IS 15037 (2011): Analysis Techniques for Dependability – Reliability Block Diagram and Boolean Methods [LITD 2: Reliability of Electronic and Electrical Components and Equipment]

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Indian Standard

ANALYSIS TECHNIQUES FOR DEPENDABILITY — RELIABILITY BLOCK DIAGRAM METHOD

ICS 03.120.01; 03.120.99

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Reliability of Electronic and Electrical Components and Equipment Sectional Committee, LTD 3

FOREWORD

This Indian Standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Reliability of Electronic and Electrical Components and Equipment Sectional Committee had been approved by the Electronics and Telecommunication Division Council.

Different analytical methods of dependability analysis are available, of which the Reliability Block Diagram (RBD) is one. The purpose of each method and their individual or combined applicability in evaluating the reliability and availability of a given system of component should be examined by the analyst prior to starting work on the RBD. Consideration should also be given to the results obtainable from each method, data required to perform the analysis, complexity of analysis, and other factors identified in this standard.

While preparing this standard, assistance has been derived from IEC 61078 (1991) 'Analysis techniques for dependability — Reliability block diagram method', issued by the International Electrotechnical Commission.

The composition of the Committee responsible for formulation of this standard is given in Annex C.

In reporting the results of a test or analysis made in accordance with this standard, if the final value, observed or calculated, is to be rounded off, it shall be done in accordance with IS 2 : 1960 'Rules for rounding off numerical values *(revised)*'.

Indian Standard

ANALYSIS TECHNIQUES FOR DEPENDABILITY — RELIABILITY BLOCK DIAGRAM METHOD

1 SCOPE

1.1 This standard describes procedures for modelling the dependability of a system and for using the model in order to calculate reliability and availability measures.

1.2 A set of symbols related to this standard is given in Annex A. Some related formulae are also given in Annex B.

2 REFERENCE

The following Indian Standard is a necessary adjunct to this standard:

IS No.	*Title*
1885 (Part 39) : 1999	Electrotechnical vocabulary: Part 39 Reliability of electronic and electrical items (*second revision*)

3 DEFINITIONS

For the purpose of this standard, the definitions specified in IS 1885 (Part 39) shall apply.

4 SYMBOLS

Symbols and abbreviations are given in Annex A.

5 APPLICABILITY

An RBD is a pictorial representation of a system's reliability performance. It shows the logical connection of (functioning) components needed for system success.

The modelling techniques described are intended to be applied primarily to systems without repair and where the order to which failures occur does not matter. For systems where the order to failures must be taken into account or where repairs are to be carried out, other modelling techniques, such as Markov analysis, are more suitable. At any instant in time, an item is considered to be in only one of two possible states: operational or faulty.

In the symbolic representation, no distinction is made between open circuit, short circuit or other fault modes, however, in the numerical evaluation this is possible.

6 SYSTEM FAULT DEFINITIONS AND RELIABILITY REQUIREMENTS

6.1 General Considerations

A prerequisite for constructing system reliability models is a sound understanding of the ways in which the system can operate. Systems often require more than one fault definition. These should be defined and listed.

In addition there should be clear statements concerning:

a) functions to be performed;
b) performance parameters and permissible limits on such parameters; and
c) environmental and operating conditions.

Various qualitative analysis techniques may be employed in the construction of an RBD. Therefore the system's fault definition has to be established. The system success is dependent on one or more system failures. For each system fault definition the next step is to divide the system into logical blocks appropriate to the purpose of the reliability analysis. Particular blocks may represent system substructures, which in turn may each be represented by other RBDs (system reduction).

For the quantitative evaluation of an RBD, various methods are available. Depending on the type of structure, simple Boolean techniques and/or path and cut set analysis may be employed. Calculations may be made using basic component reliability/availability data.

It should be noted that a reliability block diagram does not necessarily represent the way the hardware is physically connected. While this is obvious to experienced reliability engineers, it may not be so to others.

6.2 Detailed Considerations

6.2.1 *System Operation*

It may be possible to use a system for more than one functional mode. If separate systems were used for each mode, such modes should be treated independently of the rest, and separate reliability models should be used accordingly. If the same system were used to perform all these functions, then separate diagrams should be used for each type of operation. Clear statements of the reliability requirements associated with each aspect of system operation is a prerequisite.

6.2.2 *Environmental Conditions*

The system performance specifications should be accompanied by a description of the environmental conditions under which the system is designed to operate. This should include a description of all the conditions to which the system will be subjected during transportation, storage and use.

A particular piece of equipment is often used in more than one environment, for example, on board ship, in an aircraft or on the ground. When this is so, reliability evaluations may be carried out using the same reliability block diagram each time but using the appropriate failure rates for each environment.

6.2.3 *Duty Cycles*

The relationship between calendar time, operating time and on/off cycles should be established. When it can be assumed that the process of switching equipment on and off does not in itself promote failures, and that the failure rate of equipment in storage can be negligible, then only the actual operational time of the equipment need be considered.

However, in some instances the process of switching on and off is in itself the prime cause of equipment failures, and equipment may have a higher failure rate in storage than when operational. In complex cases where only parts of the system are switched on and off, modelling techniques other than reliability block diagrams (for example Markov analysis) may be more suitable.

7 ELEMENTARY MODELS

7.1 Developing the Model

The first step is to select a system success definition. If more than one definition is possible a separate reliability block diagram may be required for each. The next step is to divide the system into blocks of equipment to reflect its logical behaviour of the system so that each block is statistically independent and as large as possible. At the same time each block should contain (where possible) no redundancy. For same of numerical evaluation, each block should contain only those items which follow the same statistical distributions for times to failures.

In practice it may be necessary to make repeated attempts at constructing the block diagram (each time bearing in mind the steps referred to above) before a suitable block diagram is finalized.

The next step is to refer to the system fault definition and construct a diagram that connects the blocks to form a 'success path'. As indicated in the diagrams that follow, the various paths, between the input and output ports of the diagram, pass through those combinations of blocks which must function in order that the system functions. If all the blocks are required to function for the system to function then the corresponding block diagram will be one to which all the blocks are joined in series as illustrated in Fig. 1.

