GUIDANCE FOR WRITING

NATO

R & M REQUIREMENTS DOCUMENTS

ARMP-4
(Edition 2)

OCTOBER 2001

NORTH ATLANTIC TREATY ORGANIZATION

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Rear Admiral, NONA
Chairman MAS

RECORD OF CHANGES

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CHAPTER 1

INTRODUCTION

101. GENERAL

In order to achieve high operational effectiveness with low life cycle cost the Reliability and Maintainability (R&M) of defence materiel should be given full consideration at all stages of the procurement cycle. This process should begin at the concept stage of the project and be continued, in a disciplined manner, as an integral part of the design, development, production and testing process and subsequently into service.

This ARMP provides guidance on writing R&M requirement documents during the life cycle of a project using the NATO PHASED ARMAMENTS PROGRAMMING SYSTEM (NATO PAPS) as a framework.

This document also contains the necessary information and advice to write quantitative reliability and maintainability requirements, and availability and risk requirements which are derived therefrom.

102. PURPOSE

Realistic R&M requirements should be stated properly and consistently in each milestone of the NATO PAPS. The purpose of this document is to:

a. Describe the concepts and factors affecting the formulation of R&M requirements to assist operational requirements staff to define the basic R&M requirements, and the procurement agency to convert these requirements into contractually agreed specifications.

b. Describe a framework for the development of the R&M content of each PAPS milestone.

103. APPLICABILITY

This document applies to all materiel developed for use by NATO. It complements ARMP-1 and ARMP-2 by providing guidance for writing R&M requirements documents. ARMP-4 deals mainly with quantitative R&M requirements, whereas ARMP-1 and ARMP-2 deal with the requirements for R&M programmes.

104. RELATED DOCUMENTS

ARMP-1	“NATO Requirements for Reliability & Maintainability”
ARMP-2	“General Application Guidance on the use of ARMP-1”
ARMP-3	“List and Source of National and International R&M Documents”
ARMP-5	“Guidance on Reliability & Maintainability Training”
ARMP-6	“In-Service Reliability & Maintainability”
ARMP-7	“NATO R&M Terminology Applicable to ARMPs”
ARMP-8	“Reliability & Maintainability of OFF-the-shelf-Equipment”

STANAG 4174	“Allied Reliability and Maintainability Publications” (ARMPs)
AQAP-110	“NATO Quality Assurance Requirements for Design, Development and Production”
AQAP-119	“NATO Guide to AQAPs - 110, -120, -130”
AQAP-120	“NATO Quality Assurance Requirements for Production”
AQAP-150	“NATO Quality Assurance Requirements for Software Development”
AQAP-159	“NATO Guide to AQAP-150”
AAP-20	NATO Phased Armaments Programming Systems

CHAPTER 2

CONCEPTS AND FACTORS

201. GENERAL

This chapter describes some concepts and factors which affect R&M requirements.

Staff requirements for R&M are usually written in operational terms such as availability, mission success, maintenance manpower and logistic support.

As these requirements may not be directly transferable to the Contractor, a two step approach is recommended:

a. First, the R&M requirements should be operationally justified such that the consequences of any shortfalls can be identified, and technically and economically feasible in life cycle cost terms;

b. Secondly, the procurement agency should translate these requirements into contractually demonstrable terms

In addition, qualitative R&M requirements may be considered as follows:

a. requirements for the employment of certain materials/electronic components;

b. requirements for the observance of specific design and safety regulations;

c. transportation, handling and storage requirements;

d. requirements concerning set-up/arrangement/assembling of the units;

e. requirements concerning accessibility/exchangeability.

A detailed analysis of the operational, environmental and logistic support conditions, under which the system/equipment is expected to operate, should be undertaken by the operational requirements staff. This analysis, which is to be developed at system level, should make use of:

a. the operational model describing the mission profile, the required functions, mission cycle and the environmental/operational conditions under which the system is expected to be used (see para 206 and the example given in table 2);

b. the description of the user environment to which the system is expected to be exposed, especially the maintenance concept (lines and levels of maintenance, maintenance facilities, personnel skill level, support equipment and logistics (see para 207);

c. It is necessary to develop a comprehensive description of these conditions and include a narrative on how the R&M parameters should be measured, verified and validated as the system level requirements are being developed.

At equipment level, i.e. in later PAPS phases, the contractor should be involved in the allocation of the R&M requirements.

202. IMPORTANCE OF USING QUANTITATIVE R&M REQUIREMENTS

There are general R&M requirements which are applicable at the weapon system level. However, those which are used as design requirements by the contractors are derived from these general requirements. They should be specified in terms of reliability, maintainability, testability, shelf life, or in more specific characteristics such as Probability of mission success, or Mean Time Between Failure (MTBF) for reliability, Mean Time To Repair (MTTR) for maintainability, and failure detection rate for testability.

In the earlier phases of a system's/equipment's life cycle it may not be possible to state the R&M requirements in quantitative terms. It is important, however, that as soon as possible and at the latest by the end of the feasibility study, the R&M requirements are stated in quantitative terms, supplemented where necessary by qualitative specifications (see para 201).

The R&M requirements should be defined in quantitative terms in all related documents for the following reasons:

a. To define the levels of R&M required to meet (see paragraph 205) operational commitments, consistent with the plans for deployment, use manpower resources and environment. Having stated these, the designer can decide in examining the total requirement, whether these levels of R&M can be achieved in conjunction with all the other operational and support requirements, or whether some compromise is necessary;

b. The Contractor cannot be expected to examine the feasibility of meeting a requirement if it is not specified in a quantitative way;

c. Quantitative R&M requirements can also be used as a basis for R&M demonstrations at the end of development/production. It is therefore important, when specifying the R&M requirements, to consider how the contractual R&M values can be demonstrated. The purchaser's procurement agency should at an early stage decide how compliance with the R&M requirements is to be demonstrated and the action to be taken by the contractor if these requirements are not met. This applies especially when In-Service R&M demonstrations are intended. If graceful degradation is permissible, the demonstration directive should clearly state the lowest level of acceptable performance

203. NEED FOR TRACEABILITY PROCESS

The need for traceability is to document and maintain all records in a database, which should be used as bases to assess the program progress throughout the procurement and the life cycle.

To provide traceability, documentation should be maintained which relates all programme decisions which impact on R&M requirements with the basis of rationale for each decision. There should be a logical relationship between the R&M in the (operational) requirement documents and all programme and contractual documents.

It is particularly important to record the operational justification for the original requirements so that the effect of any subsequent shortfalls can be assessed.

It is also important to note that R&M data can be stored (thus easy to find and traceable!) in a database such as a Product Support Database or Integrated Weapon System Database. Because R&M data are critical to calculate the support required for any given weapon system, specific data elements are available for R&M data storage (for example MTBF, MTTR, FMECA and RCM results). From a Product Support perspective, R&M data are used mostly to carry out Level of Repair and Sparing Analysis.

204. CONFIDENCE STATEMENTS

Military requirements state what performance is required of a system/equipment and should not include statements on how compliance with these Requirements is to be verified. The methodology for the demonstration of compliance with contractual requirements should be included in the procurement specification. Statistical confidence statements are therefore incorporated into the system/equipment specifications, programme plans and test plans. They are an integral part of the test plan for Reliability Qualification Testing (RQT) and In-Service Reliability and Maintainability Demonstrations (ISRMD) which may be based on trade-off studies which also involve decision risks such as Consumer's risk and Producer's risk.

205. SELECTION OF R&M PARAMETERS

A. GENERAL

R&M affect operational and support aspects such as availability, mission success, maintenance and logistic support (see also ARMP-2, paragraph 101, General). Therefore, R&M requirement documents should contain statements which apply to these categories.

The statements should address together the hardware, software and human elements of the system/equipment.

The selection of the R&M parameters should be tailored for each system/equipment. In this respect, the different operational and storage modes of the system/equipment (for instance: Battlefield-Day, peace time operations, long term storage, transportation) have to be considered. Great care should be taken that the selected parameters which describe the R&M behaviour of the system - and consequently the categories mentioned above - are compatible with each other. Therefore, a thorough analysis of all the specified parameters in terms of consistency should be carried out before the requirements are passed to the Contractor.

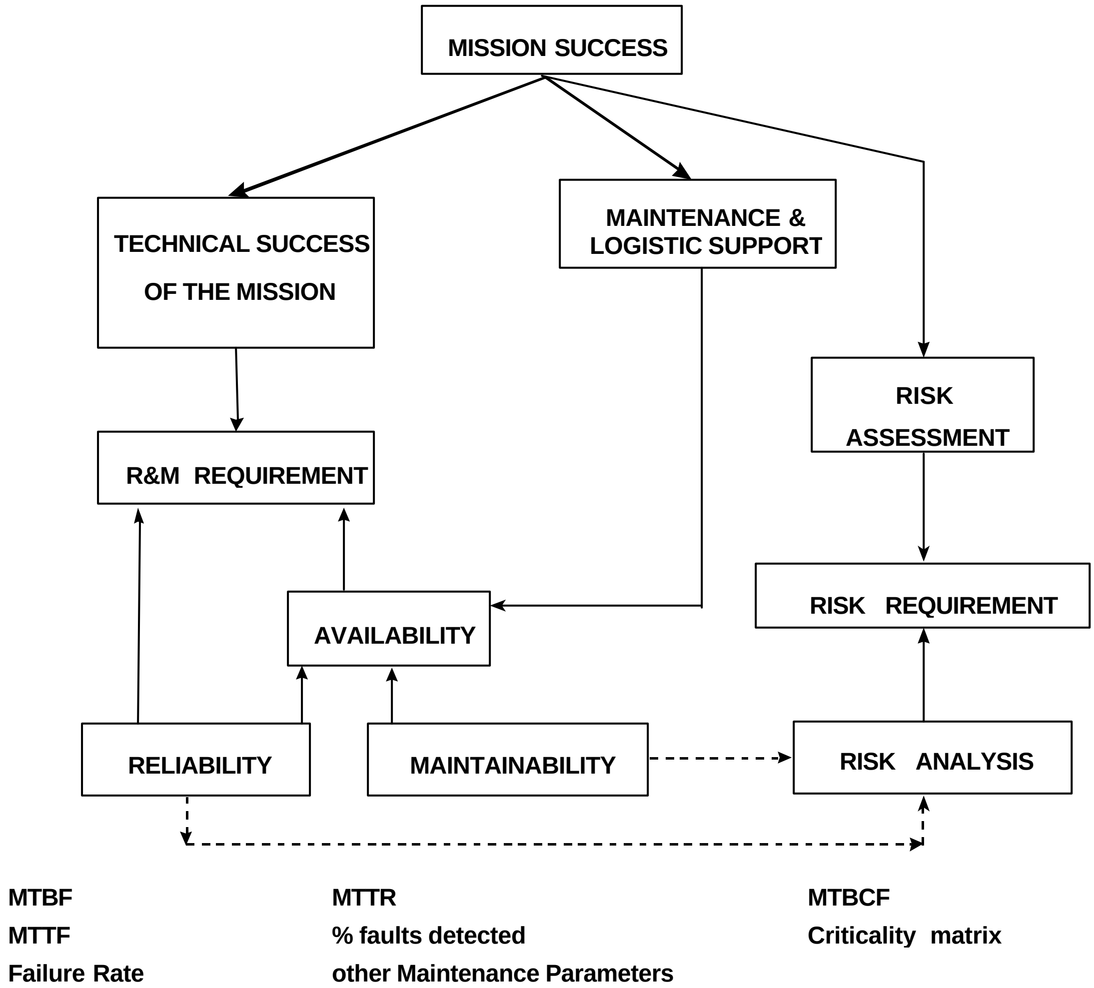

FIGURE 1: RELATIONSHIP BETWEEN OPERATIONS, LOGISTICS AND R&M

Figure 1: Mission success depends upon having a Prime Equipment (PE) available to perform the mission, and no critical failure (ie mission abort) during the mission. The requirement for technical success drives the reliability requirements and the reliability specifications for the PE. The availability of a PE for a mission depends upon adequate maintenance and logistic support (ie: having adequate and sufficient resources such as: spare parts, documentation, support and test equipment, facilities, qualified personnel, etc) to quickly perform the restoration activities. How quickly these actions need to be performed drives the maintainability requirements and the maintainability specifications. Examples of possible R&M parameters are listed in Figure 1.

