An Availability Study for a SME

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Abstract

A case study of an availability analysis for a small commercial company is presented. The analysis was carried out to meet a customer requirement for the availability of an electronic ground based system in a benign environment. Availability calculations were based on failure data provided and an explanation of the methodology and problems encountered and dealt with are discussed. The methodology includes failure classification according to MIL-HDBK-781A and how it may be used to promote and develop internal processes. A commentary on the background to reliability/availability specification is provided and a number of recommendations for monitoring reliability and availability are given.

Background

Reliability requirements are typically specified in customer documentation for products which need to be reliable and safe (e.g. aerospace systems, nuclear facilities). The requirements are met by the supplier (usually a large manufacturing organisation) by a variety of well established reliability methods (e.g. Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Reliability testing). The techniques are usually very costly and resource intensive and so only large companies have the facilities to carry them out. The tools and techniques are well established within standards for the military, aerospace and nuclear sectors and these large suppliers can afford to carry out quite complex reliability analyses (Pate-Cornell and Fischbeck (1993) for an example of a probabilistic risk analysis, Pages and Gondran (1986) for examples of FMEA and FTA). However, SMEs do not have the resources to carry out such complex analyses. The aim of this paper is to show how an availability analysis was carried out on a product developed by an SME using simple statistical techniques. The approach can be applied to any SME that manufactures redundant systems as long as they have a data collection system for reliability data as part of their in-house quality management systems.

The small company (the supplier) in this case study manufactures ground benign electronic switching systems containing typically approximately 8000 electronic components. A prospective customer for a fixed price product that comprised of a number of systems which needed to meet an availability requirement requested the supplier to submit a proposal. The company maintained a quality system comprising all the elements of ISO 9001 and mainly offered customers off-the-shelf systems. As such, any customer requirement was met with the standard package (e.g. warranty and repair conditions similar to when a new car or television is bought) which was covered by the company's internal practices. Previously, one of the authors had been involved with the company in a training exercise on the understanding and interpretation of reliability requirements but all the staff who had taken the course had subsequently left the company. A process had been put in place to record the date of delivery of new units and any failure and repair information on returned units. This was to provide information for a future availability assessment. This process had been running from the time of the course, approximately three years previously. Senior management at the company thought it was time to submit proposals for customers who required more costly and complex systems with more comprehensive specifications.

Customer Requirements

Customer requirements are usually detailed within a specification, a statement of work or contractual documents and in the case of the contract being considered here there was a customer requirement that the availability of a system should be 0.99995. This may have been derived as about an hour of downtime per year which would equate to the amount of lost revenue by the end-user per year which is the contractual worth for the product development phase. The customer required a minimum of twenty of these systems that comprised the end product. Each system comprises of three separate electronic units. This requirement equates to $0.99995^{20} = 0.999$ for the product. There were no other stated reliability requirements. This is surprising because usually in contracts containing reliability requirements there are preferred guidelines or procedures on how the requirement should be met.

Initial Questions to Supplier

One of the authors was contacted to carry out the work required to meet the requirement and initially a number of questions were asked by the author to determine the type of analysis to be carried out.

These questions were:

1. How many of the same or similar systems are in service use?
2. State the operating times for each system or percentage of service use time these systems have been operating?
3. How many failures have occurred in service use for these systems?
4. Are failures classified by when in service use they happened (before or after two years, severity, random, systematic (solved/unsolved).
5. Is the repair policy for a system in terms of full system or units? If a full system, then what is the time to get a system available again: list average and worst case times. Go to 10.
6. Is MTBF data available for units? If no, go back to 5.
7. List lifed units.
8. State repair policy for non-lifed units: replace on site or return to factory for repair?
9. State the time to replace units in field for non-lifed units.
10. Carry out availability analysis.

This information was collected when one of the authors went to the company to carry out the assessment.

Methodology

When carrying out any reliability study, a methodology is established and used so that operating conditions and engineering assumptions (of equipment usage, failure time distributions, environment, etc.) can be taken into account. If any conditions or assumptions change, then results may not be relevant for the proposed system.