In this diagram *"I"* is the input port, *"O"* the output port and *A*, *B*, *C*......*Z* are the blocks which together constitute the system. Diagrams of the type are known as 'series reliability block diagrams'.

A different type of block diagram is needed when failure of one component or 'block' does not affect system performance as far as the system fault definition is concerned. If in the above instance the entire link is duplicated (made redundant), then the block diagram is as illustrated by Fig. 2. If, however, each block within the link is duplicated the block diagram is as illustrated by Fig. 3.

Diagrams of this type are known as parallel reliability block diagrams. Block diagrams used for modelling system reliability are often mixtures of series and parallel diagrams. Such a diagram would arise if we were to consider an example consisting of a duplicated communication link comprising three repeaters *A*, *B*

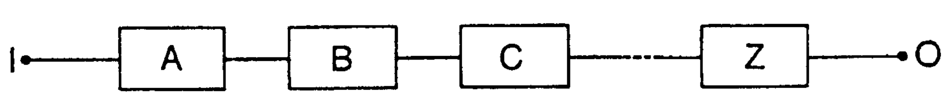


FIG. 1

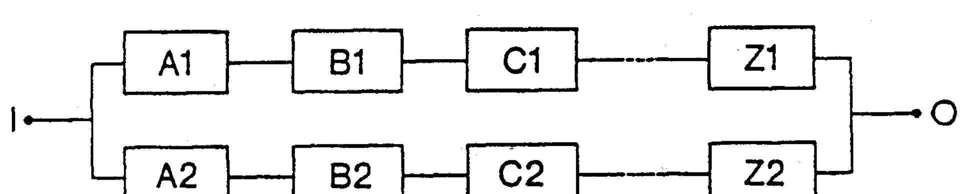


FIG. 2

and *C*, and a common power supply item (*D*). The resulting diagram would become as illustrated in Fig. 4 and 5.

On account of the statistical independence stated above, failure of any block must not give rise to change in the probability of failure of any other block within the system, in particular, failure of a duplicated block must not affect system power supplies or signal sources.

The need frequently arises to model systems where the success definition is that *m* or more of *n* items connected in parallel are required for system success. The block diagram then takes the form of Fig. 6 or Fig. 7.

Thus, in Fig. 6, failure of one item is tolerated but two or more are not.

Most reliability block diagrams are easily understood and the requirements for system success are evident. Not all block diagrams, however, can be simplified to combinations of series or parallel systems. The diagram in Fig. 8 is an example.

Again, the diagram is self-explanatory. System success is achieved if items *B*1 and *C*1 are working both, or items *A* and *C*1, or *A* and *C*2, or finally *B*2 and *C*2, only *B*1 and *C*2 or *B*2 and *C*2 are not enough for the system to work. Figure 8 could represent the fuel supply to the engines of a light aircraft. Item *B*1 represents the supply

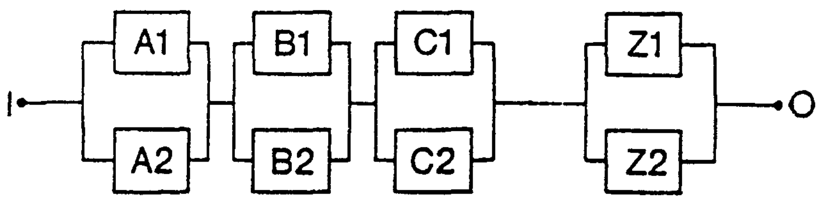


FIG. 3

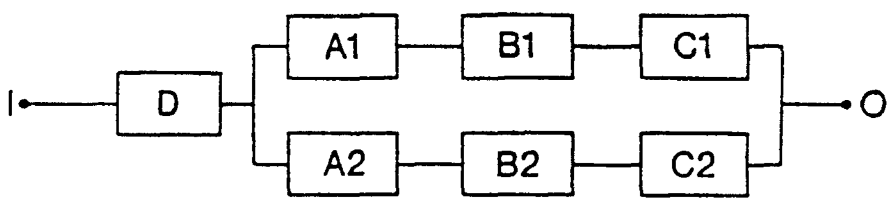


FIG. 4

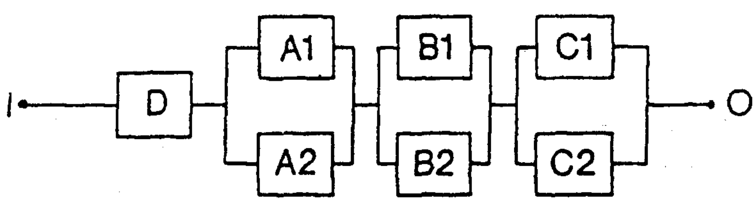


FIG. 5

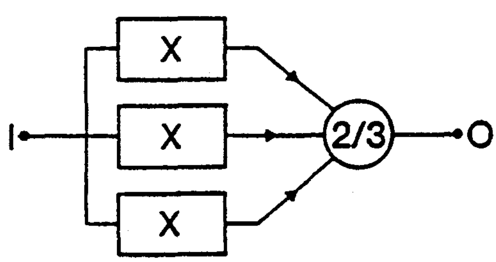


FIG. 6

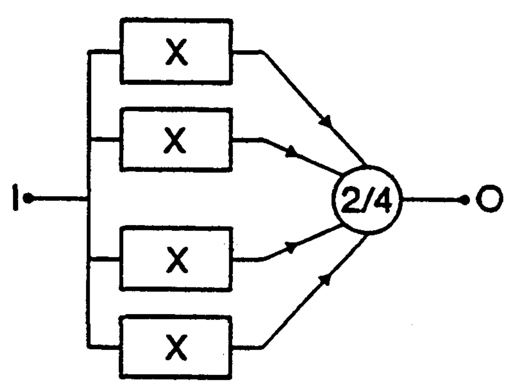


FIG. 7

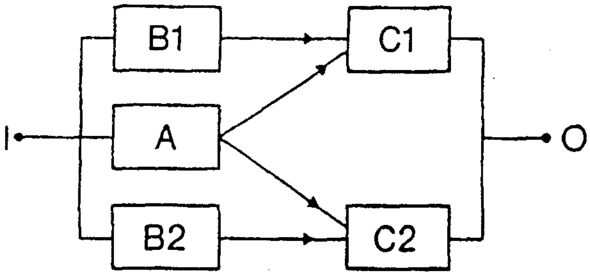


FIG. 8

to the port engine ($C1$), item $B2$ the supply to the starboard engine ($C2$) and item A a backup supply to both engines. The system fault definition is that both engines must fail before the aircraft fails.