B. SYSTEM/EQUIPMENT R&M PARAMETERS

Great care should be taken when using R&M parameters in requirement documents for the following reasons:

a. the R&M parameters referred to above do not necessarily apply to all types of system/equipment. The concept of operation or support for a particular system/equipment may dictate that one or more of the R&M parameters is not applicable;

b. the R&M parameters are not the only measures of availability and mission success. Other factors such as Logistic Delay Times and Performance should also be included in any definition of the level of the operational availability and mission success of a system/equipment;

c. the parameters which describe operational and support aspects are interrelated. For instance, mission success can be improved either through redundancy which should cause increased logistic and manpower costs, or changing to higher reliability and reduce materiel requirements. Also, maintenance manpower and logistic support directly affect availability.

B.1 Availability

Availability can be expressed as the probability that the system or equipment used under stated conditions is in an operable and committable state at any given time.

Availability can depend on several parameters. It can be influenced by the R&M characteristics of the system/equipment and, dependent on the type of availability, the logistic support provided, and the required probability of mission success. The system should be designed such that an individual hardware or software failure does not result in a critical failure while operating under pre defined conditions.

The logistics support factors include personnel, training, spares supplies etc.

There are several types of Availability. The two most commonly used are Intrinsic Availability (Ai) and Operational Availability (Ao).

Intrinsic Availability is the probability that the system/ equipment is operating satisfactorily at any point in time when used under stated conditions, where the time considered is operating time and active repair time. Thus, intrinsic availability excludes all free time, preventive maintenance, storage time, administrative and logistic delay times. For continuously operating equipment, it can be expressed as follows (for the steady state case):

$$A_i = \frac{MTBF}{MTBF + MART}$$

where MART is Mean Active Repair Time.

Operational availability is the probability that a system/equipment at any instant in the required operating time operates satisfactorily under stated conditions where the time considered includes operating, corrective and preventive maintenance, administrative and logistic delay time.

Operational Availability may be defined, for the steady state case, as follows:

$$Ao = \frac{OT + ST}{OT + TCM + TPM + ST + ALDT}$$

Where:

OT = Operating Time

ST = Standby Time (time during which an equipment is in a standby mode)

TCM = Total Corrective Maintenance Time per specified time period

TPM = Total Preventive Maintenance Time per specified time period

ALDT = Administrative and Logistic Delay Time

The specification of A_o should be based on the identification of the system/equipment life profile, including the mission and service profile(s).

The specification of Availability should normally be seen as complementing the specification of R&M, but not replacing it. It should be recognised as a characteristic of the combination of the system/equipment R&M and the Maintenance Manpower and Logistic Support that is provided.

If A_o(or any other type of availability) is specified, great care should be taken to ensure that there is no conflict with the required levels of R&M.

Additional reasons for not specifying R&M solely in terms of A_o are:

a. It is insensitive, as an index, to changes in R&M parameters.

b. There are many other factors which determine the value of A_o such as personnel, training and supplies. These frequently affect A_o more than R&M, e.g. long logistic delay times.

c. It is difficult to design for A_o, because of the many factors (e.g. spares provisioning) which are beyond the control of the designer.

d. It can usually be demonstrated only in the field.

Therefore the level of both Reliability and Maintainability should be specified. As stated earlier, Reliability and Maintainability jointly determine the A_i of a system/equipment. It is unwise to specify only A_i because A_i depends only on the ratio of MART/MTBF. Obviously, innumerable combinations of MART and MTBF can yield the same A_i. Therefore, availability specifications should always be accompanied by, at least, reliability requirement(s).

Technical and life cycle cost studies should be performed to optimize the mission success and the operational availability relative to life cycle costs (see figures 2 and 3). Figure 2 illustrates the factors that should be taken into account and figure 3 illustrates the inter-relationship between the various model employed.

For naval requirements, the term Effective Availability is often used. This takes into account the fact that a ship carries its own organic repair and maintenance capability, which can be employed during a mission(often measured in days). The definition of Effective Availability also recognizes the difference between those items which are repairable at sea and those which are not.

Effective Availability is defined as the probability that the ship system is available at any instant during the maximum operational period, taking into account all critical failures, both repairable and not repairable at sea, and preventive maintenance. A critical ship system failure is normally defined for each system or equipment, and usually implied the loss of a specified function.

Effective Availability ($A_{E)}$ can be expressed as the following empirical formula:

$$A_E = 1 - \frac{MART}{MTBCF + MART} - \frac{PMdowntime}{Missiontime} - 0.5 * \frac{Missiontime}{MTTCFnr}$$

Where:

MTBCF	=	Mean Time Between Critical Failures (Repairable at sea)
MART	=	Mean Active Repair Time
MTTCFnr	=	Mean Time To Critical Failures (Not Repairable at sea)
PM downtime	=	Total preventive maintenance downtime for mission

An example of Effective Availability is given at Annex A.

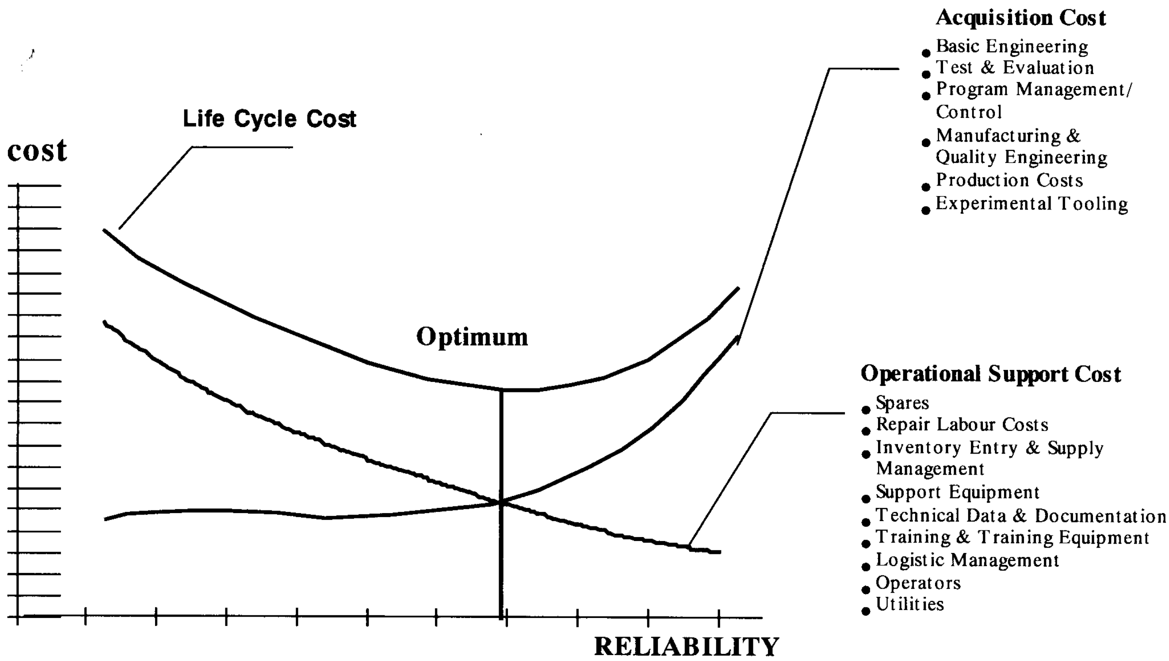

Figure 2: Life Cycle Costs In Terms of Acquisiiton and Operational Support Costs VS Reliability

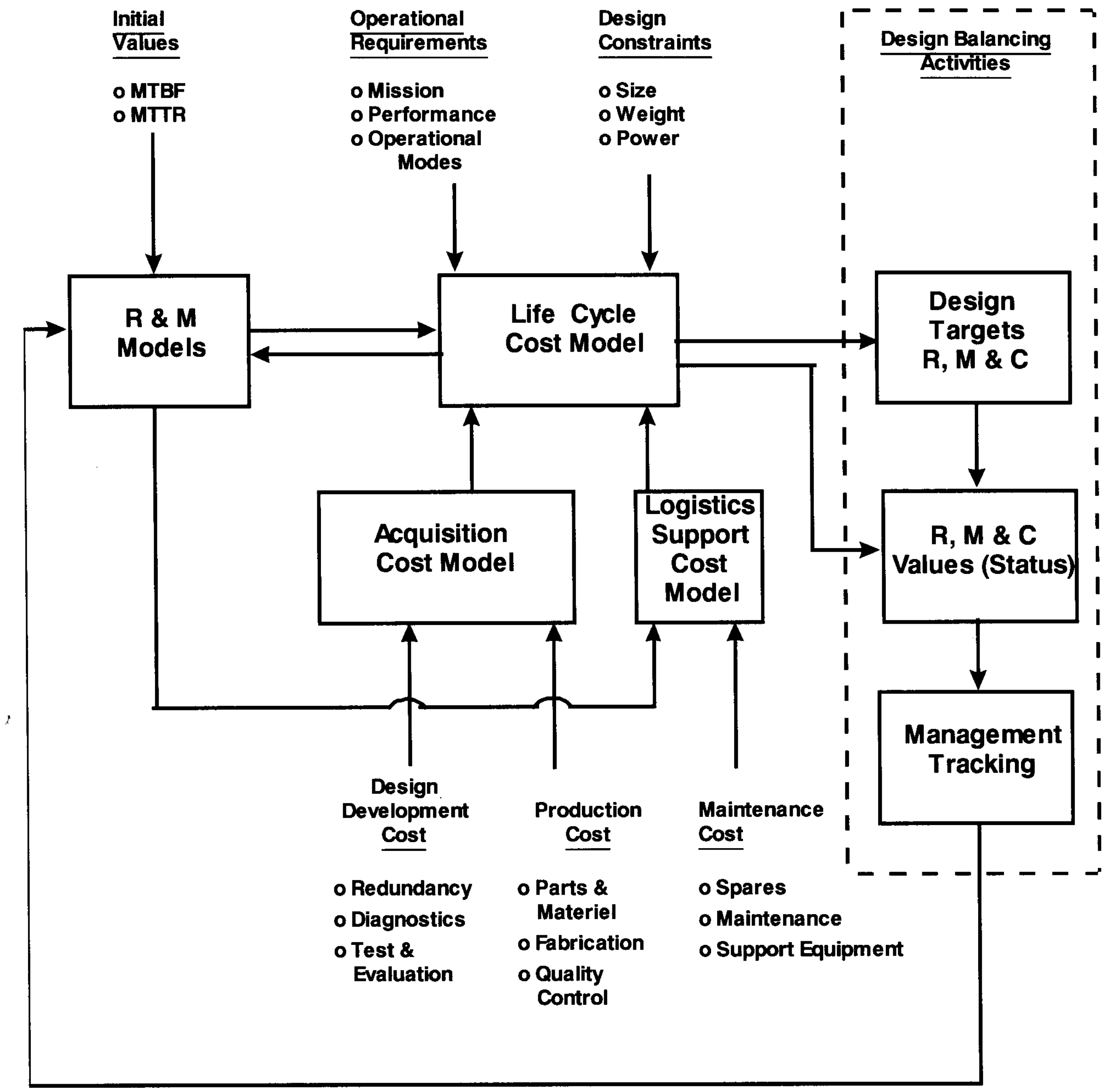

FIGURE 3 : R&M AND COST METHODS

B.2 Mission Success

Mission Success R&M parameters relate to the probability of failures occurring during a mission which would cause an interruption of that mission and to the probability of correcting these failures during the mission itself.