The analysis is based on available data from existing systems and provides an estimate of availability of the proposed product at the present time. There are methods of reliability and maintainability analysis which are based on reliability data bases and repair activities e.g. US MIL-HDBK-217 and US MIL-HDBK-338 section 5 but these are extremely labour intensive and would not have been as relevant as using 'live' data. The availability calculation should only be used to determine contractual compliance with a customer's availability figure for a particular part of the product life cycle. Actual availabilities of the proposed equipment in service use may be determined at a later date. The preliminary availability assessment presented here is in accordance with method 2 section 8.7 of A Guide to System Reliability and Availability (CCTA 1988) which is as follows:

1. Obtain the service requirements and specifications
2. Identify the major system components
3. Identify the component inter-relationships
4. Assign reliability values
5. Identify an average downtime
6. Calculate the expected figures
7. Compare figures with customer's requirement and carry out sensitivity analysis
8. Identify corrective action.

Lifed units are treated independently since they fail at known intervals. However, there were no lifed units in this product.

Availability Calculations

There are five definitions of availability namely instantaneous, mission or average, asymptotic or steady state, operational and intrinsic. The one the authors used was the intrinsic availability since the others require either complex mathematics (Markov chains), detailed data on failure distributions or in the case of operational availability - waiting time, administration time and logistic time. The formula for the intrinsic system availability is $A_S = \frac{MTBF}{(MTBF+MTTR)}$ where MTBF is the Mean Time Between Failures for each system and MTTR is the Mean Time to Repair the system at first line (O'Connor 1991, pp120). This is the formula used to evaluate the availability of a system. The formula does not take into account that units may degrade over time and thus a period of preventive maintenance may be required, say at 3 monthly to yearly intervals (or on the occasion of a unit failure). The need for redundancy has to be compared with the reliability of the units within the system since if the requirement can be met without using redundant systems this reduces the cost of spare systems. Hence calculations are required for MTBF and MTTR and evaluation of these parameters are discussed below.

The product availability calculations are the minimal cut set steady state availabilities assuming the time to failure and time to repair are exponentially distributed (Pages and Gondran, 1986). The formulae are the same as the application of the binomial distribution for k-out-of-n components (systems) using the system availability as the probability of success.

Maintainability Analysis

On failure of the product, the failed system will be replaced on the customer site within a 24-hour period. The repair time will include the time taken to remove the failed system, the time to send for a new unfailed system, the time to install the new system and the time to bring the product to full operational status. There was no

information available on the time to repair the systems, e.g. the fault localisation time, isolation time, disassembly time, interchange time, re-assembly time, alignment time (if needed) and checkout time. Thus the worst case MTTR is specified as the time to repair the system at first line level (in the hands of the customer), i.e. 24 hours.
At second line, the failed system will be returned to the supplier for repair.

Definitions of Failure and MTBF Calculations

For the MTBFs of the systems in the product, the simplest and cheapest method of evaluating MTBF is to record the delivery dates of units currently in service use, determine the duty cycle (in this case it was assumed that each delivered unit was operating all the time) and record all failures but classify them according to whether they are applicable to the calculation of MTBF. MTBFs should be calculated as if the box was a mature unit in service use (i.e. there should be no systematic design or manufacturing failures in the unit). Two failures were discounted as they were failures on commissioning and would not re-occur. In the case of two of the units never having failed, there is no universally approved calculation possible for MTBF however the point estimate availability will be one as the units have never failed. Using a worst case MTBF based on a formula using the Chi-squared distribution for the units will provide worst case availability figures so a sensitivity analysis will not be needed since if the requirement is met with the worst case figures, no further analysis is needed. Also, using provided operating time gives an indication of how reliable a unit may be. Another reason that a hazard rate has been allocated to units that haven't failed is that unseen contingencies during future design and service use can be allowed for.

The Chi-squared method is not recommended (Nelson 1982) but no other method of MTBF calculation has been found in the literature. However the authors have shown that if the best case availability figures are chosen for units 1 and 3, the same conclusion is met for the best configuration of systems.

The following definitions are applicable for MTBF calculations for mature products accepted into service use.
A failure is the inability of a system to operate and is further defined as follows:
A Failure is "Any departure from the declared manufacturing drawings and specifications which is observed on the equipment, which is detrimental to the operability or performance of the product and which, if it occurred in service use would require unscheduled maintenance action to correct." (US MIL-HDBK-781)
The occurrence of failures as defined above will be the basis for the estimation of Mean Time Between Failures (MTBF).
Failures are classified as being relevant or non-relevant to MTBF calculation according to the glossary at the end of the paper.

