

A means of avoiding this problem is to use non-parametric techniques where no assumptions are made concerning the distribution of failures during either the mission or operational life of the equipment. This however can result in the loss of statistical efficiency when compared with the situation where the actual frequency distribution to failure is known from a large accumulation of data and/or experience.

9.2 Non-parametric theory (based on order statistics) on reliability estimation

9.2.1 General. The theory which follows has been directly derived from annex A (as amended by Amendment No. 1) of BS 2846 : Part 3 : 1975.

In the case of a continuous distribution represented by a simple random sample of size n where the data are very limited, information about the degree of spread of the distribution can be obtained from the extreme values of the sample (X_m the smallest and X_M the largest) or from only one of these.

9.2.2 One-sided spread. Between the sample size n , the confidence level $1-\alpha$ and the value of reliability R of the whole system above X_m (or below X_M) one has the relation

$$R^n = \alpha \quad (1)$$

This relation implies the following:

- (a) if one takes values for n and R , this relation enables $1-\alpha$ to be evaluated; there is a probability at least equal to $1-\alpha$ that the reliability of the whole system is at least equal to R which is superior to X_m (or inferior to X_M);
- (b) if one takes values for n and $1-\alpha$, this relation (1) enables R to be evaluated; there is a probability at least equal to $1-\alpha$ that the reliability of the system is at least equal to R which is superior to X_m (or inferior to X_M);

and

- (c) if one takes values for R and $1-\alpha$, this relation enables one to determine the minimum sample size n with which it is possible to assert with a confidence level at least equal to $1-\alpha$ that the reliability at least equal to R of the system or population will be superior to the smallest value (or inferior to the largest value) in a sample of that size.

9.2.3 Two-side spread. Between the sample size n , the reliability R which falls between X_m and X_M and the confidence level $1-\alpha$, one has the relation

$$nR^{n-1} - (n-1)R^n = \alpha \quad (2)$$

This relation implies the following:

- (a) if one takes values for n and R , the relation (2) enables us to evaluate $1-\alpha$; there is a probability at least

equal to $1-\alpha$ that the reliability of the whole system is at least equal to R which falls between X_m and X_M ;

- (b) if one takes values for n and $1-\alpha$, the relation (2) enables R to be evaluated; there is a probability at least equal to $1-\alpha$ that the reliability is at least equal to R which falls between X_m and X_M ;

and

- (c) if one takes values for R and $1-\alpha$, the relation (2) enables one to determine the minimum sample size n with which it is possible to assert with a confidence level at least equal to $1-\alpha$ that the value of the reliability at least equal to R will fall between the smallest and the largest value in a sample of that size.

9.3 Numerical example

9.3.1 Introduction. The following example demonstrates the use of a non-parametric technique in the assessment of aero engine component reliability.

9.3.2 Achieved test results. In a fatigue test by rotational stress carried out on a component of an aeronautical engine, a sample of 15 items has given the following results in ascending order of magnitude

0.200, 0.330, 0.450, 0.490, 0.780, 0.920, 0.950, 0.970, 1.040, 1.719, 2.220, 2.275, 3.650, 7.000, 8.800 ($\times 10^6$ cycles)

9.3.3 Information required. Answers to the following questions are required to check compliance with the specification.

- (a) What is the maximum proportion of the population of components that will fall below $X_m = 0.200$ ($\times 10^6$ cycles)?
- (b) What sample size has to be taken to make it possible to assert (at a confidence level of 95 %) that the value of reliability is at least $R = 0.90$ of the population of components which will be found below the largest of the values from that sample?
- (c) At the confidence level 95 %, what is the minimum value of reliability of components that fall between $X_m = 0.200$ and $X_M = 8.800$?
- (d) What sample size has to be taken to make it possible to assert (at a confidence level of 95 %) that the value of reliability is at least $R = 0.90$ of the population of components which will be found to fall between the smallest and the largest of the values from that sample?

9.3.4 Results obtained. Assuming a desired confidence level of 95 % ($1-\alpha = 0.95$) use table 9 of BS 2846 : Part 3 : 1975.

This gives, for the minimum proportion above X_m , a value p slightly higher than 0.75 (75 %) and hence, for the maximum proportion below X_m , a value $1-p$ slightly lower than 0.25 (25 %).