B.3 Maintenance Manpower

In determining the appropriate system/equipment R&M parameters, it is necessary to consider the system's/equipment's intended operations and the maintenance concept (see paragraph 205 of ARMP-2 “R&M Programme management, interfaces and co-ordination”).

Typical parameters used are Mean Time Between Maintenance Actions for reliability, and Direct Man-hours Per Operating Hour for maintainability. All levels of maintenance should be considered in developing the requirements which affect Maintenance Manpower Cost.

It is important to consider Maintenance Manpower Cost constraints in defining R&M requirements. This is because the manpower, and its associated costs, required to maintain a system/equipment are driven by the attainment of those R&M requirements.

Such constraints may be expressed either in terms of money or in terms of number and skill level of personnel.

B.4 Logistic Support Cost

The parameters which influence the Logistic Support Costs of systems/equipment are dependent on both time and money. They address those aspects of R&M which are concerned with the consumption of material. (The consumption of materiel also affects availability by being directly related to materiel demands and the ability of the logistics pipeline to meet those demands).

Parameter examples are Mean Time Between Removals for reliability and Total Parts Costs Per Removal for maintainability.

C. SPECIFYING R&M REQUIREMENTS

The R&M requirements should be specified as the minimum values which meet the purchaser's/user's operational and logistics needs.

C.1 Reliability

To be meaningful a reliability requirement should be specified quantitatively.

There are four basic ways in which a reliability requirement may be defined:

(1) As a Mean Time To Failure (MTTF), for non-repairable items, or Mean Time Between Failure (MTBF), for repairable items. This definition is useful for long life systems/equipments in which the form of reliability distribution is not critical or where the planned mission lengths are always short relative to the specified MTTF or MTBF.

(2) As a probability of survival for a specified period of time. This definition is useful when a high reliability is required during the mission period but Mean Time Between Failure (MTBF) beyond the mission period is of little tactical consequence, except when it influences availability. Furthermore, survival for a specified time is particularly relevant to mechanical systems such as engines

and aircraft structures, where Time between Overhaul (TBO) is a common parameter.

(3) As a probability of success, independent of time. This definition is useful for specifying the R of one shot devices such as the flight reliability of a missile, the detonation reliability of a warhead etc. It is also specified for those items which are cyclic such as the launch reliability of a launcher.

(4) As a Failure Rate "Lambda" (l) over a specified period of time. This definition is useful for specifying the reliability of parts, units and assemblies whose mean lives are too long to be meaningful or whose reliability for the time period of interest approaches unity. It may also be useful for those components whose failure behaviour is time dependent or which are combined in a serial reliability structure.

When writing reliability specifications, aspects such as duty cycles (para 206 A), environmental envelope (para 206 B), failure definitions (para 208) should be taken into consideration.

Where applicable, mission and basic reliability requirements should be separately identified. As failures may also occur during non operational periods, reliability requirements should also take storage and transportation reliability into account. This applies especially to defence materiel which is subject to long term storage, such as mines, missiles, ammunition or torpedoes, or to systems which are subject to frequent transportation.

C.2 Maintainability

The Purchaser/User is concerned with the time it takes from detecting a system/equipment failure to corrective action being completed. Included in this time is not only the time to diagnose the failure and complete the repair, but also the time to obtain the necessary spares and the availability of skilled manpower (Administrative or Logistic Delay Time). These last two aspects are not entirely under the designer's control. They are determined by maintenance policy and life cycle costs which are managed and controlled by Logistics Staff.

Maintainability requirements are often specified by parameters such as Mean Time To Repair (MTTR) or other average periods for maintenance actions (preventive and corrective). In this context, the mean active repair time component only (sometimes called MART) should be considered, excluding Logistics delay time. It is essential that the relationships between the single parameters and the different types of time (Figure 4) are clearly defined and that the different specified parameters are not contradictory.

However, these may not fully address all maintainability characteristics. For example, time to repair parameters generally follow a log-normal probability distribution. Therefore, when establishing parameters, it may be useful to specify two points on a log-normal distribution. Annex B - QUANTIFYING MAINTAINABILITY REQUIREMENTS gives further information about the use of the log-normal distribution.

C.3 Combat Resilience

During a conflict the natural environment includes battlefield loads. Therefore, the following requirements should be specified on the basis of the user requirements:

(1) sufficient combat resilience (e.g. by armour protection, shielding, relocation of sensitive components to protected areas, easy replacement of particularly

vulnerable components etc.).

(2) quick maintenance even at the cost of limited mission accomplishment.

Figure 4 shows time relationships.

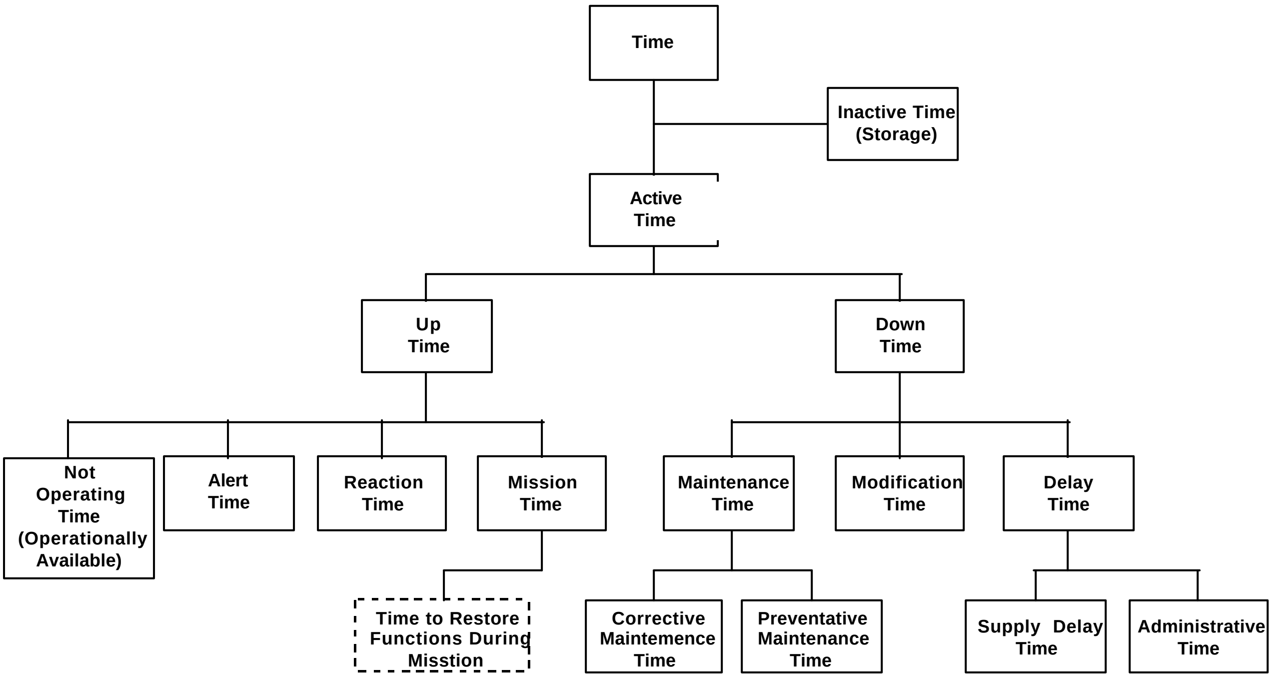

FIGURE 4: TIME RELATIONSHIP

C.4 Testability

The use of Built-In-Test (BIT), Built-In-Test Equipment (BITE) or External Test Equipment (ETE)is an extremely useful means of improving the maintainability and mission effectiveness. The requirements for system test (BITE, BIT, ETE) should include statements specifying:

(1) FDR (Failure Detection Rate) - the percentage of total number of failures which should be detected and indicated;

(2) FAR (False Alarm Rate)- indication of a failure where no failure exists such as operator error or test deficiency;

(3) The indenture level (i.e. Line Replaceable Unit, module) to which a specified percentage of failures should be isolated; and

(4) that 100% of safety critical systems should be continuously monitored, failures being detected and indicated at the time of occurrence by BIT.

It is highly recommended that specialist advice is sought when formulating testability requirements, especially where software is involved. No single failure may be safety critical.

It is important to note that Reliability, Maintainability, Availability and Testability parameters are inter-linked. When it is necessary to specify R&M, A and T requirements, care should be taken to ensure consistency between them.

	% Capability	Repair Level
Fault Detection (All Means)	90-100 100 100	1st line 2nd line 3rd/4th line
Fault Detection: BIT & ETE **BIT & ETE** **BIT & ETE**	90-98 95-98 95-100	1st line 2nd line 3rd/4th line
Fault Isolation Resolution		
Three or fewer LRUs	100	1st line
One LRU	90-95	1st line
Four or fewer SRUs	100	2nd line
One SRU	75-85	2nd line

Notes:
- LRU - Line-Replacement Unit (e.g., Box, Power Supply, etc.)
- SRU - Shop-Replaceable Unit (e.g., Circuit Card)
- BIT - Built-in-Test
- ETE - External Test Equipment
- 1st line - Also equivalent to Organizational
- 2nd line - Also equivalent to Intermediate
- 3rd and 4th line - Also equivalent to Depot

TABLE 1: EXAMPLES OF TESTABILITY REQUIREMENTS

206. DUTY CYCLES AND ENVIRONMENTAL ENVELOPE

The duty cycles and environmental envelope for a system/equipment should be described.

The description should include all situations in the life profile of a system/equipment from the time of delivery until the time of disposal, or in the case of a one-shot item, until it has accomplished the required mission.

A. DUTY CYCLES

Time is essential to the quantitative specification of reliability because it is the independent variable in the reliability function. The usage should be clearly stated at the outset of any requirement as it heavily influences the selection of an appropriate form and time interval for the reliability statement.

Usage or duty cycles usually differ between wartime and peacetime scenarios and this can have a significant effect on reliability, availability, logistic support costs and mission success criteria.

In such cases different usage/duty cycle statements should be made for each scenario.

For each phase of the mission profile, the system/equipment functions have to be considered through a functional analysis.

Some typical system/equipment functions are:

(1) structural support;

(2) navigation and guidance;

(3) attitude control and stabilisation;

(4) electric power;

(5) Propulsion;

(6) Communication and telemetry;

(7) Command and sequencing;

(8) Environmental control, and

(9) Terrain following.

For those cases where a system/equipment is not required for continuous operation, the total anticipated time profile or time sequences of operation should be defined either in terms of duty cycle or profile charts. Usage or duty cycle profiles should identify whether the system-equipment is in an active, standby or storage (inactive) role during each phase of the mission.

An example is given, in Table 2, which shows an operational sequence for a hypothetical Fighter Aircraft Mission.