The MTBF of each subassembly is calculated by the similar items method as described in MIL-HDBK-338 and failure is defined for MTBF purposes as a relevant failure as described below and MIL-HDBK-781 and DEF-STAN-0041. Only one relevant failure has occurred on similar units to units 1, 2, and 3 in service use. The formula for MTBF of each subassembly is given as the operating time of the similar subassemblies in service use (T), (see table 1) divided by the number of failures (r): MTBF=T/r. The hazard rate is the inverse of the MTBF.

Table 1: In-service Information for Delivered Units

Unit	Service Reference	Number in Service	Operating Hours	Number of Failures
1	1	7	9000	0
1	2	3	56000	0
1	3	3	57000	0
1	4	4	48000	0
2	1	4	50000	0
2	1	4	26000	0
2	1	2	13400	1
2	1	4	11000	0
2	1	1	2000	0
2	1	5	9000	0
2	1	4	2000	0
3	1	4	67000	0
3	1	3	34000	0
3	1	3	8000	0

Assumptions of the Analysis

The following assumptions are made regarding the availability analysis:
The product is mature (i.e. all systematic manufacturing and design failures have been removed from the product. Hence the product is in the random failures in time part of the bathtub curve (O'Connor 1991) and the exponential distribution is appropriate for analysis.
The units in service use are assumed to be operating 24 hours a day, 365 days a year (supplier knowledge). Hence, the time since delivery in hours is the operating time. This assumption is reasonable for this type of equipment.
This is a preliminary assessment based on current knowledge. The availabilities on award of the contract may be determined for any actual system by the same formulae for intrinsic availability.

Configurations

A number of configurations was considered to determine the best layout of systems to meet the availability requirement. This list is not exhaustive but takes into account that extra systems would increase product cost and are symmetrical configurations to reduce extra loading on specific systems. Irrespective of the hazard information, the more redundancy used in a configuration will provide the more reliable system and the more reliable configurations will be the ones with the least sets of a given number of redundant systems. The following configurations were considered:

1. 20 systems with no redundant systems: 1 set of 20 systems in total

2. 20 systems with one active redundant system: 1 set of 21 systems in total

3. 20 systems with two active redundant systems: 1 set of 22 systems in total

4. 10 systems with one active redundant system each (2 sets of 11 in series): 22 systems

5. 10 systems with two active redundant systems each (2 sets of 12 in series): 24 systems

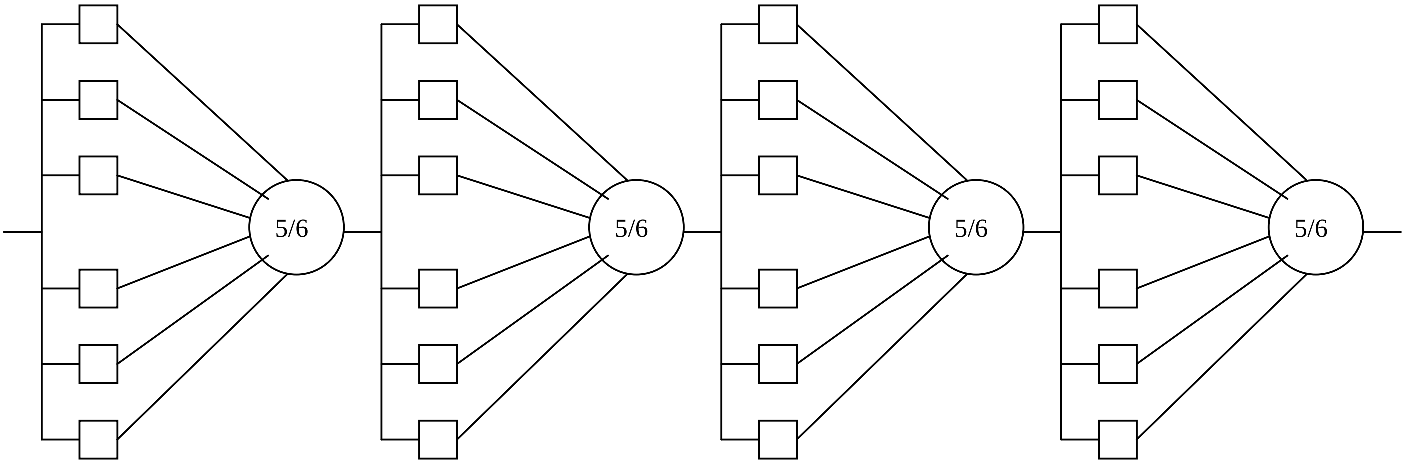
6. 5 systems with one active redundant system each (4 sets of 6 in series): 24 systems.