Notice that in all the above diagrams, no block appears more than once in a given diagram. The procedures for developing the reliability expression for diagrams of this type are outlined in **8**.

7.2 Evaluating the Model

The reliability of a system, $R_S(t)$, is the probability that a system can perform a required function under given conditions for a given time interval (O, t). in general it is defined by the relationship:

$$R_S(t) = \exp[-\int_0^t \lambda(u)\,du$$

where $\lambda(u)$ denotes the system failure rate at $t = u$, u being a dummy variable. In what follows $R_S(t)$ will be written for simplicity as R_S. The unreliability of a system (probability of failure), F_S, is given by:

$$F_S = 1 - R_S$$

7.2.1 *Series Models*

For systems as illustrated by Fig. 1, the system reliability R_S is given by the simple expression:

$$R_S = R_A R_B R_C \ldots\ldots R_Z \qquad \ldots(1)$$

that is by multiplying together the reliabilities of all the blocks constituting the system.

7.2.2 *Parallel Models*

For systems of the type illustrated by Fig. 9, the system probability of failure (F_S) is given by:

$$F_S = F_A F_B$$

Hence system reliability (R_S) is given by

$$R_S = R_A + R_B - R_A R_B \qquad \ldots(2)$$

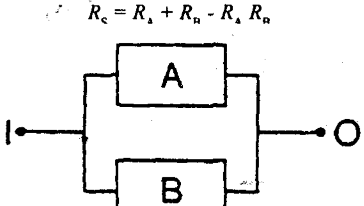


FIG. 9

Formulae (1) and (2) can be combined. Thus if we have a system as depicted by Fig. 2, but with only three items in each branch, the system reliability is:

$$R_S = R_{A1} R_{B1} R_{C1} + R_{A2} R_{B2} R_{C2} - R_{A1} R_{B1} R_{C1} R_{A2} R_{B2} R_{C2} \qquad \ldots(3)$$

Similarly, for Fig. 3 we have:

$$R_S = (R_{A1} + R_{A2} - R_{A1}R_{A2})(R_{B1} + R_{B2} - R_{B1} R_{B2})(R_{C1} + R_{C2} - R_{C1} R_{C2}) \qquad \ldots(4)$$

For Fig. 4 and 5, the system reliability expressions are obtained simply by multiplying expressions (3) and (4) by R_D.

7.2.3 *m out of n Models (Identical Items)*

The system reliability expression corresponding to Fig. 6 and 7 is a little more complicated than those above. In general, if the reliability of a system can be represented by n identical items in parallel where m out of n are required for system success, then the system reliability R_S is given by:

$$R_S = \sum_{r=0}^{n-m} \binom{n}{r} R^{n-r}(1-R)^r \qquad \ldots(5)$$

Thus the reliability of the system illustrated by Fig. 6 is given by:

$$R_S = R^3 + 3R^2(1 - R) = 3R^2 - 2R^3 \qquad \ldots(6)$$

where R is the reliability of the individual items.

Similarly for Fig. 7:

$$R_S = R^4 + 4R^3(1 - R) + 6R^2(1 - R)^2 = 3R^4 - 8R^3 + 6R^2 \qquad \ldots(7)$$

If the n items are not identical, use of a more general procedure is recommended (*see* **8.3**).

7.2.4 *Standby Redundancy Models*

Another frequently used form of redundancy is what is known as standby redundancy. In its most elementary form, the physical arrangement of items is represented in Fig. 10.

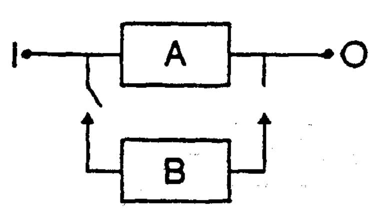


FIG. 10

In Fig. 10, item A is the on-line active item, and item B is standing by waiting to be switched on to replace A when the latter fails. The RBD formulae already established are not applicable for the reliability analysis of standby redundant systems. The expression for system reliability is :

$R_S(t) = e^{-\lambda t}\ (1 + \lambda t)$, with the following assumptions :

a) when operating, both items have a constant failure rate λ and have zero failure rate in standby mode;
b) the switch is perfect;
c) switching-over time is negligible; and
d) standby unit does not fail while in standby mode.

If there are *n* items in standby, this expression becomes:

$$R_S(t) = e^{-\lambda t}\ [\ 1 + \lambda t + (\lambda t)^2 / 2! + (\lambda t)^3 / 3! + \ldots\ldots + (\lambda t)^n / n!\ ]$$

It is to be noted that a practical block diagram should include blocks to represent the reliability of the switch plus sensing mechanism, which is often the 'weak link' in standby systems. Further, unlike all the examples considered so far and in the remainder of this standard, the probability of survival of one item (item *B*) is dependent upon the time when the other item (item *A*) falls. In other words items *A* and *B* cannot be regarded as failing independently. As a consequence, other procedures, such as Markov analysis, should be used to analyze standby systems.

8 MORE COMPLEX MODELS

8.1 General Procedures

It is possible to evaluate the reliability R_S of all the systems considered so far by the application of a suitable reliability formula selected from expressions (1) to (7). However, for some systems the corresponding RBDs may not conveniently be evaluated by any of the above formulae. These systems are considered to be more complex and their reliability analysis techniques have to be employed. Note that complex RBDs can usually be evaluated using Monte Carlo simulation. However, the use of such procedures is not dealt with in this standard.

For the procedures which follow, the same condition of independence as stated in **7.1** applies.

8.1.1 *Use of the Conditional Probability Rule*

When dealing with block diagrams of the type illustrated by Fig. 8, a different kind of approach is required..