From table 9 of BS 2846 : Part 3 : 1975, for $1-\alpha = 0.95$ and $R = 0.90$, $n = 29$.

From table 10 of BS 2846 : Part 3 : 1975, for $1-\alpha = 0.95$ and $n = 15$, R is slightly below 0.75 (i.e. 75 %).

From table 10 of BS 2846 : Part 3 : 1975, for $1-\alpha = 0.95$ and $R = 0.90$, $n = 46$.

10. Example of parts count reliability assessment/prediction techniques for television subassemblies

10.1 Introduction. During the design and development of any equipment it is necessary to carry out an assessment of, and to predict the reliability of, the equipment at the earliest possible stage, so that possible reliability hazards in the design may be eliminated and the overall system may be assessed against contractual requirements. This will invariably be required before a 'design freeze' stage and initially before any model building and reliability test activities.

The following example illustrates the use, at a 'first off' level, of the parts count reliability assessment technique which, although statistically unsophisticated and limited in its consideration of detailed equipment parameters, provides a valid initial indication of equipment, or sub-system, reliability and a valid means of comparing alternative designs.

This particular example looks at the reliability prediction for a colour television power supply panel which was carried out as soon as the circuitry was sufficiently developed to itemize, by class at least, the individual components within that circuit.

10.2 Procedure. For the initial assessment all components are assumed to be series dependent, i.e. the correct functioning of the circuit requires the correct operation

of each of its components. The procedure is as follows.

(a) From the preliminary circuit diagram a tally is drawn up for each class of component. See figure 7.

(b) Failure rates are assigned to each class of components. In this case two operating stress levels are stated to encompass the normally used range of stress levels allowed for components.

(c) Total failure rates are assessed for each class of components, and connections, and the total failure rate calculated for the assembly by summing the totals for each class of components (see figure 8).

NOTE. This procedure assumes an exponential failure frequency distribution.

(d) Given the total failure rate λ for the assembly, the reliability may then be assessed for the panel using the exponential distribution expression for reliability $R(t) = e^{-\lambda t}$.

(e) Hence the predicted reliability for the power supply panel may be assessed at whatever period is desired, e.g. if the annual usage is 1500 h then the reliability may be assessed to be

$$\exp \{ - (1500 \times 16.059 \times 10^{-6}) \} \text{ or}$$

$$\exp \{ - (1500 \times 50.802 \times 10^{-6}) \}$$

dependent upon the stress levels of the components; i.e.