7. 5 systems with two active redundant systems each (4 sets of 7 in series): 28 systems

8. 4 systems with one active redundant system each (5 sets of 5 in series): 25 systems.

A reliability block diagram is shown for configuration 6 below.

Figure 1: Reliability Block Diagram for Configuration 6



The availability calculation is based on given a unit (1, 2 or 3 within a system) has failed, then the system is taken off line and repaired. For the configuration containing 24 operating systems split into four sets in series of 6 systems in a 5 from 6 redundant configuration, the 5 from 6 redundant configuration means that all 6 systems are available however only 5 are required to meet the requirement (e.g. a 4 engine aircraft can still fly with 3 engines operational).

The hazard rate of a system is calculated as the sum of the hazard rates of units 1, 2 and 3, (see table 2). When no failure had occurred on a unit, the hazard rate was calculated as $\frac{\chi^2_{50\%,2}}{2T}$ where T is the operating time for a unit and $\chi^2_{50\%,2}$ can be taken from statistical tables, (e.g. Murdoch and Barnes 1988).

Table 2: Reliability Data for System Availability Calculation

	Unit 1	Unit 2	Unit 3	System	Availability A_S
Total Hours	170000	113400	109000		
Number of Failures	0	1	0		
Hazard rate in failures per million hours	4.076	8.818	6.358	19.252	0.9995381

The availability of the product with configuration number 6 is given by the formula $A_{P6} = (A_S^6 + 6A_S^5(1 - A_S))^4$. This is the availability of six systems operating continuously or five from the six systems operating continuously with one of the six failed. On inputting the hazard rates above into the equation, the product availability is 0.9999872.

The equations for the product availabilities for each configuration are as follows:

1. 20 systems with no redundant system: 20 systems in total - $A_{P1} = A_S^{20} = 0.9908034$

2. 20 systems with one redundant system: 21 systems in total - $A_{P2} = A_S^{21} + 21A_S^{20}(1 - A_S) = 0.999950$

3. 20 systems with two redundant systems: 22 systems in total - $A_{P3} = A_S^{22} + 22A_S^{21}(1 - A_S) + 231A_S^{20}(1 - A_S)^2 = 0.9999998$

4. 10 systems with one redundant system each (2 sets of 11 in series): 22 systems - $A_{P4} = (A_S^{11} + 11A_S^{10}(1 - A_S))^2 = 0.9999766$

5. 10 systems with two redundant systems each (2 sets of 12 in series): 24 systems - $A_{P5} = (A_S^{12} + 12A_S^{11}(1 - A_S) + 66A_S^{10}(1 - A_S)^2)^2 = 0.9999999$

6. 5 systems with one redundant system each (4 sets of 6 in series): 24 systems - $A_{P6} = (A_S^6 + 6A_S^5(1 - A_S))^4 = 0.9999872$

7. 5 systems with two redundant systems each (4 sets of 7 in series): 28 systems - $A_{P7} = (A_S^7 + 7A_S^6(1 - A_S) + 21A_S^5(1 - A_S)^2)^4 = 0.9999999$

8. 4 systems with one redundant system each (5 sets of 5 in series): 25 systems - $A_{P8} = (A_S^5 + 5A_S^4(1 - A_S))^5 = 0.9999893$

Comparison with Requirement and Feedback from the Customer

The availability requirement for the product is 0.999. Thus, based on the above calculations, the proposed product meets the availability requirement for every configuration with a redundant system. The cheapest configuration to produce is configuration 2 with 21 systems.

The results were sent to the customer with a list of recommendations. The customer replied stating "What happens if a front line system (for which spares are held at site and subject to a short term replacement time-scale) fails and the spare system is used then immediately a second failure occurs for which there is no replacement unit." Looking at each configuration, the only ones to meet this further requirement are the configurations with two extra redundant systems i.e. configurations 3, 5 and 7. Each of these requires 22, 24 or 28 systems to be manufactured respectively. Now since these systems are highly reliable, the chance of a second failure on the same day must be quite small. This can be evaluated for the one redundant system configurations.

An assumption of this analysis as that the configuration will be periodically maintained at yearly intervals This is a reasonable assumption as electronics is inherently reliable and requires little periodic maintenance.