The mission profile and utilisation data should allow the determination of the duty cycle imposed on the system/equipment during the intended operational use.

B. THE ENVIRONMENTAL ENVELOPE

The system/equipment may have to be stored, transported and operated in widely different conditions. It may experience extreme climatic conditions concurrently with induced environmental conditions arising from the service applications.

Some typical system/equipment parameters are:

(1) pressure;

(2) thermal radiation;

(3) acceleration;

(4) humidity;

(5) corrosive atmosphere;

(6) vibration and acoustic noise;

(7) shock;

(8) electromagnetism, and

(9) sand and dust.

However, it is usually difficult to define the complete combination and variation of conditions, which each system/equipment is expected to meet in service use. It is therefore necessary to utilize standards (see ARMP-3) which specify repeatable environmental conditions, as starting points and then modify them with information obtained from a detailed analysis of the use of the system/equipment. Table 2 provides an example of an analysis of a system/equipment environment.

The above environmental analysis may be addressed in the system/equipment specifications and other R&M related documents. This analysis should be used in test planning to ensure realistic test environments.

For each phase of duty cycle, the environmental condition can be classified as follows:

(1) normal operating environment: the range of environmental conditions encountered during normal service operations. Within this environmental range, the equipment should function without failure;

(2) design Limit environment: The worst environmental conditions encountered during normal service operations. Performance may be degraded, but within safety limits. Performance should return without degradation when the operating environment returns to normal;

(3) extreme environment: Environmental conditions which exceed the Design Limit environment. Performance may be degraded permanently, but without catastrophic failure. Risk and safety analyses for this environment are essential.

MISSION PHASES	TAXI	TAKE-OFF	CRUISE	ACCELERATION	COMBAT	DESCENT	LANDING
MISSION/ENVIRONMENTAL PARAMETERS							
Duration of Phase	5 min	5 min	30 min	5 min	5 min	5 min	5 min
Duration total	5 min	10 min	40 min	45 min	50 min	55 min	60 min
Altitude (1000 ft)	0	0 to 0.5	20	20 to 30	10 to 40	40 to 3	3 to 0
Mach Number	0	0 to 0.4	0.8	0.8 to 1.7	2.0 to 0.8	0.8	0.3 to 0
q (aerod press (psf)	-	-	550	620	1800	450	-
Vibration (g^2/Hz)	0	0.002	0.0012	0.002	0.003	0.004	0.002
(120-200 Hz)							0.006
Temperature°C Extreme (Hot day/Cold day)	75°C/-54°C°	56°C/-50°C	56°C/-50°C	5°C/-54°C	93°C/-26°C	71°C/-54°C	71°C/-54°C
Humidity	Dewpoint 31°C or greater						
SYSTEM/EQUIPMENT FUNCTIONS							
Avionic Functions							
Attack & Identification			x	x	x	x	x
Defensive Aids			x	x	x	x	x
Navigation		x	x	x	x	x	x
Communications		x	x	x	x	x	x
Displays & Controls		x	x	x	x	x	x
Armament	x						
Armament Control					x		
Carriage, Installation & Gun					x		
General Systems Functions							
Flight Control		x	x	x	x	x	x
Secondary Power	x	x	x	x	x	x	x
Hydraulics Supply	x	x	x	x	x	x	x
Electrical Supply	x	x	x	x	x	x	x
Environmental Control	x	x	x	x	x	x	x
Landing Gear Operations	x	x					
Fuel Supply	x	x	x	x	x	x	x
Life Supply			x	x	x	x	
Propulsion	x	x	x	x	x	x	x

TABLE 2: MATRIX OF ENVIRONMENTS, FUNCTIONS AND MISSION PHASES FOR A HYPOTHETICAL FIGHTER AIRCRAFT MISSION

207. MAINTENANCE CONCEPT

The maintenance concept is a series of statements and/or illustrations defining criteria covering maintenance lines (i.e. how many should be used), major functions accomplished at each line of maintenance, effectiveness factors (Mean Time Between Maintenance Action, Mean Time To Repair, Maintenance Man-hours/Operating Hour, Cost per Maintenance Action, etc.) and primary logistics support requirements. The maintenance concept is defined at the programme inception and is a prerequisite to systems/product design and development. The maintenance concept takes operational and performance specifications and translates them into goals for maintainability and supportability as illustrated in Figure 5. Each repair option is evaluated in terms of an appropriate effectiveness figure of merit and life cycle cost. Input data is based on experience obtained from similar systems as projected into the new operational environment. The final maintenance concept should be based on the relative merits of each option when compared on an equivalent basis.

As an example, the system availability or operational readiness is specified, along with some usage data (i.e., missions/mix of missions/number of mission per year, etc.). This establishes baseline reliability, maintainability and availability criteria. Likewise, the maintenance concept may define support facility requirements, optimization of affordability or the number of maintenance personnel required. For example, it might be decided early on in a programme that the operator should be the first line maintainer on board ship. This means that the maintenance concept should direct the designers of the system to accommodate this requirement. Built-in-test equipment, performance monitoring systems, redundant circuitry, degraded performance abilities or easily replaceable modules are possible ways to meet this requirement. The maintenance concept should also emphasize any accessibility requirements for maintenance, as well as the need for standardization of tools, hardware or software and the use of NBC clothing if required. In some cases, requirements for safety, technical documentation, standard electrical connectors and a whole host of other items may be involved in the same project and also with the customer who has an opportunity to reject any of the maintenance concept ideas at an early stage.

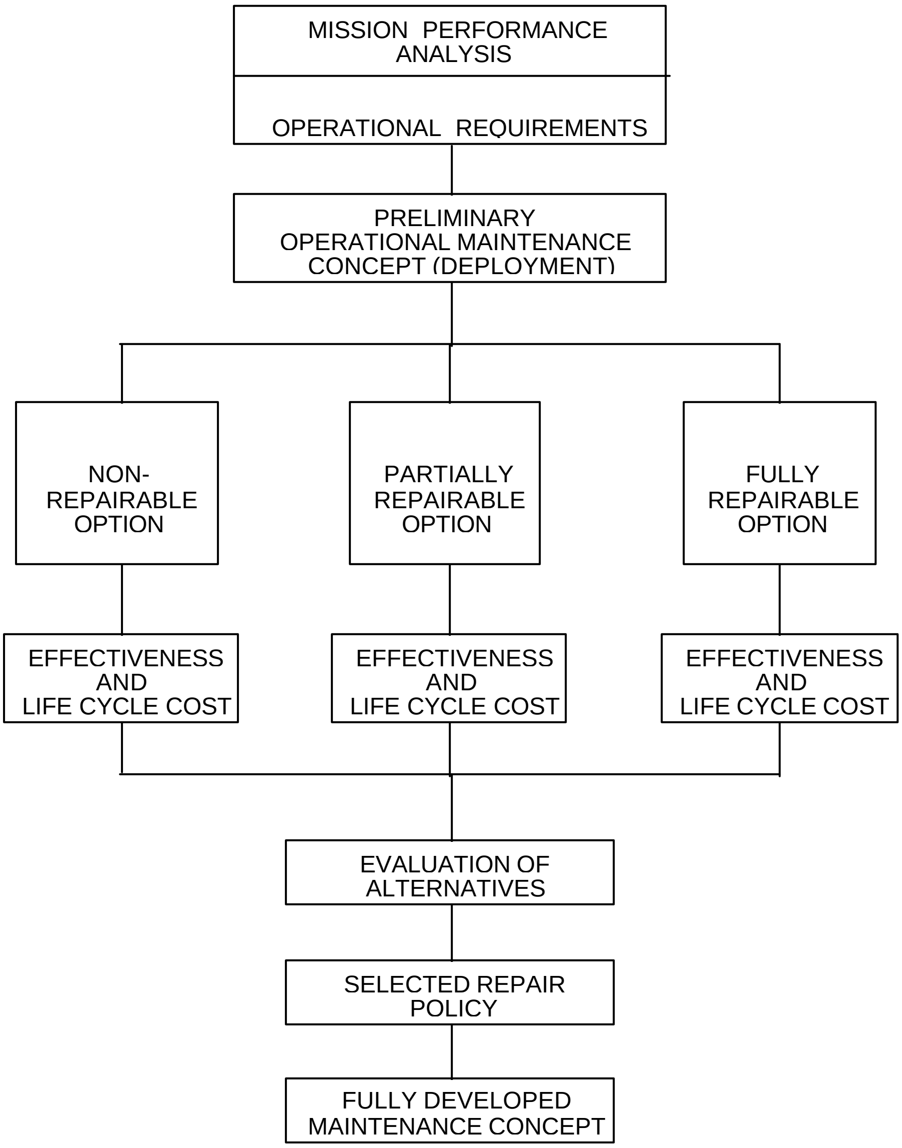

FIGURE 5: MAINTENANCE CONCEPT DEVELOPMENT

While the maintenance concept is a key factor in the design process of a system or equipment, the actual planning for day-to-day maintenance does not start until much later in the LSA process and culminates in the development of a Maintenance Plan.

208. DEFINITIONS OF FAULT AND FAILURE

A fault is any non conformance which requires unscheduled maintenance action to correct it, whilst a failure is a loss of function (for full definition, refer to ARMP-7). Therefore clear, unequivocal definitions of fault and failure should be established for the system/equipment in relation to its functions and performance parameters. This is important in terms of providing a contractual framework acceptable to both the purchaser and the contractor for the proper accounting of faults and failures; from there, contractually meaningful R&M data can be derived. Any contract should clearly state agreed failure definitions and specify any conditions under which faults are not the contractors liability such as battle damage, operations outside agreed limits, and user negligence.

Successful system/equipment performance should be defined and expressed in terms which should be measurable during demonstration testing, in particular during In-Service Reliability, Maintainability and Testability Demonstrations which are not conducted under laboratory conditions.

Parameter measurements should usually include both “go/no-go” performance attributes and variable performance characteristics.

209. SOURCES OF INFORMATION

The preparation of Requirement documents involves consultation with many sources of information.

Specialist engineers can advise on future technology developments and their possible impact on the system under consideration, identify problems with similar systems/equipments currently in service and suggest how these could be prevented, and provide specialist advice on service engineering and maintenance concepts.

The User should be consulted for information on systems/equipments currently in service. Similarly, advice should be taken from specialist R&M branches within the procurement agency. Various kinds of data are required for R&M planning and control during the design, development, test and evaluation process and servicing. The required information is of two kinds, operational information and maintenance planning information. A list of such data, which is not exhaustive, is as follows:

A. OPERATIONAL INFORMATION

(1) mission reliability;

(2) required mission duration;

(3) reaction time;

(4) availability;

(5) planned utilisation rate;

(6) required turn around time;

(7) operational and maintenance environmental conditions;

(8) basic reliability, and

(9) usage Time during Peace Time.

B. MAINTENANCE PLANNING INFORMATION

(1) time between scheduled maintenance functions which is allowable for mission accomplishment; this activity should be performed for each applicable level of preventive maintenance;

(2) mean down time allowed to return the equipment to serviceable conditions;

(3) the maintenance concept;

(4) the degree of repair desired by component assembly replacement;

(5) test and check-out methods;

(6) reliability after storage;

(7) maintenance staff level and skills; and

(8) spares ranging.

In establishing the information for the new system/equipment, usage and maintenance data/information from previous similar systems/equipment can be very helpful.

For example:

(1) operating environment;

(2) duty cycles;

(3) failure histories;

(4) storage environments; and

(5) maintenance Concepts and Plans.