$$R(1500) = 0.976 \text{ or } 0.927$$

Laboratory: Developed by: Date of parts list: Prediction by:			Type of apparatus: C T V Type number: Dev. number: Part of apparatus: Power Supply panel																																																																																																																																																																																																																																																																																																																																							
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Classification according to CLASS. YX000 is meant to include all components with classification YA000 up to YZ999 and YA120 includes YA120 up to YA129. * For potm. with switch, tally for switch under SW or SM. † Ge semiconductors being a minority, are not counted separately. For semiconductor stacks and packages, count the individual diodes/transistors. Double electron tubes to be counted as 1.5 unit. ‡ For slide switches the number to be taken is the number of 'overs' actually used in the circuit. § Sockets for optional outside connections to be counted as half a connector.						1 Class	Description	2 Tally marks	3 n	RC000	carbon comp. resistor			RM200	metal resistor (lacq. film)	I	1	RM500	metal resistor (power film)	I	1	RV000	carbon potm. per carb. track*	I	1	RW000	wire-wound rst. and potentiom.		6	RF000	carbon film resistor > 1 MΩ			RF000	carbon film resistor ≤ 1 MΩ		31	Σ resistors				CE000	electrolytic capacitor		6	CF100	naked foil	I	1	CF310	minipoco (foil)			CF200	foile, lacq.			CG000	foile, metall.		9	CT000	trimmer			CC600	cer. c. miniat.			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ED000	diode and rectifier (Si)†		12																																																																																																																																																																																																																																																																																																																																							
ED000	diode and rectifier (Ge)†																																																																																																																																																																																																																																																																																																																																									
ED000	zener (ref.)†		3																																																																																																																																																																																																																																																																																																																																							
ED000	zener (reg.)†																																																																																																																																																																																																																																																																																																																																									
ET000	transistor ≤ 1W, NPN†		7																																																																																																																																																																																																																																																																																																																																							
ET000	transistor > 1W, NPN†		3																																																																																																																																																																																																																																																																																																																																							
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ET000	transistor > 1W, PNP†																																																																																																																																																																																																																																																																																																																																									
EV000	electron tube†																																																																																																																																																																																																																																																																																																																																									
VR200	relay																																																																																																																																																																																																																																																																																																																																									
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RS000	resistors (NTC, VDR, LDR, PTC)																																																																																																																																																																																																																																																																																																																																									
LA000	rod aerial																																																																																																																																																																																																																																																																																																																																									
LN000	nova coil																																																																																																																																																																																																																																																																																																																																									
LB000	baby, intelco, toko coil																																																																																																																																																																																																																																																																																																																																									
LV000	various coils																																																																																																																																																																																																																																																																																																																																									
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EI000	integrated circ. (lin.)																																																																																																																																																																																																																																																																																																																																									
EP300	picture tube																																																																																																																																																																																																																																																																																																																																									
EP400	black-white																																																																																																																																																																																																																																																																																																																																									
EP500	picture tube																																																																																																																																																																																																																																																																																																																																									
EP600	colour																																																																																																																																																																																																																																																																																																																																									
ER000	delay line																																																																																																																																																																																																																																																																																																																																									
EL000	lamp neon																																																																																																																																																																																																																																																																																																																																									
EL000	lamp incandesc.																																																																																																																																																																																																																																																																																																																																									
CV000	variable cap																																																																																																																																																																																																																																																																																																																																									
UL000	line output transformer																																																																																																																																																																																																																																																																																																																																									
UT000	radio tuner																																																																																																																																																																																																																																																																																																																																									
UV000	vhf tuner																																																																																																																																																																																																																																																																																																																																									
UU000	uhf tuner																																																																																																																																																																																																																																																																																																																																									
UW000	integrated t.																																																																																																																																																																																																																																																																																																																																									
T _K 000	c-core-transf.	I	1																																																																																																																																																																																																																																																																																																																																							
TS000	stacked core transformer																																																																																																																																																																																																																																																																																																																																									
VH200	recorder head																																																																																																																																																																																																																																																																																																																																									
VR100	reed relay																																																																																																																																																																																																																																																																																																																																									
UD000	deflection unit																																																																																																																																																																																																																																																																																																																																									
UE000	convergence/corr. unit																																																																																																																																																																																																																																																																																																																																									
BX000	loudspeaker																																																																																																																																																																																																																																																																																																																																									
VH100	pick up head																																																																																																																																																																																																																																																																																																																																									
VF000	fuse/sparkgap		2																																																																																																																																																																																																																																																																																																																																							
SW000	pushb. switch																																																																																																																																																																																																																																																																																																																																									
SM000	mains switch																																																																																																																																																																																																																																																																																																																																									
SS000	slide switch‡																																																																																																																																																																																																																																																																																																																																									
FC200	FXC-cores for entertainment																																																																																																																																																																																																																																																																																																																																									
MD000	motor-battery																																																																																																																																																																																																																																																																																																																																									
MW000	motor-asynchr.																																																																																																																																																																																																																																																																																																																																									
MR000	motor-synchr.																																																																																																																																																																																																																																																																																																																																									
VU100	connector N ≤ 8 §		6																																																																																																																																																																																																																																																																																																																																							
VU100	connector N > 8 §		12																																																																																																																																																																																																																																																																																																																																							
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total																																																																																																																																																																																																																																																																																																																																										

Figure 7. Tally lists for components

Laboratory Developed by: Date of parts list: Prediction by:									Type of apparatus: CTV Type number: Dev. number: Part of apparatus: Power supply panel			
Date:												