One such approach is to make repeated use of the relationship:

$$R_S = Pr\ (SS \mid X \text{ operational}) \times Pr\ (X \text{ operational}) + Pr\ (SS \mid \times \text{ faulty}) \times Pr\ (X \text{ faulty}).$$

In the above expression R_S denotes the reliability of the system, *Pr* (*SS* | *X* operational) denotes the reliability of the system given that a particular block *X* is operational, and *Pr* (*SS* | *X* faulty) denotes the reliability of the system given that the particular item *X* has failed. For example, if in Fig. 8 the item *A* has failed, the block diagram becomes simply:

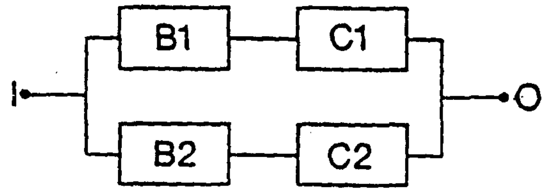


FIG. 11

So that:

$$Pr\ (SS \mid A \text{ faulty}) = R_{B1} R_{C1} + R_{B2} R_{C2} - R_{B1} R_{C1} R_{B2} R_{C2}$$

Similarly, when *A* is operational, the block diagram is simply:

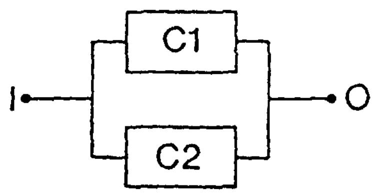


FIG. 12

So that

$$Pr\ (SS \mid A \text{ operational}) = R_{C1} + R_{C2} - R_{C1} R_{C2}$$

Hence

$$R_S = (R_{C1} + R_{C2} - R_{C1} R_{C2}) R_A + (R_{B1} R_{C1} + R_{B2} R_{C2} - R_{B1} R_{C1} R_{B2} R_{C2})\ (1 - R_A)$$

if $R_{C1} = R_{C2} = R_C$

and $R_{B1} = R_{B2} = R_B$

The above expression simplifies to:

$$R_S = (2R_C - R_C^2)\ R_A + (2R_B R_C - R_B^2 R_C^2)\ (1 - R_A) \qquad \ldots(8)$$

The above can be applied to verify expressions (5) to (7) inclusive.

8.1.2 *Use of Boolean Truth Tables*

8.1.2.1 *General*

The system success paths depicted by RBDs can also be represented by Boolean expressions. For example, three items *A*, *B* and *C* which are connected in parallel (one required for system success) can be represented by the RBD illustrated in Fig. 13, or by the Boolean expression:

$$SS = A \cup B \cup C \qquad \ldots(9)$$

where *SS* denotes system success, while *A*, *B* and *C* denote success events of components *A*, *B* and *C*. However, the Boolean terms *A*, *B* and *C* cannot be directly replaced by probabilities (R_A, R_B, R_C) in order to obtain a value for system reliability. This is because expression (9) is in effect a set of 'overlapping' terms. This can be seen by studying a Venn diagram (not shown) representing expression (9). From such a diagram it can be seen that expression (9) can be written as the sum of non-overlapping terms:

$$SS = A\overline{BC} \cup \overline{A}B\overline{C} \cup \overline{AB}C \cup A\overline{B}C \cup AB\overline{C} \cup \overline{A}BC \cup ABC \quad ...(10)$$

in purely Boolean terms, expression (9) and (10) are identical. In expression (10) each literal (A, $\overline{A}$, B, $\overline{B}$, C, $\overline{C}$) can be replaced by the corresponding reliability term:

$$R_A, (1 - R_A), R_B, (1 - R_B), R_C, (1 - R_C)$$

to yield an expression for system reliability R_S:

$$R_S = R_A(1 - R_B)(1 - R_C) + (1 - R_A)R_B(1 - R_C) + (1 - R_A)(1 - R_B)R_C + R_A(1 - R_B)R_C + R_A R_B(1 - R_C) + (1 - R_A)R_B R_C + R_A R_B R_C \quad ...(11)$$

It can be demonstrated by use of a Venn diagram that an even simpler way of writing expression (9) in non-overlapping terms is:

$$SS = A + \overline{A}B + \overline{B}\overline{A}C \quad ...(12)$$

So that

$$R_S = R_A + (1 - R_A)R_B + (1 - R_B)(1 - R_A)R_C \quad ...(13)$$

It can be shown that once simplified expressions (11) and (13) are identical.

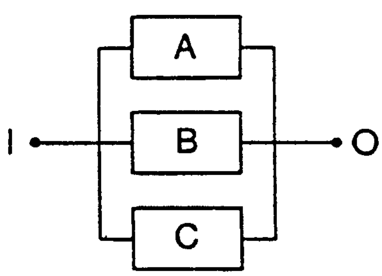


FIG. 13

The process of arriving at expression (11) can be more systematically carried out by using a truth table to convert expression (9) to expression (10), as shown in Table 1.

From Table 1 the success terms are (from top to bottom):

$$\overline{AB}C,\ \overline{A}B\overline{C},\ \overline{A}BC,\ A\overline{BC}, A\overline{B}C, AB\overline{C}, ABC$$

These terms are added together to give expression (10).

Table 1 Application of Truth Table to Fig. 13
(*Clause* 8.1.2.1)

Item			System
A	*B*	*C*	
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	1

NOTE — 1 = operational
0 = faulty

8.1.2.2 *Application of truth table to example of Fig. 8.*

If we list all combinations of operational and faulty items as they might exist we would have a table as illustrated in Table 2.

Table 2 Application of Truth Table to Fig. 8
(*Clause* 8.1.2.2)

Item					System
*B*1	*B*2	*C*1	*C*2	*A*	
0	0	0	0	0	0
0	0	0	0	1	0
0	0	0	1	0	0
0	0	0	1	1	1
0	0	1	0	0	0
0	0	1	0	1	1
0	0	1	1	0	0
0	0	1	1	1	1
0	1	0	0	0	0
0	1	0	0	1	0
0	1	0	1	0	1
0	1	0	1	1	1
0	1	1	0	0	0
0	1	1	0	1	1
0	1	1	1	0	1
0	1	1	1	1	1
1	0	0	0	0	0
1	0	0	0	1	0
1	0	0	1	0	0
1	0	0	1	1	1
1	0	1	0	0	1
1	0	1	0	1	1
1	0	1	1	0	1
1	0	1	1	1	1
1	1	0	0	0	0
1	1	0	0	1	0
1	1	0	1	0	1
1	1	0	1	1	1
1	1	1	0	0	1
1	1	1	0	1	1
1	1	1	1	0	1
1	1	1	1	1	1