210. SAFETY AND ASSOCIATED RISK ANALYSIS

This paragraph is not intended to describe general safety criteria, but to highlight those R&M criteria which are safety related.

A reliability requirement should define the probability of mission success. A safety requirement should define the probability of occurrence of a hazardous event. Therefore, when setting reliability requirements, the safety requirements should be taken into account. Indeed, safety requirements may determine the minimum acceptable level of reliability. For example, an armament safety switch may have an allowable hazard rate of 1 per 10^6 flying hours. The design and reliability analysis of the switch should, therefore, take this hazard rate into account.

Similarly, a Mission Criticality Analysis should be performed for the weapon system functionality.

211. R&M PROGRAMS

Once the R&M requirements are available, an approach to achieve R&M programs should be established. The approach should identify specific actions necessary to enable the project-related requirements to be met. The scope of actions should be based on the risk analysis and the possible cost savings during the life of the equipment. They should address the following areas:

a. evaluate the requirements;

b. ensure compliance with these requirements;

c. demonstrate compliance with these requirements;

d. maintain the achieved R&M standard during procurement and In-Service;

e. ensure information feedback for follow-on projects;

f. establish data collection and evaluation procedures; and

g. prepare and present reports, results and documentation.

R&M should be verified and approved by the purchaser. Since the scope of the planned approach to achieve R&M requirements has an essential influence on the costs, the price-relevant portions (i.e. R&M activities and R&M demonstrations) should be established at the time of contract award.

CHAPTER 3

DEVELOPMENT OF THE R&M CONTENT OF THE Phase Armaments Programming System (PAPS) MILESTONES

301. GENERAL

This chapter gives a brief description of the actions to be taken during the different phases of a weapon system life cycle to develop the R&M content of the PAPS milestones.

The complete PAPS process, with all the relevant phases and milestones, is shown in Figure 6.

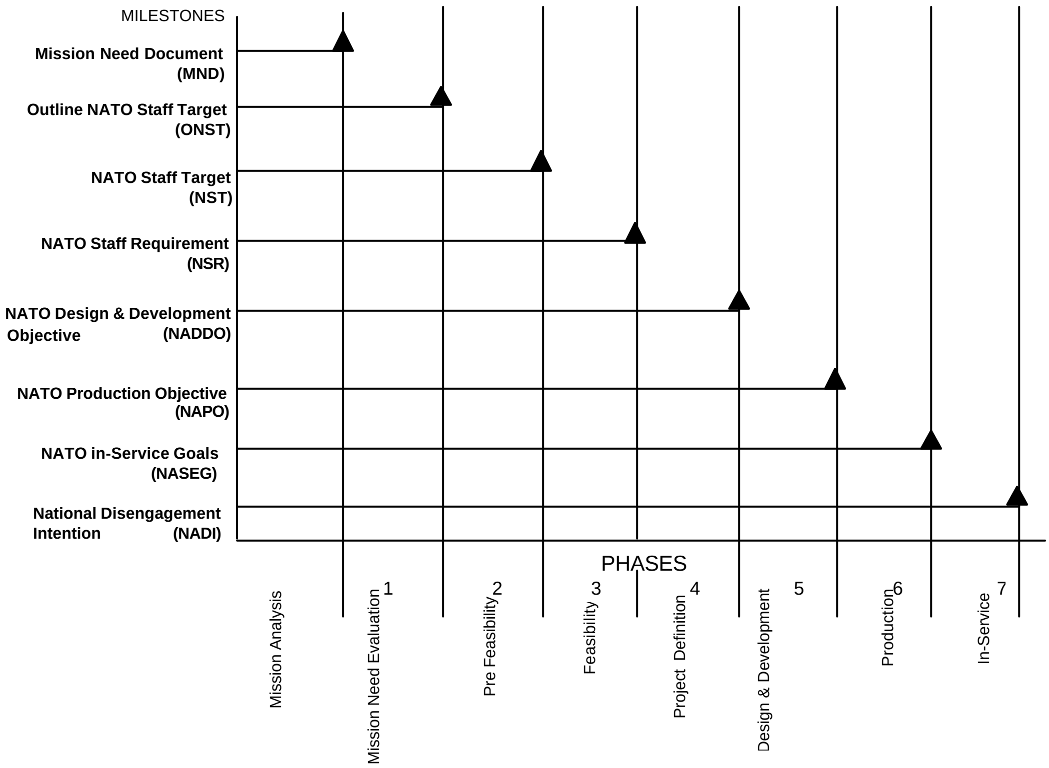

FIGURE 6: PAPS PHASES AND MILESTONES

The Mission Need Document (MND) and the Outline NATO Staff Target (ONST) are both rather broad outlines of the function and desired performance of a new system/equipment. The ONST should contain R&M requirements in general operational terms.

302. THE R&M CONTENT OF THE NATO STAFF TARGET

A. PRE-FEASIBILITY STUDIES

It is essential that, from the start of a project, the R&M requirements are carefully studied in the context of the total operational requirements for the system/equipment, and that early in-depth consideration is given to the project objectives. Unrealistic aims or ambiguities can lead to expensive and time consuming waste of effort in later stages.

It is crucial that during the earliest phase of a programme, a group of technical and essential participants is formed to exchange information and ideas and define preliminary requirements which are in compliance with the operational and logistics needs and objectives. As a minimum, this group should consist of the following:

(1) the User;

(2) the Maintainer;

(3) the Service and Procurement R&M specialists;

(4) the Project Manager; and

(5) the Project Integrated Logistic Support (ILS) Manager.

The R&M group may agree to R&M requirements consistent with the operational requirements, logistics support objectives, risks and life cycle cost considerations.

In support of these discussions, preliminary studies should be carried out to define mission objectives, specific mission characteristics (environment, tactics, duty cycles), mission implementation constraints and system/equipment performance and environmental profiles. Sensitivity analyses should be carried out. The development of the R&M objectives in the categories defined in paragraph 205B, should be established by compiling and evaluating:

(1) the system/equipment function profile which shows, on a time scale, all the system/equipment level functions that should be performed to accomplish the mission under its specified conditions;

(2) the system/equipment environmental profile which shows on a time scale the significant properties of the environment (and the limits) which are likely to have an effect on the operation or survival of the system/equipment.

Some typical system/equipment functions and environmental parameters are listed in paragraph 206A and B.

B. FORMULATION OF THE R&M CONTENT OF THE STAFF TARGET

The R&M section of the Staff Target should be comprehensive and unambiguous. It should include:

(1) a statement of quantitative R&M objectives in the 4 categories, as applicable, together with the basic assumptions on which they are founded;

(2) a statement on the maintenance policy and procedures envisaged, together with particular maintainability features required, including interchangeability.

303. THE R&M CONTENT OF THE NATO STAFF REQUIREMENT

A. FEASIBILITY STUDIES

Before the Staff Target is accepted for action it is important that its R&M objectives are assessed with the other main objectives of the project and that any ambiguities in the stated objectives are resolved. As a part of these studies, the organization performing the feasibility studies is required to look at the feasibility of the objectives quoted above. During the feasibility studies the Staff Target should be re-examined and, if necessary, revised.

The revised targets should then become formal requirements in the Staff Requirement.

They should be realistic and feasible and they should be optimised, as far as possible, for operational effectiveness and minimum life cycle cost. The feasibility study starts with the determination of the system/equipment functional and related environmental profiles, which set the stage for a series of iterative trade-off studies.

In-service R&M levels of current systems/equipment operating in similar environments then are examined. Where possible, specific problem areas at the system, sub-system or equipment level are evaluated for the achievement of the Staff Target, for assessment of the projected operating and support cost and for potential for Maintenance Manpower and Logistic Support cost reduction.

In order to establish agreed R&M clauses for the Staff Requirement the purchaser(s)/user(s) should be involved in trade-off studies concerning the major parameters of systems/equipment, such as the:

(1) time and resources required for the design, development and production;

(2) in-service support resources;

(3) overall system/equipment performance;

(4) date of entry into service;

(5) level of risk associated with new technologies; and

(6) mission performance.

B. FORMULATION OF THE R&M CONTENT OF THE NATO STAFF REQUIREMENT

The Staff Requirement incorporate a refined statement of the R&M requirements based on the results of the feasibility studies.

R&M requirements should be defined in quantitative terms, but not in such a way as to preclude design options which would otherwise attain the desired results. In general, the overall system R&M requirements and the environmental and operating conditions should be specified. In special cases, the R&M requirements for major sub-systems may also be specified. It is important at this stage to include clear definitions of what constitutes mission success and from this clear definitions of mission failure can be derived. For logistic or basic reliability and maintainability, definitions of fault and failure specific to the project may need to be defined.

The Maintenance Concept and Requirements should be stated together with any constraints on numbers and skills of men, tools, test equipment, access and spares holdings.

304. THE R&M CONTENT OF THE NATO DESIGN & DEVELOPMENT OBJECTIVE AND THE DESIGN & DEVELOPMENT SPECIFICATION

A. PROJECT DEFINITION PHASE

The aim of the project definition phase is to develop further details of the system/equipment specification, sub-systems specifications and design and manufacturing approaches.

The specifications should include quantitative and qualitative R&M requirements which are traceable to the established R&M statements.

They also include an R&M programme which is to be established and conducted by the contractor.

ARMP-2 provides guidance on what to include in the R&M specifications and/or contract.

An R&M group should be established, chaired by the Project Manager, to undertake the following tasks:

(1) to assist the Project Manager in defining the R&M aspects of the Procurement Specification including the assessment criteria for the tender proposals and the method of demonstrating the achievement of R&M requirements to acceptable statistical levels of confidence;

(2) to recommend amendment or adoption of formal R&M plans, programmes and trials, prepared by the contractor;

(3) to ensure that the relevant details from these plans and programmes are included as integral parts of the overall development cost plans;

(4) to recommend verifiable milestones to monitor progress in R&M;

(5) to monitor all R&M aspects which result from development activities and user trials, as well as all maintainability and testability assessments;

(6) to agree an assessment of achieved R&M levels for acceptance purposes;

(7) to ensure trade-off studies between reliability, availability and life cycle costs are undertaken, with the aim of striking the optimum balance.

B. FORMULATION OF THE R&M CONTENT OF THE NATO DESIGN & DEVELOPMENT OBJECTIVE AND THE DESIGN & DEVELOPMENT SPECIFICATION

The result of the Project Definition phase is the NATO Design & Development Objective (NADDO), which is an agreed set of specifications, and the proposed programme for the Design & Development. The Design & Development Specification contains the more detailed technical information which is to be used by the design and development engineer. The R&M requirements in the Design & Development Specification should be stated in enforceable quantitative terms.

The NADDO and the Design & Development Specification should include the R&M output from the Project Definition phase and should normally include, but not necessarily be limited to:

(1) quantitative R&M requirements at system, sub-system and equipment level, which are traceable to the Staff Requirement;

(2) an initial R&M Programme for the development and production phases which should form an integral part of the overall development plan with cost and time scales embodied in it. This plan should address together hardware. software and the human elements of the system/equipment;

(3) initial identification of lifed items, long lead time items and critical items to determine the need for preventive and corrective maintenance;

(4) an initial estimate of the need for special test equipment (built-in or separate) and other special facilities including those for software testing, together with their support costs.

The R&M group formed in accordance with paragraph 304A should continue to advise the Project Manager and in addition has the following functions:

(1) to provide advice to both Project Manager and User on any proposed amendments to project time scales or targets subject to contract and cost factors. To bring to the attention of the Project Manager and User any conflict found to exist between the various R&M requirements and detailed performance requirements, or where significant shortfalls become apparent, and to discuss the in-service effects of any amendments;

(2) to assess the results of ISRMDs, where these are called for as a part of the equipment procurement strategy.