A									B			
1	2	stress 0.2		stress 0.8		stress chosen			1	2	8	9
Class	n	λ	$n\lambda$	λ	$n\lambda$	inter-pol.	λ	$n\lambda$	Class	n	λ	$n\lambda$
RC000		0.03		0.06		fig. 1			RS000		0.3	
RM200	1	0.006	0.006	0.009	0.009	linear			LA000		0.3	
RM500	1	0.4	0.4	1.3	1.3	fig. 1			LN000		0.3	
RV000	1	1.3	1.3	4.5	4.5	linear			LB000		0.3	
RW000	6	0.06	0.36	0.3	1.8	fig. 1			LV000		0.3	
RF000 > 1M Ω		0.06		0.12		fig. 1			LW000	1	0.3	0.3
RF000 $\leq$ 1M Ω	31	0.03	0.93	0.06	1.92	fig. 1			Σ coils			
Σ resistors									EI000 (dig.)		0.5	
CE000	6	0.13	0.78	0.5	3.0	fig. 2			EI000 (lin.)		1.6	
CF100	1	0.1	0.1	0.26	0.26	fig. 2			EP300		20	
CF310									EP400			
CF200		0.05		0.1		fig. 2			EP500		40	
CG000	9	0.008	0.072	0.024	0.216	fig. 2			EP600			
CT000		0.04		1.4		fig. 2			ER000		0.2	
CC600		0.012		0.15		fig. 2			EL000 neon			
CC200		0.007	0.007	0.077	0.077	fig. 2			EL000 inc.		1.0	
CC400	1								CV000			
CC100	3	0.012	0.036	0.15	0.45	fig. 2			UL000*		0.8	
Σ capacitors									UT000*		20	
ED000 (Si)	12	0.064	0.768	0.54	6.48	fig. 3			UV000*			
ED000 (Ge)		0.12		6.8		fig. 3			UU000*		30	
ED000 (ref.)	3	0.18	0.54	1.6	4.8	fig. 3			UW000*			
ED000 (reg.)		0.13		1.1		fig. 4						
ET000 $\leq$ 1W, NPN	7	0.24	1.68	1.2	8.4	fig. 4			T _A 000†	1	0.17	0.17
ET000 > 1W, NPN	3	0.48	1.44	2.4	7.2	fig. 4			K			
ET000 $\leq$ 1W, PNP	1	0.35	0.35	2.3	2.3	fig. 4			TS000†		0.17	
ET000 > 1W, PNP		0.7		4.6		fig. 4			VH200‡		15	
EV000		6.6		9.0		fig. 4			VR100		0.05	
VR200		0.13		1.3		fig. 3			UD000		0.3	
ED001	2	0.3	0.6	0.7	1.4				UE000		0.3	
									BX000		1.0	
									VH100			
									VF000	2	0.1	0.2
total A			9.369		44.112				SW000		0.2	
									SM000			
									SS000§		0.15	
									FC200		0.05	
									MD000		18	
									MW000		5	
									MR000			
									VU100 N $\leq$ 8	6	0.05	0.30
									VU100 N > 8	12	0.12	1.44
									sc --- mach.	214	0.02	4.28
									sc --- hand		0.1	
									total B			6.69

C	stress factors		
	0.2	0.8	chosen
total A	9.369	44.112	
total B	6.69	6.69	
grand total	16.059	50.802	

N.B. All λ and $n\lambda$ values in 10^{-6} /h.

*For tuners, use values given only if no separate prediction calculation is available.
 †For transformers with terminal cut-out, take $\lambda = 0.27$.
 ‡Valid for
 §See footnote (§) on tally list.

Figure 8. Prediction form for failure rates

11. Example of the reliability assessment of alternative pumping systems

11.1 Introduction. As part of a study into the economics of alternative feed water pumping systems a Monte Carlo simulation was carried out to predict the availability of the two alternatives shown in figures 9 and 10. The results of the simulation were subsequently checked using a Markov technique. The results of both methods of prediction are discussed below.

11.2 Data. Data were collected for times to failure and times to repair of steam and electrically driven feed pumps, the results of which were summarized as follows in table 2.

Table 2. Data for times to failure

	Mean time between failures $m = 1/\lambda$	Mean time to repair $r = 1/\mu$	Availability ratio $A = \mu/(\lambda + \mu)$
	h	h	%
Steam pumps A	920	91	90.9
Electric pumps B	369	165	69.1

NOTE. Normally the number of failures upon which the means are based would be tabulated so that the limits may be calculated, but they have been omitted here to simplify this example.

11.3 Assumptions. Exponential times to failure and repair were assumed, although other distributions could have been used in the simulation. Failure and repair events were assumed to be independent.