The probability of the configuration failing during operation within the period of maintenance (one year) =

The probability that the configuration is available * the probability of the configuration failing within one year =

The availability of the configuration * The probability of at least one block within the configuration fails = $A_P(1-(1-P_B)^N)$ where

A_P is the availability of a particular configuration,

P_B is the probability a block fails = the probability of one system failure within one year and at least one system failure in the same redundant block within the period of repair (24 hours) or at least two failures in any block within the period of repair, and

N is the number of blocks in a configuration.

To evaluate P_B, the following are required.

The probability of one system failure within one year =
$M(\lambda Te^{-\lambda T})^1(1-\lambda Te^{-\lambda T})^{M-1}$ where M is the number of systems in a block and T is one year (8760 hours).

The probability of at least one system failure in the same redundant block within one day = $1-(1-\lambda te^{-\lambda t})^{M-1}$ where t is 24 hours.

The probability of at least two failures in any block within the period of repair = $1-(1-\lambda te^{-\lambda t})^M - M\lambda te^{-\lambda t}(1-\lambda te^{-\lambda t})^{M-1}$.

Thus, $P_B =$
$$M(\lambda Te^{-\lambda T})^1(1-\lambda Te^{-\lambda T})^{M-1}(1-(1-\lambda te^{-\lambda t})^{M-1})+(1-(1-\lambda te^{-\lambda t})^M - M\lambda te^{-\lambda t}(1-\lambda te^{-\lambda t})^{M-1})$$

Using these formulae, the probability of the configuration 2 failing during operation within the period of maintenance = $1.38*10^{-3}$.

The probability of the configuration 4 failing during operation within the period of maintenance = $2.98*10^{-3}$.

The probability of the configuration 6 failing during operation within the period of maintenance = $2.85*10^{-3}$.

The probability of the configuration 8 failing during operation within the period of maintenance = $2.49*10^{-3}$.

These figures are comparable with the risk of a disastrous flood in London or the chance of an aircraft crash in the UK killing more than

500 people (both $1.0*10^{-3}$ (HMSO 1988)). If an unlikely event happens, Boeing, for example, direct their suppliers to come up with a list of recommendations and the most cost effective are implemented.

In the case of the customer's product requirement, costs of extra system manufacture should be balanced up with the risks of downtime. In the author's opinion configuration number 2 still provides the best option since the risk of a second failure is so small.

It is assumed that the systems are in active redundancy or standby redundancy with perfect switching (another reason for using worst case values is that certain components of the system may have been left out of the analysis, e.g. cabling, switches, etc). For more than two systems failing in a given day, then the authors think that there may be some dependency of failures, e.g. common cause failures (such as common vibration) or common mode failures (such as changeover systems to activate standby redundant systems or maintenance actions which are common to all failure paths). This may require further work by the supplier on design and maintenance procedures.

So far as meeting any availability requirement on award of the contract, the supplier should have procedures for failure reporting and classification and recording of the operating time and actual repair time accumulated. Failures occurring over a short time period would have to be analysed for possible dependencies and whether they should be discounted from the analysis. From an operational point of view, a Service Record Review may be run periodically to consider the ongoing operation of the delivered units, failures encountered and possible recommendations. However, given the ground benign environment and the performance history of the units so far, there will probably not be much to report.

However, depending on the type of failure, the availability requirement may still be met since the failure(s) may be out of the supplier's control e.g. vandalism, voltage transient. Responsibility for the failure types may need clarifying with the customer to see who takes the responsibility and hence the possible repair cost. The availability figure would not include these discounted failures and repair time in the analysis if they were not the supplier's responsibility and so even though the system is unavailable, the availability requirement is still met.
The supplier will need to look at the types of failure which may occur if there is a system failure on demand. Based on the field data for the availability analysis, there were two discounted failures on commissioning however there have been no failures on demand. This is why the availability analysis is applicable to both active and standby systems because the observed reliability on demand based on the supplier's data is one.

Recommendations for the Supplier

Since the customer does not specify how to meet the requirement; does not require the supplier to implement any methods which would make the system more reliable (e.g. FMEA, reliability growth programme, burn-in, design reviews, FTA, use of preventive maintenance, design life, etc.) and does not specify any contractual clauses for not meeting the requirements (e.g limited liability, reliability improvement warranty, penalty costs, etc), then there is no financial justification to the supplier for introducing more redundancy than necessary.