305. THE R&M CONTENT OF THE NATO PRODUCTION OBJECTIVE AND THE PRODUCTION SPECIFICATION

A. DESIGN & DEVELOPMENT PHASE

Detailed engineering, prototype fabrication and full validation of systems and auxiliary equipment are conducted in this phase. It also includes complete system/equipment integration and test to establish conformance to specifications and readiness for deployment.

The NATO Production Objective (NAPO) is one product of the Design & Development phase. It contains sufficiently detailed manufacturing and logistics data to permit the Production phase to proceed.

The Production Specification, which consists of the more detailed technical specifications, should contain R&M requirements to ensure that the design R&M results are not to be degraded by the production process. During the Design & Development phase the R&M specification for production should be adjusted and refined as necessary.

B. FORMULATION OF THE R&M CONTENT OF THE NATO PRODUCTION OBJECTIVE AND THE PRODUCTION SPECIFICATION

The NAPO and the Production Specification should specify:

(1) the quantitative and qualitative R&M requirements;

(2) the R&M programme plan;

(3) the test conditions, methods, acceptance criteria and decision risks to be applied during production in order to demonstrate that the level of R&M achieved has been maintained during production;

(4) the special processes, intended to safeguard R&M during production, which are to be established and evaluated during development;

(5) the requirement for demonstrations or other R&M verification/guarantees;

(6) demonstration plans (if required); and

(7) critical areas of the R&M programme and significant cost drivers such as:

   (i) corrective action and validation; and

   (ii) requirement for identification of critical components.

306. THE R&M CONTENT OF THE NATO IN-SERVICE GOALS

A. PRODUCTION PHASE

Early in the production phase, the NATO In-Service Goals (NISEG) are written. They should describe the in-service R&M goals (non-mandatory requirements). The remaining task (for the Purchaser) consists of verifying the production processes and verifying the achievement of the R&M requirements.

B. FORMULATION OF THE R&M CONTENT OF THE NATO IN-SERVICE GOALS

The NISEG should normally include:

(1) a statement of the system/equipment requirement including R&M;

(2) in-service data collection requirements; and

(3) the requirements for an "In-Service R&M Assessment Plan".

C. IN-SERVICE PHASE

The In-Service phase has been defined as the operational utilisation of the system/equipment. During this phase the operational values of the system/equipment are compared with the original requirements. Where necessary, modifications to improve R&M are initiated. Minor modifications, in most cases, can only result in minor improvements to the system/equipment and its intrinsic R&M. If a considerable modification, or modification package, is proposed or needed - which by definition requires an element of re-design - then it is important to return to an earlier phase of the procurement cycle and repeat the R&M processes. This may involve returning to the stage of the NATO Staff Requirement and assessing the impact of any changes. It is only in this way that proper risk assessments and realistic cost benefit analysis can be made.

D. R&M CHARACTERISTICS AND IMPACT ON THE MAINTENANCE PLAN

Monitoring of R&M characteristics contained within a maintenance plan is very important because these performance values change as the system matures. The amount of change can have a great deal of influence on system support features. For example, if the predicted MTBF proves too optimistic, there is a danger of under-sparing. Too pessimistic, and the opposite is likely to result. The importance of the influence of predicted R&M characteristics cannot be overstated.

ILS activities may be affected if a low or high failure rate is predicted. Consider the case where a low failure rate is anticipated. If it is considered low, the decision could very well be that, because of the low number of anticipated arising, it would not be cost effective to train technicians to maintain the equipment, rather it could be considered more economical to repair the item at third line in the event of a problem. This could lead to potential savings in special tooling, test equipment, training, publications, facilities, etc. If the prediction proves to be erroneous, then remedial action to furnish the proper support would have to be taken, probably at a much higher cost.

EXAMPLES OF QUANTITATIVE R&M REQUIREMENTS

1. INTRODUCTION

In the examples given below, the numerical values are for illustrative purposes only and should not be taken as guidance for actual Staff Requirements. For each example, an indication is given of the contracting strategies that could be used.

2. R&M AS STATED IN STAFF REQUIREMENTS

A. RECONNAISSANCE HELICOPTERS

The probability of a single helicopter completing a 2 hour mission [reference could be made to a detailed “mission profile” document or attachment] without failure is to be at least 95%, where a failure is any event which adversely affects the mission.

95% indicates that the user is prepared to accept no more than 5% probability that a mission cannot be successfully completed. This figure is derived from wargaming (computer simulations), attrition studies and takes into account the probability that the mission can be achieved by other means.

When deployed in groups of three, each sortie may consist of two aircraft flying a 2 hour mission. Up to 5 sorties are required in each battlefield day. There shall be at least 90% probability of successfully completing 5 battlefield days.

The structural life of the airframe shall be at least 7000 hours and the Time Between Overhaul of the engine and transmission shall exceed 1000 hours at entry into service.

Corrective maintenance at 1st line should be by replacement only. All tasks at 1st and 2nd line should be completed using a maximum of 3 maintenance personnel.

B. MISSILE

The reliability of the missile, given a successful launch, shall be 99%. The reliability of the missile, from factory to target shall exceed 90% (reference could be made to a detailed “sequence mission profile” document or attachment) over a missile life of 10 years. No preventive maintenance shall be required during the missile life.

3. R&M AS SPECIFIED IN PROCUREMENT DOCUMENTATION

The helicopters shall not generate more than 25 mission affecting failures per 1000 flying hours. The (basic) logistic fault rate (including faults discovered during scheduled maintenance) shall not exceed 400 per 1000 flying hours.

95% of all faults shall be repairable at 1st /2nd line within 2 hours. The Mean Active Repair Time shall not exceed 45 minutes, using a maximum of 3 maintenance personnel.

The logistic R&M requirements are based on the maximum tolerable maintenance burden, derived from the available manpower and materiel at the various lines of maintenance. They are often justified on life cycle cost grounds. The mission reliability requirement is generated from the 95% probability of completing a 2 hour mission.

Using a maximum of three persons and an engine change unit, engine change time should not exceed 45 minutes.

A contracting strategy for the above requirements could be based on an in-service demonstration period of several thousand flying hours (approximately 1 year elapsed time), supported by a separate set-piece demonstration of maintainability requirements if required. In the event of failing to pass the demonstration, the contractor could be required to undertake corrective action at his own expense, including retrospective modification of those aircraft already in-service. Additionally, the contractor could be required to provide fixed price spares support, based on the R&M requirements, until compliance with the specification is satisfactorily demonstrated.

The Prime Contractor may further break these requirements down into sub-system requirements such as: The radio shall have a design life of 10 years (assuming 500 operating hours per year*)* with a minimum MTBF of 5000 hours.

4. EXAMPLE OF AVAILABILITY REQUIREMENTS - SELF PROPELLED HOWITZER

A 24-hour battlefield day consists of: an operating time of 19.2 hours (including 2 hours of preventive maintenance), an average number of 300 rounds fired and a total tactical movement of 125 km. The intrinsic availability over a battlefield day is to be at least 80%. Additionally, the howitzer shall meet a mission reliability requirement under the above conditions of at least 60%, where a mission failure is defined as an event which degrades any specified mission requirement by more than 20%.

A contracting strategy could be to demonstrate the reliability by trials at the end of development and to assess the maintainability by separate trials. Both values should result in a statement of the intrinsic availability. In the event that the equipment fails to achieve these requirements, the contractor should be required to undertake corrective action at his expense and demonstrate that the corrective action is effective, by further trials if required by the purchaser.

5. ARMOURED TRANSPORT VEHICLE

The reliability of the vehicle is expressed in the following terms, according to the conditions under which it is operated.

A. MISSION RELIABILITY

An overall mission reliability of 0.90 is required. The mission reliability should be against the 48 hour battlefield mission for the vehicle. The battlefield mission includes power on/off cycles, travelling on road and cross country and a number of rounds to be fired and should be specified in detail.

B. INHERENT RELIABILITY

The MTBF for the complete system, with reference to "peace-time" employment profile, shall be at least 450 operational hours. Hereby, only failures or faults preventing the completion of the mission are to be taken into account.

C. RELIABILITY ON REMOVAL FROM STORAGE

The rate of failure on removal of the vehicle from storage should be, at the most, 10 % of the failure rate while in use (as defined under the Operational Requirements of the Equipment).

Note: This specification of reliability refers to the removal from long-term storage where precautionary actions have been taken.

D. BASIC RELIABILITY

The vehicle is to achieve a basic reliability figure of 40% against a specified typical mission profile. For reliability assessment purposes the following failure criterion is to be used: "A maintenance relevant or basic failure is defined as an unsatisfactory equipment condition which requires unscheduled (corrective) maintenance to restore the equipment to its full peacetime repair standard; this excludes preventive maintenance, but includes unscheduled maintenance activities found to be necessary during scheduled maintenance". Failures discounted from any reliability assessment are either those of components beyond their specified life or those caused through misuse, accident, human error or maintenance not in accordance with defined procedures.

A contracting strategy could be to demonstrate basic and mission reliability during trials at the end of development and to apply in-service reliability demonstrations for the assessment of the inherent reliability requirement. For an assessment of the storage reliability requirement, suitable databases could be consulted.

6. COMMERCIAL TRANSPORT AIRCRAFT AVAILABILITY REQUIREMENTS

The contractor shall maintain a 90% schedule reliability of the aircraft. Schedule reliability is defined as scheduled flights started and completed without any interruption chargeable to a primary (not secondary or consequential) malfunction of an aircraft system or component resulting in cancellations, air turnbacks, diverted landings, or scheduled departure delays greater than 15 minutes. Failure to maintain the required schedule could prejudice the contractor's prospect of securing contract renewal.

7. EXAMPLE RELIABILITY, AVAILABILITY, MAINTAINABILITY REQUIREMENTS FOR SHIPS

A. AVAILABILITY, RELIABILITY & MAINTAINABILITY (ARM)

The achievement of the ARM parameters is being given equal priority with those for performance, timescale and cost, with the objective of maximizing availability at minimum Life Cycle Costs (LCC).

B. EFFECTIVE AVAILABILITY

The probability that the Ship system is available at any instant during the maximum operational period, taking into account all critical failures, both repairable and not repairable at sea and preventative maintenance, shall be greater than 98%.

Effective Availability is defined by the following empirical relationship:

$$A_E = 1 - \frac{MART}{MTBCF + MART} - \frac{PMdowntime}{Missiontime} - 0.5 * \frac{Missiontime}{MTTCFnr}$$

Where:

MTBCF = Mean Time Between Critical Failures(Repairable at sea)

MART = Mean Active Repair Time

MTTCFnr = Mean Time To Critical Failures (Not Repairable at sea)

PM downtime = Total preventive maintenance downtime for mission

C. AVAILABILITY (INTRINSIC)

The Long Range Radar (LRR) ship system Intrinsic Availability shall exceed 99% during unsupported operations at sea for the maximum operational period of 45 days, at the defined usage and with the agreed complement of on-board spares. MTBCF and MART requirements shall be addressed and met individually and in the context of Intrinsic Availability.

D. RELIABILITY

In respect of critical ship system failures which are repairable at sea, the MTBCF of the ship system shall exceed 750 hours.

In respect of critical ship system failures which are not repairable at sea, the LRR shall have a probability of surviving the maximum operational period of 45 days without a critical failure of greater than 98%.