When feed pump A is operating, it is assumed that neither of the two 50 % standby pumps B are operating, that is, neither can fail. As soon as A fails both pumps B are started up if available. If neither is available, no operation is possible until at least one pump is repaired. As soon as pump A is repaired, it is assumed to be in operation immediately and any pump B operating at the time of A's repair is shut down. There are six possible states for the system as shown in the Markov state diagram, figure 11.

11.4 Results of Monte Carlo simulation. The computer program written for the purpose was run for 10^6 simulated operating hours to ensure that the estimates of the times in the various states were as close as practicable to the true values. The results are given in table 3.

Table 3. Results of Monte Carlo run

	% of total time
Time steam feed pump A was running	91.0
Time both electric pumps B were running	6.5
Time one electric pump was running	2.2
Time no pumps were running	0.3
	100.0

NOTE. Simulation procedures are referred to briefly in 8.2 of BS 5760 : Part 2 : 1981.

11.5 Markov results

NOTE. The Markov, or state transition rate method is described in reference (1), reference (2) or 8.1.7 and 8.1.8 of BS 5760 : Part 2 : 1981. Details of the method of solution can be obtained from reference (1) or reference (2).

The transition probability matrix is as follows:

		Final state					
		1	2	3	4	5	6
Initial state	1	$1 - \lambda_A \Delta t$	$\lambda_A \Delta t$	0	0	0	0
	2	$\mu_A \Delta t$	$1 - (\mu_A + 2\lambda_B) \Delta t$	$2\lambda_B \Delta t$	0	0	0
	3	0	$\mu_B \Delta t$	$1 - (\mu_B + \mu_A + \lambda_B) \Delta t$	$\mu_A \Delta t$	0	$\lambda_B \Delta t$
	4	$\mu_B \Delta t$	0	$\lambda_A \Delta t$	$1 - (\lambda_A + \mu_B) \Delta t$	0	0
	5	0	0	0	$2\mu_B \Delta t$	$1 - (\lambda_A + 2\mu_B) \Delta t$	$\lambda_A \Delta t$
	6	0	0	$2\mu_B \Delta t$	0	$\mu_A \Delta t$	$1 - (\mu_A + 2\mu_B) \Delta t$

The state equations in matrix form are as follows:

$$\begin{bmatrix} -\lambda_A & \mu_A & 0 & \mu_B & 0 & 0 \\ \lambda_A & -(\mu_A + 2\lambda_B) & \mu_B & 0 & 0 & 0 \\ 0 & 2\lambda_B & -(\mu_A + \lambda_B + \mu_B) & \lambda_A & 0 & 2\mu_B \\ 0 & 0 & \mu_A & -(\lambda_A + \mu_B) & 2\mu_B & 0 \\ 0 & 0 & 0 & 0 & -(\lambda_A + 2\mu_B) & \mu_A \\ 0 & 0 & \lambda_B & 0 & \lambda_A & -(\mu_A + 2\mu_B) \end{bmatrix} \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{bmatrix} = 0$$

The determinant is zero but it can be combined with the following equation, where P_i is the probability of remaining in state i :

$$P_1 + P_2 + P_3 + P_4 + P_5 + P_6 = 1$$

Solving for the P_i and substituting the values of λ_A , λ_B , μ_A and μ_B give the results in table 4. The table also repeats the Monte Carlo results for comparison.

Table 4. Results of using matrix analysis

	Markov result	Monte Carlo result
Probability of steam feed pump A running $P_1 + P_4 + P_5$	0.909	0.910
Probability of both electric pumps B running P_2	0.066	0.065
Probability of one electric pump B running P_3	0.022	0.022
Probability of no pumps running P_6	0.003	0.003
Probability of any of the above events	1.000	1.000

11.6 Expected value of output capacity. From these results we can calculate an expected value (reference (3), p.35) of output capacity available

$$E(C) = 100 \% \times 0.91 + 100 \% \times 0.065 + 50 \% \times 0.022 = 98.6 \%$$

This compares with the value for the pump system without standby of 91 %.

11.7 Discussion and conclusions. Comparison of the two sets of results shows that they are virtually identical, which shows in turn that the number of steps (10^6) in the Monte Carlo simulation was sufficient to approach closely the exact values of the Markov solution. The Monte Carlo method was used originally in this particular case because it was intended to allow for failure and repair distributions other than the exponential. If other distributions had been used, the Markov method would not have been applicable.