NOTE — 1 = operational
0 = faulty

On inspecting Table 2, we can pick out the success combinations of items and write down the expression for system reliability as the set of mutually exclusive terms:

$$SS = \overline{B1}.\overline{B2}.\overline{C1}.\overline{C2}.A + \overline{B1}.\overline{B2}.C1.\overline{C2}.A + ... + B1.B2.C1.C2.A \quad ...(14)$$

from which

$$R_S = (1 - R_{B1})(1 - R_{B2})(1 - R_{C1})R_{C2}R_A + (1 - R_{B1})(1 - R_{B1})(1 - R_{B2})R_{C1}(1 - R_{C1})R_A + ... + R_{B1}R_{B2}R_{C1}R_{C2}R_A$$

Expression (14) contains 19 terms (one for each combination that results in success), all of which must be summed to give the desired result. From this it can be seen that the Boolean approach can soon become unwieldy, although the principle involved is quite straightforward.

8.2 Models with Common Blocks

Note that in **7** no block appeared more than once in the RBDs. It may however be advantageous to model by block diagrams of the type illustrated by Fig. 14. For example, items *C* and *D* might be two functionally similar items acting as duplicates for one another, but item *D* can be powered only by item *B*, whereas item *B* is capable of supplying power to both *C* and *D*. This is illustrated by Fig. 14 which represents not only the physical arrangements of the items, but also the reliability block diagram as well, it is important to include the arrows in Fig. 14.

Alternatively the system success paths in the above example may be represented by a block diagram in which some blocks appear more than once, as in Fig. 15. This diagram was derived from Fig. 14 by examining the latter and noting which pairs of items, if failing together, would cause the system to fail. Fig. 15 is thus a series combination of such pairs.

When dealing with a block diagram of the above type, it would be incorrect to treat the blocks as independent pairs and then multiply the reliabilities of the pairs together. Instead, use should be made of either of the methods given in **8.1.1** and **8.1.2.** As an example, using the method described in **8.1.1** we have:

$$R_S = Pr\ (SS \mid B \text{ operational}) \times Pr\ (B \text{ operational}) + Pr\ (SS \mid B \text{ faulty}) \times Pr\ (B \text{ faulty})$$

where *Pr* (*SS* | *B* operational) is given by the reliability block diagram comprising blocks *C* and *D* in parallel, but

$$Pr\ (SS \mid B \text{ faulty}) = Pr\ (SS \mid B \text{ faulty} \mid C \text{ operational}) \times Pr\ (C \text{ operational}) + Pr\ (SS \mid B \text{ faulty} \mid \text{ faulty}) \times Pr\ (C \text{ faulty}) = R_A R_C + 0$$

hence

$$R_S = (R_C + R_D - R_C R_D) R_B + R_A R_C(1 - R_B)$$
$$= (R_A R_C + R_B R_C + R_B R_D - R_A R_B R_C + R_D R_B R_C$$

Note that Fig. 14 and 15 are different ways of modelling the same failure definition. Namely system failure occurs when blocks *A* and *B* fail, or *B* and *C* or *C* and *D*. In other words the Boolean expressions for system success (*SS*) or for system failure (*SF*) are the same for both Fig. 14 and 15 that is

$$SS = (A\ C) \cup (B\ C) \cup (B\ D)$$

$$SF = (\overline{AB}) \cup (\overline{BC}) \cup (\overline{CD})$$

By applying the method described in **8.1.2** we have:

Table 3 Application of Truth Table to Fig. 14 and 15

Item				System
A	*B*	*C*	*D*	
1	1	1	1	1
1	1	1	0	1
1	1	0	1	1
1	1	0	0	0
1	0	1	1	1
1	0	1	0	1
1	0	0	1	0
1	0	0	0	0
0	1	1	1	1
0	1	1	0	1
0	1	0	1	1
0	1	0	0	0
0	0	1	1	0
0	0	1	0	0
0	0	0	1	0
0	0	0	0	0

NOTE — 1 = operational
0 = faulty

From the above table, we may write down

$$R_S = R_A R_B R_C R_D + R_A R_B R_C (1 - R_D) + R_A R_B (1 - R_C) R_D + R_A (1 - R_B) R_C R_D + R_A (1 - R_B) R_C (1 - R_D) + (1 - R_A) R_B R_C R_D + (1 - R_A) R_B R_C (1 - R_D) + (1 - R_A) R_B (1 - R_C) R_D$$

which simplifies to:

$$R_S = R_A R_C + R_B R_D + R_B R_C - R_A R_B R_C - R_B R_C R_D$$

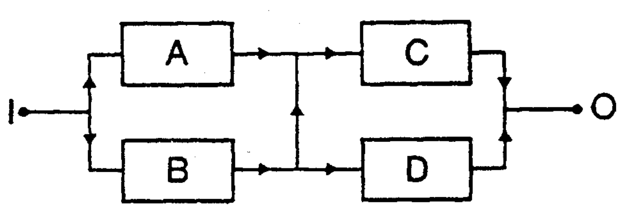


FIG. 14

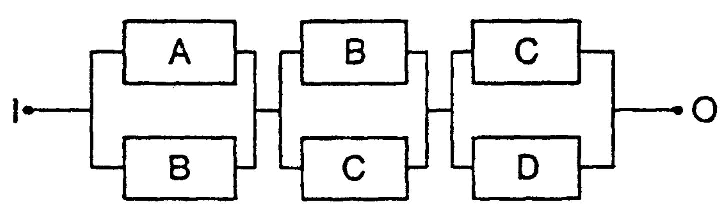


FIG. 15

Yet another method of dealing with common blocks is as follows: first ignore the fact that some blocks appear more than once and write down the expression for system reliability R'_S in the usual way

$$R'_S = (R_A + R_B - R_A R_B)(R_B + R_C - R_B R_C)(R_C + R_D - R_C R_D)$$

If these brackets are now multiplied out (producing 27 terms in all) and terms the $R_A R_B R_C^2$ and $R_D R_B R_C^2$ replaced by their Boolean equivalents $R_A R_B R_C$ et $R_D R_B R_C$ respectively and so on, then the expression for system reliability (R_S) will reduce to:

$$R_S = R_A R_C + R_B R_D + R_B R_C - R_A R_B R_C - R_D R_B R_C$$

8.3 *m* out of *n* Models (Non-identical Items)

The procedure described in **7.2.3** is not applicable here. As an example, consider a system represented by the block diagram in Fig. 16.