A critical ship system failure is defined as any performance degradation, failure or combination of failures, affecting ship system hardware, software or both, resulting in:

(1) loss of the ability to detect and track targets in all specified environments and conditions, to the levels specified in the staff requirements;

(2) loss of the ability to process, display and output radar data in all specified, environments and conditions to the level specified in the staff requirements;

(3) loss of the ability to successfully execute Command, Control, BIT, Training and other functions specified in the staff requirements;

(4) loss of the ability to successfully communicate with any one of the interacting systems.

In respect of Logistics Failures of the ship systems, the MTBF shall be greater than 200 operating hours.

A Logistic Failure is defined as any fault, affecting either hardware or software (including BIT), which results in any departure from the agreed performance specification, or which requires a corrective maintenance action.

The ship system shall be designed such that an individual hardware or software failure does not result in a critical failure, and that there is graceful degradation of equipment function or performance under failure conditions.

E. MAINTAINABILITY

(1) General Policy

The general on-board maintenance policy should be to replace failed items at LRU or sub-assembly level.

Electronic test equipment, excluding BITE, required for repair and maintenance should be selected from the Common Range Electronic Test Equipment (CRETE) range, whenever practicable. Any exceptions to this are subject to the Participants Project Manager approval.

(2) Active Repair Time

The median (50th percentile) and the upper (95th percentile)active time to repair/restore the system performance after failure using specified repair procedures and resources shall not exceed 35 minutes and 150 minutes respectively.

(3) Corrective Maintenance

Failures, which are capable of being repaired at sea, shall be repaired by replacement at module or sub-assembly level. Any requirements for system tuning after such replacement shall be minimized (ideally eliminated). Non Repairable at sea failures (i.e. those relating to units not normally carried as on-board spares) shall be minimized.

(4) Preventive Maintenance

Major preventive maintenance activities should be carried out outside the normal operational period. The following shall apply to Preventive Maintenance activities undertaken during the operational period:

(i) the down-time for any one Preventive Maintenance activity during the 45 day operational period shall not exceed one hour;

(ii) the total down-time for Preventive Maintenance activities during a 45 day operational period shall not exceed 20 hours.

8. GROUND RADAR AVAILABILITY REQUIREMENTS

This is an example of the specification of requirements for equipment which has long periods of continuous operation, such as an Air Traffic Control Radar, which can operate for 365 days a year, and which can only be taken out of service for preventive maintenance at strictly pre-determined limited periods. It is assumed that the contractor is to provide all support necessary to maintain the required availability.

a. "The radar system shall have a minimum operational availability of 98%";

b. No single unplanned downtime event shall exceed 15 minutes;

c. The contractor shall provide total support to maintain the above requirements, and shall describe the arrangements for providing such support, including facilities to be supplied by the purchaser;

d. The contractor shall stipulate preventive actions that are required and their duration and periodicity. The contractor shall also state the MART and the 95% percentile repair time for the radar system.

9. EXAMPLE RELIABILITY, AVAILABILITY, MAINTAINABILITY, SAFETY REQUIREMENTS FOR MISSILE

A. QUANTITATIVE REQUIREMENTS - LIFE PROFILE

(1) Quantitative system effectiveness requirements

The system effectiveness is the probability that the missile can successfully meet an operational demand within a given time when operated under specified condition of environment and mission. It is the combined probability that the missile is available at launch and successful after launch and is defined as the probability of success P for a specified life profile and mission. See example in Table A1 below.

TEST	TEST	TEST		TEST	
STORAGE-DORMANCY MODE		TRANSPORT	STORAGE	AIRCRAFT	MISSILE LAUNCH
(Ground Benign 20°C)		(Ground Mobile 30°C)	(Ground Fixed 30°C)	(Aircraft Unmanned) Fighter 70°C)	(Missile Launch 70°C)
(19.5 years)		(10 h)	(6 month)	(2h)	(10 min)
PHASE: A		B	C	D	E

TABLE A1: <u>MISSILE LIFE PROFILE AND MISSION</u>

The effectiveness requirements are expressed as:

Operational effectiveness (Po): includes the effect of logistic delay times etc., and is based on operational availability:

Po = Ao*Rm

and a typical requirement could be Po > 85%

Where:

Ao = Operational Availability

Rm = Mission Reliability (see ARMP-7)

A similar approach can be used for Intrinsic Effectiveness, based on Intrinsic Availability (Ai) and a typical requirement for Intrinsic Effectiveness could be > 0.95.

Intrinsic availability concerns only phases A, B and C.

B. QUANTITATIVE RELIABILITY REQUIREMENTS

(1) Basic reliability (see ARMP-7)

This reliability includes of all technical non-conformance failures (component, design, manufacture, ageing), but excludes failures that are not attributable to the contractors such as improper handling and misuse. These requirements concern A, B and C phases.

The requirement is R = 90%

(2) Mission Reliability

The probability that a missile performs its required functions for the duration of the specified mission profile.

The requirement is Rm = 97%

C. QUANTITATIVE MAINTAINABILITY REQUIREMENTS

This requirement covers fault detection, disassembly, repair, re-assembly and verification times.

A typical requirement is:

(1) 75% of active repair time shall be less than 3 hours; and

(2) 95% shall be less than 8 hours.

Note: The missile shall be designed such that the maximum maintenance time does not exceed 24 hours. This could be verified by design analysis.

D. QUANTITATIVE TESTABILITY REQUIREMENTS

Using External Test Equipment, the following shall be achieved:

(1) 90% of all known faults shall be detected and identified to one LRU, 95% to 2 LRUs and 100 % to 3 LRUs;

(2) the false alarm rate shall not exceed 0.1%; and

(3) 100% of safety critical failures shall be detected and indicated.

E. LIFETIME

The missile shall be designed for a:

(1) storage life time of 20 years (10 years for pyrotechnic equipment); and

(2) air carriage time of 250 hours.

F. QUANTITATIVE SAFETY RISK REQUIREMENT(SEE PARA 210)

Safety hazards are categorised according to the severity of their consequence as follows:

Description	Category	Consequence
CATASTROPHIC	I	Death or system loss
CRITICAL	II	Severe injury or illness Major system damage
MARGINAL	III	Significant injury or illness Significant system damage
NEGLIGIBLE	IV	Minor injury or illness Minor system damage.

TABLE A2: HAZARD SEVERITY CATEGORIES

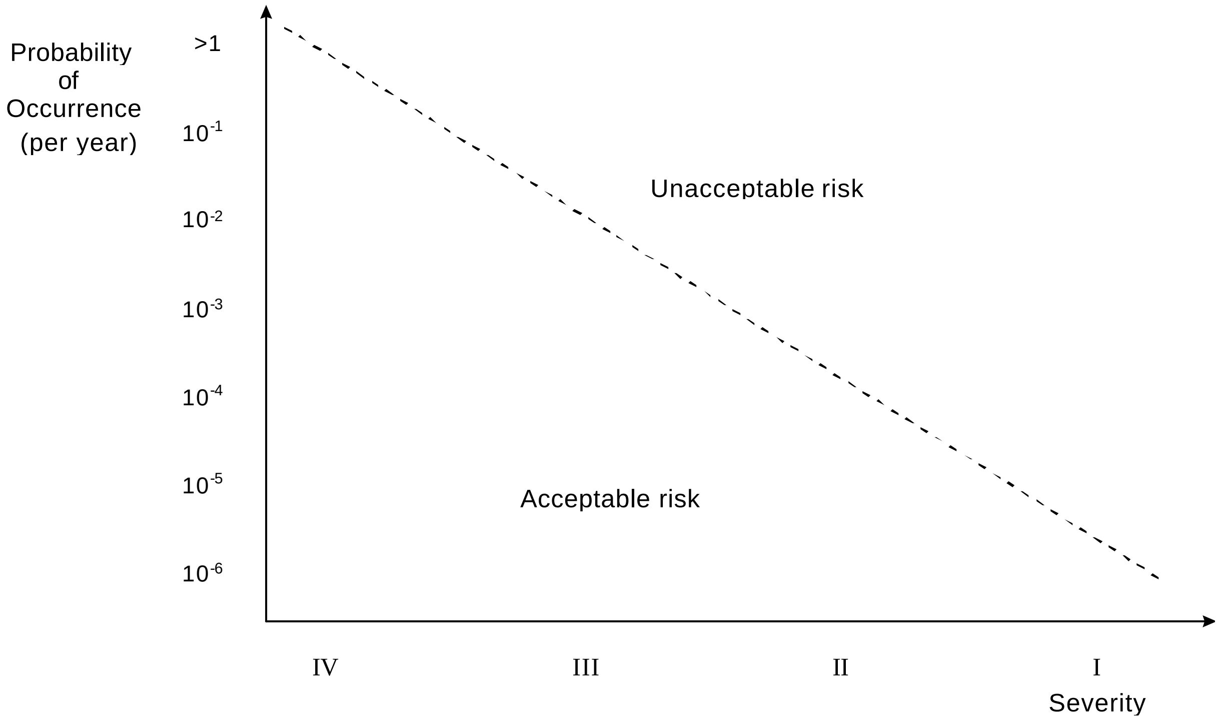

FIGURE A1: CRITICALITY GRAPH

The maximum risk, (i.e. the probability of occurrence of the hazardous event) is specified for each category, and is often stated as the probability of occurrence per year. Typical examples for a missile are:

(1) I Catastrophic 10^{-6}/year (e.g. Unintentional initiation of propulsion motor);

(2) II Critical 10^{-5}/year (e.g. Unintended deployment of control surfaces); and

(3) III Marginal 10^{-4}/year (e.g. Unintended operation of thermal battery).

The contractor is required to conduct a detailed risk analysis, demonstrating that risks are identified, categorised and reduced to the required maximum levels. This analysis is to be performed to the satisfaction of the purchaser.

QUANTIFYING MAINTAINABILITY REQUIREMENTS

1. INTRODUCTION

It has been found through experience that most equipment active repair times follow a log-Normal distribution, i.e. one where the logarithm of the variant (in this case, active repair time) is distributed normally. Mean Active Repair Time (MART) is a parameter often used to specify Maintainability requirements. Active Repair Time is the time actually expanded by the maintainers, assuming that all necessary tools, spare parts and documentation are available. It excludes administration and logistic delay times. The achievement of MART requirement is a function of the design of the equipment and lies therefore within the control of the contractor. It is thus a contractable parameter.

This Annex considers the relevant characteristics of the log-Normal distribution and how they may best be expressed in specifications. It also provides, for guidance, some examples of the values of the relevant parameters for different types of equipment and servicing policies.

2. REPAIR TIME DISTRIBUTION

A. LOG-NORMAL DISTRIBUTION

A log-Normal distribution (with random variable T) requires two parameters to define it, the two most convenient ones mathematically being its median value t_m and its dispersion σ. The dispersion is defined as the standard deviation of the Normal distribution formed after taking natural logarithms (logarithms to basis e = 2.718...) of the original distribution.

These two parameters are also convenient ones to utilise in maintainability specifications because:

(1) t_m is the value such that 50% of repair times are less and 50% are more, i.e. it indicates the general level or magnitude of repair times;

(2) the dispersion σ indicates the proportion of short, medium and long term repair times and it has been found that σ has a relationship (independent of t_m) with the type of maintenance policy designed into equipment (see para 4 and Table B1).