Careful consideration should always be given to the choice of method. In this particular case the Markov solution was, in the end, the more appropriate.

Because there are only six possible states in this case, the transition probability matrix has six columns and six rows. In many cases, systems are much more complex than in this example, and so the matrices become correspondingly large and computer methods are required for a solution. There is a practical limit to the size of problem that can be handled by the Markov method, even when using a computer.

The assumption that failures are independent has to be carefully considered. A significant occurrence of dependent failures would make the prediction invalid, the effect being to reduce the system availability below the value derived in the study. An example of a dependent failure would be the loss of essential supplies to the steam feed pump caused by a fire in the electric feed pump motor. Both simulation and Markov methods can accommodate dependent events, but the system logic then changes.

NOTE. The accuracy of simulation depends upon the number of *events*, not the time simulated, and all good simulation programmes operate on this basis.

As expected, the arrangement with the two electric pumps has higher availability. However, the results of the study have to be used in an economic calculation to determine which is the preferred alternative. The economic assessment would need to determine total lifetime costs (terotechnology) by taking into account capital costs, costs of loss of production resulting from having 50 % or no capacity, maintenance cost and any difference in the energy costs of the two arrangements.

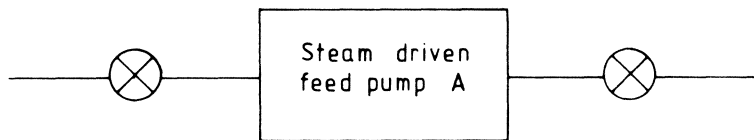


Figure 9. Arrangement of pumping system with no standby

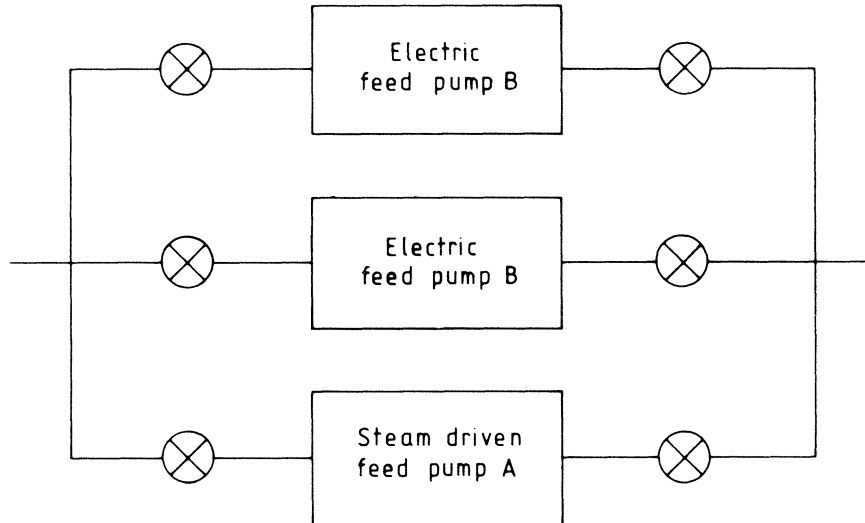


Figure 10. Arrangement of pumping system with two 50 % standby pumps

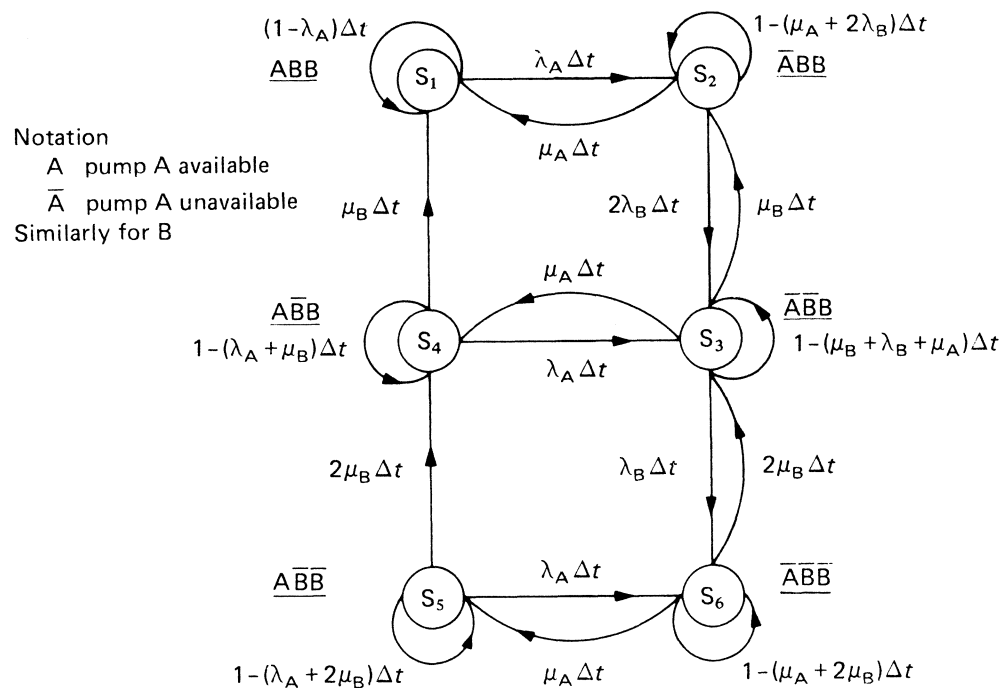


Figure 11. State diagram for pumping system shown in figure 10

12. Example of the availability of alternative compressor systems