The reliability of such a system may be evaluated by either of the techniques described in **8.1.1** or **8.1.2**. Of these, the technique described in **8.1.2** will require 32 entries from which the probability of system failure F_S can be derived as:

$$F_S = (1 - R_A)(1 - R_B)(1 - R_C)(1 - R_D)(1 - R_E) + (1 - R_A)(1 - R_B)(1 - R_C)(1 - R_D) R_E + (1 - R_A)(1 - R_B)(1 - R_C) R_D (1 - R_E) + (1 - R_A)(1 - R_B) R_C (1 - R_D)(1 - R_E) + (1 - R_A) R_B (1 - R_C)(1 - R_D)(1 - R_E) + R_A (1 - R_B)(1 - R_C)(1 - R_D)(1 - R_E)$$

and so $R_S = (1 - F_S)$ can be found.

NOTE — More efficient techniques have become available.

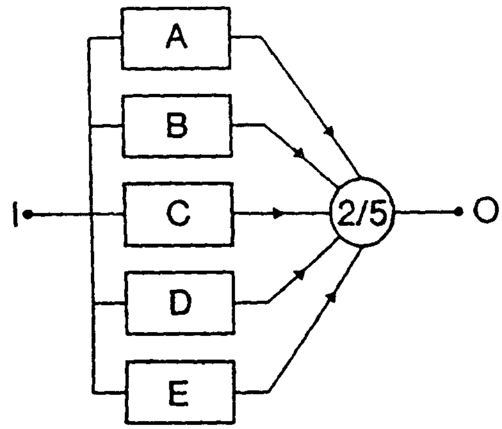


FIG. 16

8.4 Method of Reduction

Occasionally block diagrams seen very complicated. By careful examination, however, the blocks in the diagram can often be grouped into more manageable items; such items must be statistically independent. This means that no two (or more) manageable items can contain the same lettered block. For example, consider the block diagram illustrated by Fig. 17.

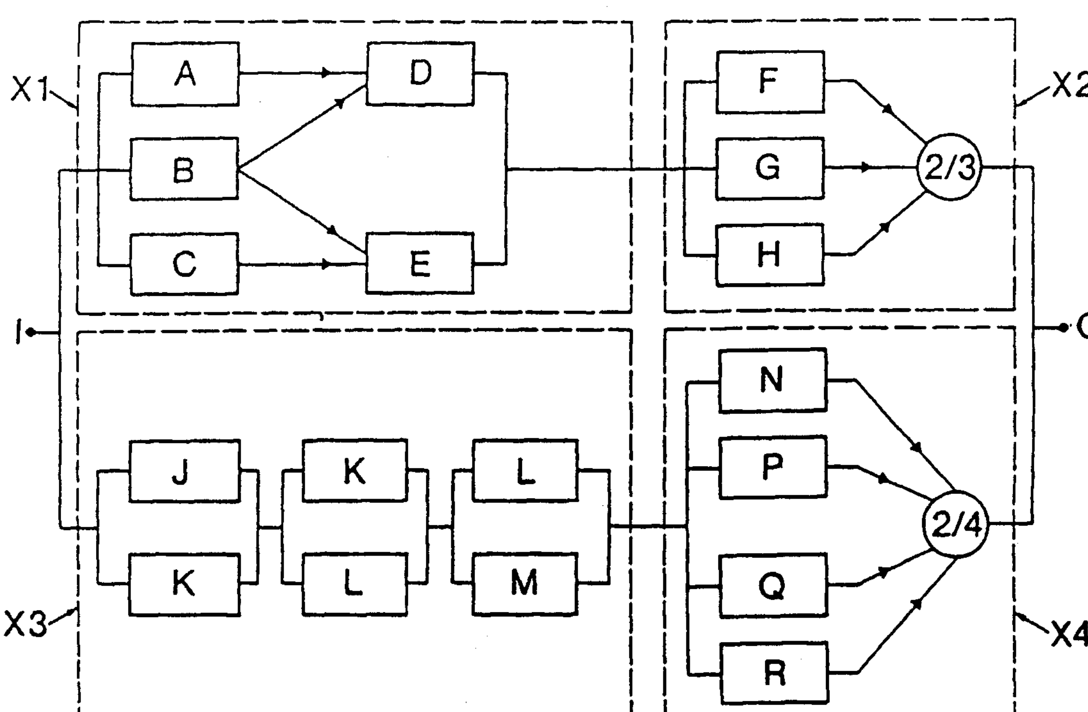


FIG. 17

The above diagram can be reduced to the one shown in Fig. 18 (a), by evaluating the reliability of the four dotted groups of blocks $X1$, $X2$, $X3$ and $X4$ as illustrated in **8.1**, **7.2.3**, **8.2** and **7.2.3** again, respectively. The diagram in Fig. 18 (a) can be further reduced to the one in Fig. 18 (b).

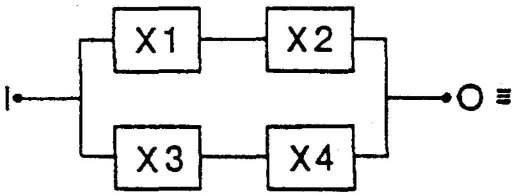


FIG. 18 (a)

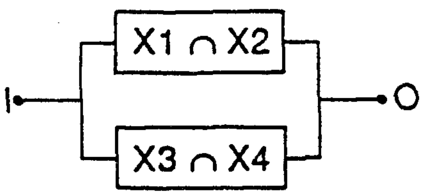


FIG. 18 (b)

Hence the final system reliability [referring to Fig. 18 (b)] is given by:

$R_S = R_{X1}R_{X2} + R_{X3}R_{X4} - R_{X1}R_{X2}R_{X3}R_{X4}$, as explained in **7.2.2**.