Some other recommendations are as follows.

A procedure is required to address the flow of uniquely specified information and responses to and from customers from and to the relevant personnel.

There is a problem if the redundant system is on standby and fails before an operating system since it won't be detected until it is needed. Hence the supplier requires more information on failures on demand (perhaps from factory data) and looking at preventatively maintaining and/or periodically testing the standby system.

To address problems with commissioning, the system should be run in before delivery with switch ons/offs as part of the test.

Also, critical components that may fail at switch on should be determined by FMEA and the supplier should feed back any reliability requirements to the specific subcontractor for these components.

Run a failure review board with designers/production/quality personnel to consider other preventive actions.

Finally, as the authors have shown, the initial availability requirement is met with any of the redundant configurations, but there is a larger risk associated with using the configurations with only one redundant system.

Conclusions

An availability requirement specified in a commercial contract has been considered and analysed. Customer reliability requirements in general are specified so that suppliers will see that these aspects are important to the customer. Typical reliability requirements are backed up by appropriate design analyses so that products can be improved at the design stage. Unfortunately most SMEs are not equipped with the personnel or resources to carry out detailed reliability analyses such as the above and generally do not cost their implications into their product schedules. Consultants, when they are used, carry out the tasks to meet the requirements but the changes to the processes, product and management structure must come from the supplier company's senior management.

Reliability requirements for commercial products are not well used or understood and for benign electronic products perhaps even irrelevant due to their inherent high reliability anyway. Requirements should provide a financial sting to suppliers (e.g. a reliability warranty clause) who do not use their quality management systems effectively and an incentive to create reliable and safe designs. Thus, reliability tools and techniques should be tailored to suit the cost constraints that commercial suppliers have to work under and be simple enough to be understood by not only the everyday reliability practitioner but also the quality engineer or manager who occasionally comes across a customer reliability specification. In the case of the analysis above, it is simply an application of the binomial distribution and probability theory using the availability as the probability and should be found in any standard reliability textbook for engineers, but it isn't. In fact, the theory has been taken from a textbook which is extremely high level and would put off most engineers who would want to carry out the analysis. Bendell, Disney and McCollin (1999) and discussants Quigley and Walls from the same paper advocate the use of simple analyses as 'complex models generate ambiguity and are misleading to design makers' (Quigley).

The authors' wish is that as statistical reliability requirements appear in more commercial contracts, that research is carried out on making reliability techniques less cumbersome, less costly and more user friendly so that SMEs can use them to improve their products at the design stage.

The authors' thanks are extended to the referee for his comments on some of the equations and to Mr Peter Dixon for his help in dealing with them.

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Glossary

These definitions have been expanded from the basic definitions in MIL-HDBK-781A and DEF-STAN-0041 and have been used in various aerospace contracts.

Non-relevant Failure: A failure which if it occurred in service would be confirmed at the point of use but would not be detrimental to the operability or performance of the equipment but would require unscheduled first line maintenance action.

Fault: A failure not detected during normal operation, but may be detected at maintenance levels other than first line, usually unrelated to the primary cause of subassembly replacement.

A list of relevant failures are defined below:
Premature wear-out: A failure of an item with a specified life expectancy, when operated within the defined replacement time of that item.
Part design: A failure due to the inadequate design of a part.
Part assembly: a failure due to the inadequate manufacture of a part.
Equipment design: a failure due to inadequate design of the equipment.
Equipment assembly: a failure due to inadequate assembly of the equipment.
Unconfirmed random: a failure which cannot be duplicated or is still under investigation or for which no cause can be determined.
Unconfirmed random: The first occurrence of a failure for a limited period of time, followed by the item's recovery to perform within specified limits without remedial action. Subsequent occurrences of the same intermittency on the same equipment shall be considered non-relevant.

A list of non-relevant failures as defined above is given below.
Associated failure: a failure that was not the cause of the equipment to fail.
Acceptable wear-out: a failure of an item with a specified life expectancy, when operated beyond the defined replacement time of that item.
Acceptable damage: a failure caused by an accident.
Adjustment: a failure corrected by acceptable types of operator or installation adjustment or other maintenance.
No fault found: a failure unconfirmed by investigation.
Documentation: a failure due to an incorrect piece of paperwork, e.g. a drawing, a part specification, an operating, maintenance or repair procedure.
Consequential: a failure resulting directly or indirectly from the failure of another item.