12.1 Introduction. A factory's compressed air is supplied by a 3-out-of-4 active parallel system of compressors of unit availability $A = 0.94$. It is proposed to replace these with a 1-out-of-2 standby system with unit availability of 0.98. System downtime costs £ 1000 per hour and the net total cost of the change is £ 200 000. Is the proposed change worthwhile, given that company policy requires projects to repay initial outlay within 2 years?

12.2 Existing system. Active parallel redundancy is dealt with in 8.1.2 of BS 5760 : Part 2 : 1981. In this case, the system is available if more than three compressors are available. This is a binomial situation in which the various probabilities are evaluated as follows:

Probability of exactly 4 compressors being available A^4	= 0.78075
Probability of exactly 3 compressors being available $4A^3(1-A)$	= 0.19934
Probability of exactly 2 compressors being available $6A^2(1-A)^2$	= 0.01909
Probability of exactly 1 compressor being available $4A(1-A)^3$	= 0.00081
Probability of exactly 0 compressors being available $(1-A)^4$	= 0.00001
Probability of any possible arrangement	1.00000

The probability of three or more compressors being available = $0.78075 + 0.19934 = 0.9801$

The cost of downtime per year = $(1 - 0.9801) \times 8760 \times 1000 = \text{£ } 174\,324$.

12.3 Proposed system. The application of the Markov or matrix method to redundant maintained systems is dealt with in 8.1.8.1 of BS 5760 : Part 2 : 1981. The state diagram for the proposed system is given in figure 12.

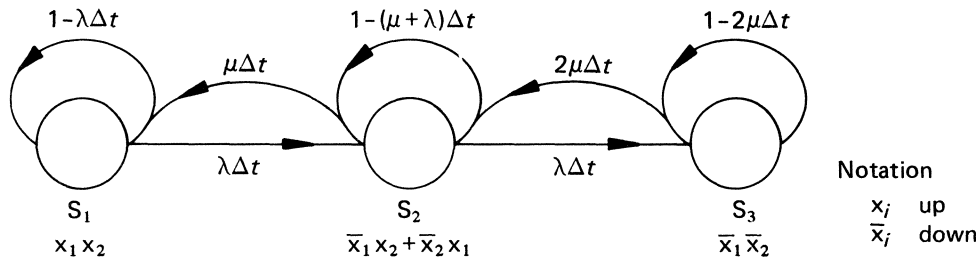


Figure 12. State diagram for system

This is a one standby system with a facility for simultaneous repair (better known as unrestricted repair) whilst in state 3.

The transition matrix for the system is as follows:

$$\begin{bmatrix} & 1 & 2 & 3 \\ 1 & 1-\lambda & \lambda & 0 \\ 2 & \mu & 1-(\mu+\lambda) & \lambda \\ 3 & 0 & 2\mu & 1-2\mu \end{bmatrix}$$

Note that $\sum_{i=1}^n = 1.0$ for each row, where n refers to an $n \times n$ matrix.