9 EXTENSION OF RELIABILITY BLOCK DIAGRAM METHODS TO AVAILABILITY CALCULATIONS

9.1 Introduction

Under certain conditions, it will be possible to make use of all the formulae and procedures in this standard, in order to carry out system steady state availability predictions. This is accomplished by simply replacing expressions for reliability, by corresponding expressions for availability.

9.2 Assumptions

The procedure described below will be valid only if the failures and repairs of the individual items are independent of one another. In practice this means that the failure of any item should in no way affect the onset of failure of any other and that there should be available, in effect, an 'infinite pool' of repairmen.

In other words the mean down time of any item should be a measure of that item alone and should not depend upon how many other items have also failed and are in need of repair. This means that, in practice, attention has to be paid to the way in which items are assembled; emphasis being placed on making sure that each item should be readily accessible and not obstructed by any other.

9.3 Examples

The following examples should clarify the procedure. Suppose we have a system for which the failure definition can be modelled by the diagram illustrated by Fig. 5, reproduced in Fig. 19.

The corresponding expression for system reliability (R_S) is given by the expression (*see* **7.2.2**):

$$R_S = R_D(R_{A1}+R_{A2} - R_{A1}R_{A2})(R_{B2} + R_{B2} - R_{B1}R_{B2})(R_{C1} + R_{C2} - R_{C1}R_{C2})$$

If the steady-state availability of item D is now A_D and of $A1$, $A2$, $B1$, $B2$, $C1$ and $C2$ are A_{A1}, A_{A2}, A_{B1}, A_{B2}, A_{C1} and A_{C2} respectively, then the expression for system steady-state availability (A_S) is simply:

$$A_S = A_D(A_{A1} + A_{A2} - A_{A1}A_{A2})(A_{B1} + A_{B2} - A_{B1}A_{B2})(A_{C1} + A_{C2}\ A_{C1}A_{C2})$$

As another example, we might consider the system fault definition modelled by Fig. 3. The corresponding system reliability (R_S) was shown to be given (*see* **8.1.1**) by:

$$R_S = (R_{C1} + R_{C2} - R_{C1}R_{C2})R_A + (R_{B1}R_{C1} + R_{B2}R_{C2} - R_{B1}R_{C1}R_{B2}R_{C2})(1 - R_A)$$

Hence the corresponding steady-state availability (A_S) is given by:

$$A_S = (A_{C1}+A_{C2} - A_{C1}A_{C2})A_A + (A_{B1}A_{C1}+A_{B2}A_{C2} - A_{B1}A_{C1}A_{B2}A_{C2})(1 - A_A)$$

Note that for items where the failure and repair rates (denoted by λ_A, λ_B, λ_C and μ_A, μ_B, μ_C respectively) are constant with respect to time, the reliability of such items is given by:

$$\exp(-\lambda_A t),\ \exp(-\lambda_B t),\ \exp(-\lambda_C t)$$

and the steady-state availabilities by:

$$\mu_A/(\mu_A+\lambda_A),\ \mu_B/(\mu_B+\lambda_B),\ \mu_C/(\mu_C+\lambda_C)$$

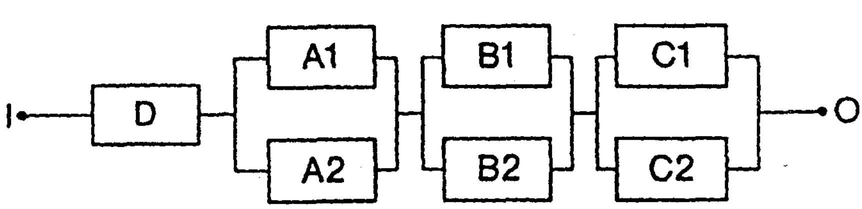


FIG. 19

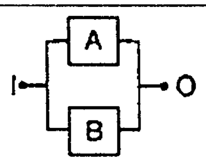
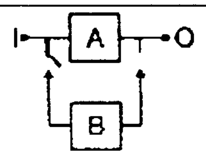
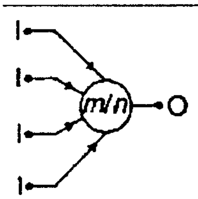
9.4 Conclusions and General Remarks

The adaptation of reliability formulae to availability calculations can be very useful but the assumptions state above should be carefully checked. These are, of course, additional to the assumptions necessary for the reliability formulae themselves to be valid. The availability assumptions include the requirement that there are no order dependent or time dependent failures. When this is not so, or when failures and repairs are not independent, recourse must be made to other methods of availability analysis, such as Markov analysis.

ANNEX A

(*Clauses* 1.2 *and* 4)

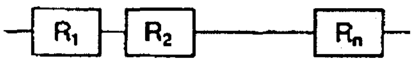
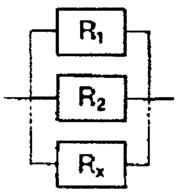
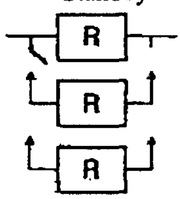
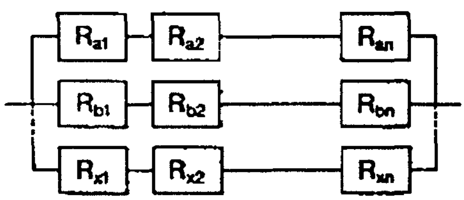
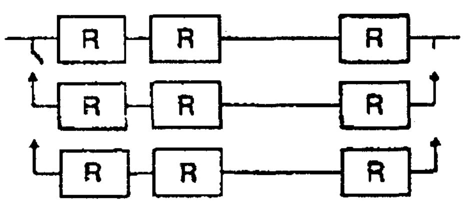
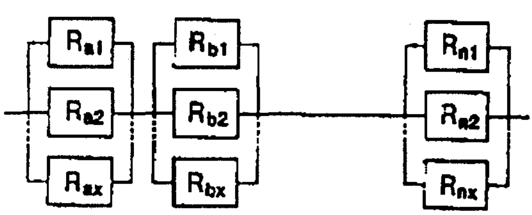
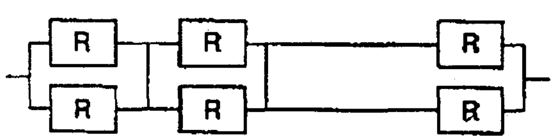
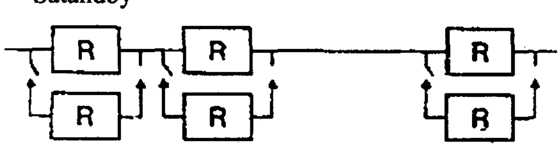
SYMBOLS AND ABBREVIATIONS