B. RELATIONSHIP BETWEEN MART AND T_M

Specification writers are often more familiar with MART than with the median t_m but should be aware that MART is not equal to t_m. MART may even deviate significantly from the 50:50 point of the distribution, being the median t_m. The difference between MART and t_m depends on the magnitude of the dispersion σ (see Table B1). The mathematical relationship is shown in equation (5) of the Appendix to Annex B.

For a log-Normal distribution, t_m is the *geometric* mean of the distribution, whereas MART is the *arithmetic* mean.

NOTE: The geometric mean of n observations is the n^{th} root of the product of the n observations, whereas the arithmetic mean is the sum of n observations divided by n.

3. EXPRESSION OF REQUIREMENTS

Whilst it would not be wrong to express a Maintainability requirement in terms of the median t_m and the dispersion σ of the repair time distribution, a less mathematical presentation may be more appropriate for readers of the specification. For example, the requirement could be expressed as:

a. '... 50% of active repair times shall be less than 'a' minutes and Y% less than 'b' minutes...'

or

b. '... X% of active repair times shall be less than 'c' hours and Z% less than 'd' hours...'

or

c. '... MART shall be 'm' hours and U% of all repairs shall be completed by time 'f'...'

NOTE: It is usually not advisable to state a mean without an additional worst case. In Appendix B1, t_m and σ describe the repair distribution.

4. QUANTIFYING THE PARAMETERS

Empirical results (see Table B1) show that dispersion σ lies generally between 0.6 and 1.4, the higher values being associated with diagnosis and repair to component level while the lower values are associated with modular repair policies. Specification writers should use this knowledge and ensure that their requirements do not imply a value inconsistent with this range without good reason.

Some typical values of t_m and σ which have been observed in practice are provided by Table B1.

Equipment Type	**Repair Policy**	**t_m [hrs]**	s	**MART [hrs]**
Missile	Component Level	1.07	1.33	2.59
Missile (more complex than above)	Module replacement	1.45	0.63	1.77
ARC Communication Set (aircraft equipment serviced in ground workshops A)	Component Level	1.83	1.08	3.28
ARC Communication Set (aircraft equipment serviced in ground workshops B)	Component Level	1.84	1.17	3.65

TABLE B1: TYPICAL VALUES OF t_m AND s

NOTE: This Table is for guidance only.

Despite the empirical association between dispersion σ and the level at which an equipment is serviced, there are as yet no precise relationships between t_m and σ on the one hand and the maintenance performance factors which determine them; e.g. maintenance environmental conditions; personnel skills, experience and training; administrative requirements, etc.

Nevertheless, when quantifying a Maintainability requirement, full account should be taken of these factors as well as repair and support policies. A clear statement should be made of all maintenance aspects appropriate to the operational scenario which have influenced the Maintainability quantification.

MATHEMATICAL BACKGROUND TO THE LOG-NORMAL DISTRIBUTION

A.1 DENSITY FUNCTION

A continuous and positive random variable T has a log-Normal distribution if its logarithm ln T is normally distributed with mean μ and standard deviation σ. The density function f(t) of the log-Normal distribution is given by

(1) $$f(t) = \frac{1}{ts\sqrt{2p}} e^{-\frac{1}{2}\left(\frac{\ln t - m}{s}\right)^2} \qquad t \geq 0,\ \sigma > 0$$

whereas μ is a scale parameter and σ indicates the shape of the distribution. The graph of f(t) is shown in Figure B1.

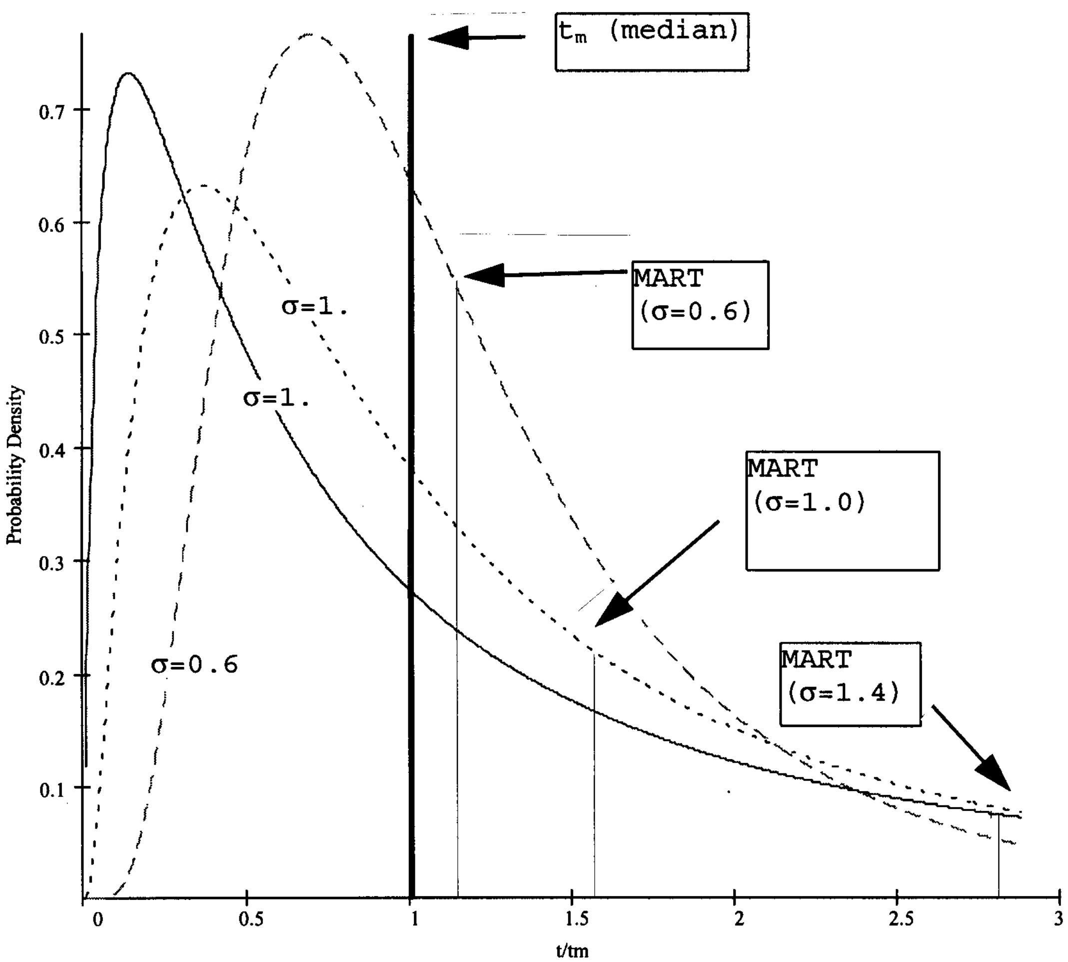

FIGURE B1: GRAPH OF DENSITY FUNCTION f(t) OF THE LOG-NORMAL DISTRIBUTION

One of the log-Normal density's properties is that it is nearly zero at the beginning, increases quickly up to the maximum and decreases then in a relatively quick manner. That is one of the major reasons why the log-Normal distribution is commonly used for repair times.

Mean E(T)and variance Var(T) of a log-normally distributed random variable can be evaluated using the equations

(2) $$E(T) = e^{m+\frac{s^2}{2}}$$

(3) $$Var(T) = \left[e^{s^2} - 1\right]e^{2m+s^2}$$

As the log-Normal density is not symmetrical mean and variance are less suitable elements to express the features of this distribution. The use of the median t_m is much more appropriate and it can be found that:

(4) $t_m = e^{\mu}$

A.2 MATHEMATICAL RELATIONSHIP BETWEEN MART AND MEDIAN

The mean of repair times that follow a log-Normal distribution (see equation (2)) is usually called Mean Active Repair Time (MART). Using additionally (4) results in

(5) $$MART = t_m * \exp\left[\frac{s^2}{2}\right]$$

This allows to convert, for known σ, MART requirements to those for the median and vice versa.

It can be seen from this relationship that there can be large differences between MART and t_m under certain circumstances; for example, if $\sigma = 1.4$, then MART = 2.66t_m and it can be found that 75% of repair times are less than the MART.

A.3 DETERMINATION OF THE DISTRIBUTION FROM THE REQUIREMENTS

The log-Normal distribution can be completely determined if the two parameters μ and σ are known. According to (4) the median t_m can also be used instead of μ.

Compared with other probability distributions the log-Normal distribution is not tabled. This disadvantage can easily be overcome by the substitution

(6) $$X = \frac{\ln T - m}{s}$$

which transforms the log-Normal distribution into the standard Normal distribution. Therefore, this relationship can be used for the examples of requirements given in paragraph 3:

Example (A):

"...50% of active repair times shall be less than 'a' minutes and Y% less than 'b' minutes..."

The median t_m is given by a = t_m.
From (6) the following equation can be derived

(7) $$b = t_m * e^{bs}$$

where β is the percentile of the standard Normal distribution to probability Y% which can be obtained from Tables. Some typical values are:

Y%	60	70	80	90	95	99	99.9
β	0.253	0.524	0.842	1.282	1.645	2.326	3.090

Therefore, the second parameter σ can be figured out from (7) to:

$$s = \frac{1}{b}\ln\left(\frac{b}{a}\right)$$

Numerical example: a = 45 minutes, b = 240 minutes, Y = 90%

These values lead to: t_m = 45 [min]; μ = ln 45 = 3.807;

$$s = \frac{1}{1.282}\ln\left(\frac{240}{45}\right) = 1.306$$

Example (B):

" X% of active repair times shall be less than 'c' hours and Z% less than 'd' hours..."

In this case equation (7) can be applied twice, replacing b and β by c and γ respectively, and then replacing b and β by d and δ. One can obtain then two equations to determine t_m and σ:

(8) $$s = \frac{1}{d - g}\ln\left(\frac{d}{c}\right)$$

(9) $$t_m = c * e^{-gs}$$

<u>Numerical example:</u> c = 2.5 hours, X = 60%, d = 18 hours, Z = 99%

This results in: $$s = \frac{1}{2.326 - 0.253} \ln\left(\frac{18}{2.5}\right) = 0.952$$

$$t_m = 2.5 * e^{-0.253 * 0.952} = 1.965$$

and μ = ln 1.965 = 0.675

Example (C):

"... MART shall be 'm' hours and U% of all repairs shall be completed by time 'f'..."

This case can be covered by using equations (5) and (7), (7) with appropriate denotations 'f' and 'φ' in lieu of b and β, which leads to a quadratic equation for σ. Depending on the discriminant one can obtain either two values for σ or possibly complex numbers. Complex numbers may indicate that the requirements are contradictory and should therefore be reviewed. If the result consists of two (real) values one of them can be solved by calculation of the median t_m which shall be within certain, realistic limits.

The solution of the quadratic equation is:

(10) $$s_{1,2} = j \pm \sqrt{j^2 + 2\ln\left(\frac{m}{f}\right)}$$

Finally the median t_m is given by

(11) $$t_m = f * e^{-j s}$$

Numerical example: m = 75 minutes; f = 240 minutes;

U = 95%

As φ = 1.645 equation (10) becomes

$$s_{1,2} = 1.645 \pm \sqrt{0.3797} = 1.645 \pm 0.616 = \begin{cases} 2.261 \\ 1.029 \end{cases}$$

Using this result and (11) leads to $$t_{m_{1,2}} = \begin{cases} 5.82 \\ 44.165 \end{cases}$$

Because a median of less than 6 minutes seems not to be realistic and, additionally, the σ value belonging to it is outside the empirically observed range (see ANNEX B, para 4) the second solution is used.

Therefore, σ = 1.029 and μ = ln 44.181 = 3.788