The resulting differential equation for the system is:

$$\begin{aligned} dP_{s1}(t)/dt &= -\lambda P_{s1}(t) + \mu P_{s2}(t) \\ dP_{s2}(t)/dt &= -(\lambda + \mu)P_{s2}(t) + \lambda P_{s1}(t) + 2\mu P_{s3}(t) \\ dP_{s3}(t)/dt &= -2\mu P_{s3}(t) + \lambda P_{s2}(t) \end{aligned}$$

In the steady state when t is large $P_s(T) = 0$

$$\begin{aligned} 0 &= -\lambda P_{s1}(T) + \mu P_{s2}(T) \\ 0 &= \lambda P_{s1}(T) - (\lambda + \mu)P_{s2}(T) + 2\mu P_{s3}(T) \\ 0 &= \lambda P_{s2}(T) - 2\mu P_{s3}(T) \end{aligned}$$

At any time t

$$P_{s1}(t) + P_{s2}(t) + P_{s3}(t) = 1$$

The steady state availability of the system $A(T)$ is given by:

$$A(T) = P_{s1}(T) + P_{s2}(T)$$

If $A = \mu/(\lambda + \mu)$ then $A(T)$ can be found in terms of A as follows:

$$A(T) = 2A/(1 + A^2)$$

If $A = 0.98$, the availability of the system is 0.9998.

Cost of downtime per year = $(1 - 0.9998) 8760 \times 1000 = \text{£ } 1752$

Saving over 2 years = $(174\,324 - 1752) \times 2 = \text{£ } 345\,144$

The total cost of the proposed change is £ 200 000 and so the cost criterion is met.

12.4 Discussion. Assuming perfect switching, standby redundant systems have a higher availability than active parallel redundant systems. It can be shown that if the new compressors have a unit availability of 0.94, the same as the old, the system availability is 0.9981 and the system would still save £ 315 163. Thus the cost criterion is again met. It is of interest to note that a compressor availability of 0.8178 for the proposed system would produce a system availability of 0.9801, the same as that of the old system. This demonstrates clearly the greater efficiency of standby availability, given perfect switching. However, the assumption should be noted that there will be no plant failures while an item is shut-down.

The transition matrix method used here was also used in the example in clause 11 and the same comments apply.

13. Example of a reliability improvement programme for existing equipment

13.1 Introduction. Analysis of failure statistics showed that the reliability of a small, moderately complex piece of electro-acoustic equipment used in the UK was appreciably lower than that of comparable equipment of different design used in other countries. A programme of activities, based on the principles of BS 5760 : Part 1, was proposed to enable a new specification to be drawn up that would result in improved reliability. The programme included reliability assessment using service reliability data; endurance testing of samples of the equipment of UK and foreign design, tests to determine the effectiveness of different packing methods in minimizing damage during transportation and a design review of the equipment.

13.2 Failure data. The failure data are given in table 5. The failure data show that the UK failure rate was more than three times that of the best foreign equipment. A new reliability target was set that would reduce the

failure rate by at least a factor of three, based on a 10 year life.

13.3 The test programme. The equipment contained an electronic circuit, an electro-acoustic transducer, two major electro-mechanical components and several mechanical components. Various models from the UK and abroad were subjected to the tests listed below. The tests were, where possible, chosen from those given in BS 2011. The other types of tests were developed by the major UK purchaser. Performance checks were carried out on each equipment before and after each set of tests. These checks covered the electrical and electro-acoustic parameters of the equipment as specified in the performance specification written by the major UK purchaser. A visual inspection (involving removal of the external cover) was also carried out on each equipment and component tested. On failed items the cause of failure was established. Table 6 describes the tests. The test results are summarized in tables 7 and 8.

Table 5. Failure data

Date	Country	No. of stations $\times 10^6$	No. of failure reports/station year	Equipment failure no./station year	Equipment failure rate expressed as failures in 10^9 service hours
1975/76	UK	20.4	0.741	0.247	28 196
1975/76	A	19.6	0.503	0.145	16 553
1975/76	B	5.4	0.258	0.066	7 580
1975/76	C	13.8	0.310	0.050	5 708
1972/74	D	13.7	0.242	0.082	9 361

NOTE. A station is one piece of equipment in one installation. An equipment failure is an event that required maintenance action.