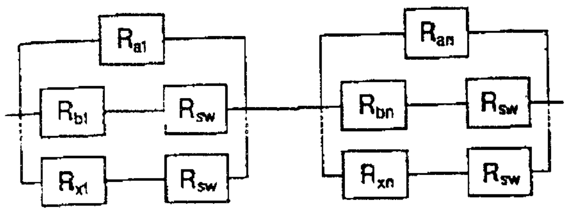
Symbol/Abbreviation	*Meaning*
$R, R(t)$	Reliability [probability that an item can perform a required function under given conditions for a given time interval $(0, t)$]
$R_A R_B$...	Reliability of blocks A, B,.....
R_S	System reliability
$\binom{n}{r}$	Number of ways of selecting r items from n items
$Pr(SS \mid X \text{ faulty})$	Conditional probability (system reliability given that item X is failed)
SS	System success (used in the Boolean expressions)
SF	System failure (used in the Boolean expressions)
A, B, C,....	When used in Boolean expressions, these quantities indicate that items A, B, C,....are in operational states
$\overline{A}, \overline{B}, \overline{C}$, ...	When used in Boolean expressions, these quantities indicate that items A, B, C... are in faulty states
0, 1	These quantities are used in truth tables to denote faulty and operational states and apply to whichever item is the column heading
$\cap$	Boolean symbol denoting AND, for example $A \cap B$ (intersection)
$\cup$	Boolean symbol denoting OR, for example $A \cup B$ (union)
	Active (parallel) redundancy
	Standby redundancy
	m/n is symbol used to show m-out-of-n items needed for system success in an active redundant configuration
I	Indicates input
O	Indicates output Such indications are used for convenience. They are not mandatory, but may be useful where connections have a directional significance
	Basic grouping of equipment

ANNEX B

(*Clause* 1.2)

SUMMARY OF FORMULAE

Basic configuration	*Equation for system reliability* R_S
1. Series 	A. *General case* $R_S = R_1 R_2 ..... R_n$ B. *With* $R_1 = R_2 .... = R_n = R$ $R_S = R^n$
2. Parallel Active  Standby 	A. *Active general case* $R_S = 1 - (1 - R_1)(1 - R_2)..(1 - R_x)$ B. *Active with* $R_1 = R_2 .... R_x = R$ $R_S = 1 - (1 - R)^x$ C. *Standby with* $R = \exp(-\lambda t)$ $R_S = e^{-\lambda t} + \lambda t\, e^{-\lambda t} + ... + \{[(\lambda t)^{x-i} e^{-\lambda t}] / (x-1)!\}$
3. Series parallel or system redundant Active  Standby 	A. *Active general case* $R_S = 1 - (1 - R_{a1} R_{a2} .... R_{an})(1 - R_{b1} R_{b2} ..... R_{bn})$ $....(1 - R_{x1} R_{x2} ... R_{xn})$ B. *Active with* $R_{a1} = R_{a2} = ... = R_a$ $R_{b1} = R_{b2} = ... = R_b$ $R_{x1} = R_{x2} = ... = R_x$ $R_S = 1 - (1 - R_a^{\ n})(1 - R_b^{\ n})...(1 - R_x^{\ n})$ C. *Active with* $R_{ai} = R_{bi} = ... = R_{xi} = R$ for $i = 1$ to n $R_S = 1 - (1 - R^n)^x$ D. *Standby with* $R = e^{-\lambda t}$ $R_S = e^{-n\lambda t} - n\lambda t\, e^{-n\lambda t} + ... e^{-n\lambda t} (n\lambda t)^{x-1} / (x-1)!$
4. Parallel series or element redundant Active   Satandby 	A. *Active general case* $R_S = [1 - (1 - R_{a1})(1 - R_{a2}) .. (1 - R_{ax})]$ $[1 - (1 - R_{b1})(1 - R_{b2})..(1 - R_{bx})]$ $....[1 - (1 - R_{n1})(1 - R_{n2}) ...(1 - R_{nx})]$ B. *Active with* $R_{a1} = R_{a2} = ... = R_a$ $R_{b1} = R_{b2} = ... = R_b$ $R_{n1} = R_{n2} = ... = R_n$ $R_S = [1 - (1 - R_a)^x].[1 - (1 - R_b)^x]...[1 - (1 - R_n)^x]$ C. *Active with* $R_{ai} = R_{bi} = ... = R_{ni} = R$ for $i = 1$ to x $R_S = [1 - (1 - R)^x]^n$ Assuming that $x = 2$ and $R = e^{-\lambda t}$ $R_S = (2e^{-\lambda t} - e^{-2\lambda t})^n$ D. *Standby with* $R = e^{-\lambda t}$ $R_S = \{e^{-(\lambda/n)t} + (\lambda t/n)\, e^{-(\lambda/n)t}\}^n$

Basic configuration	*Equation for system reliability* R_S
5. Element redundant with switching 	A. *Active, assuming all* $R_{ai} = R_{bi} = R_{xi} = R$ (except R_{sw}) $R_S = [1-(1-R)(1-R\,R_{sw})^{x-1}]^n$ B. *Active assuming* $x = 2$ *and all* $R_{ai} = R_{bi} = R_{xi} = R = e^{-\lambda t}$ (except R_{sw}) $R_S = e^{-\lambda t} + e^{-(\lambda+\lambda sw)t} - e^{-(2\lambda+\lambda sw)t}$

NOTES

1. The reliability of element redundancy with switching (configuration 5A above) will still be superior to the basic system redundant configuration (3C) as long as the reliability of the switching device exceeds the value of *RS* for the basic system redundant configuration divided by *R* for the element to be switched. In equation form:

$$R_{sw} \geq R_s / R$$

where R_s pertains to configuration 3 C in the above table.

2. For constant failure rates, *R(t)* can be replaced by $e^{-\lambda t}$.

ANNEX C
(Foreword)

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