NATO STANDARD

AOP-46

THE SCIENTIFIC BASIS FOR THE WHOLE LIFE ASSESSMENT OF MUNITIONS

Edition B, version 1

MARCH 2022

NORTH ATLANTIC TREATY ORGANIZATION

ALLIED ORDNANCE PUBLICATION

Published by the
NATO STANDARDIZATION OFFICE (NSO)

INTENTIONALLY BLANK

NORTH ATLANTIC TREATY ORGANIZATION (NATO)

NATO STANDARDIZATION OFFICE (NSO)

NATO LETTER OF PROMULGATION

11 March 2022

1. The enclosed Allied Ordnance Publication AOP-46, Edition B, version 1, THE SCIENTIFIC BASIS FOR THE WHOLE LIFE ASSESSMENT OF MUNITIONS, which has been approved by the nations in the CNAD AMMUNITION SAFETY GROUP (CASG – AC/326), is promulgated herewith. The agreement of nations to use this publication is recorded in STANAG 4315.

2. AOP-46, Edition B, version 1, is effective upon receipt and supersedes AOP-46, Edition 1, which shall be destroyed in accordance with the local procedure for the destruction of documents.

3. This NATO standardization document is issued by NATO. In case of reproduction, NATO is to be acknowledged. NATO does not charge any fee for its standardization documents at any stage, which are not intended to be sold. They can be retrieved from the NATO Standardization Document Database ((https://nso.nato.int/nso/) or through your national standardization authorities.

4. This publication shall be handled in accordance with C-M(2002)60.

Dimitrios SIGOULAKIS
Major General, GRC (A)
Director, NATO Standardization Office

INTENTIONALLY BLANK

RESERVED FOR NATIONAL LETTER OF PROMULGATION

INTENTIONALLY BLANK

RECORD OF RESERVATIONS

CHAPTER	RECORD OF RESERVATION BY NATIONS
Note: The reservations listed on this page include only those that were recorded at time of promulgation and may not be complete. Refer to the NATO Standardization Document Database for the complete list of existing reservations.	

INTENTIONALLY BLANK

RECORD OF SPECIFIC RESERVATIONS

[nation]	[detail of reservation]
Note: The reservations listed on this page include only those that were recorded at time of promulgation and may not be complete. Refer to the NATO Standardization Document Database for the complete list of existing reservations.	

INTENTIONALLY BLANK

TABLE OF CONTENTS

INTENTIONALLY BLANK

CHAPTER 1 INTRODUCTION

1.1 ANNEXES

A. The Effects of the Environment on Munitions
B. Design Assessment and Hazard Analysis
C. Acceleration of Failure Modes
D. Modelling and Modal Analysis
E. Baseline Data for Life Assessments
F. Initial Service Life Assessment
G. Initial Service Life Assessment
H. Service Life Extension
I. End of Life
J. Document Modification History

1.2 RELATED DOCUMENTS

STANAG 4297/ AOP-15	Guidance on the Assessment of the Safety And Suitability for Service of Non-Nuclear Munitions for NATO Armed Forces
STANAG 4675	In-Service Surveillance (ISS) of Munitions
AOP-62	In-Service Surveillance of Munitions General Guidance
AOP-63	In-Service Surveillance of Munitions Sampling and Test Procedures
AOP-64	In-Service Surveillance of Munitions Condition Monitoring of Energetic Materials
STANAG 4844/ AOP-4844	NATO Handbook for Munitions Health Management
STANAG 4570	Evaluating the Ability of Materiel to Meet Extended Life Requirements
AECTP-230	Climatic Conditions
AECTP-600	The Ten Step Method for Evaluating the Ability of Materiel to Meet Extended Life Requirements and Role and Deployment Changes

STANAG 4170	Principles and Methodology for the Qualification of Explosive Materials for Military Use
AOP-7	Manual of Tests for the Qualification of Explosive Materials for Military Use
STANAG 4147	Chemical Compatibility of Ammunition Components with Explosives and Propellants (Non-Nuclear Applications)

1.3 AIM

1. The aim of this AOP is to describe munition life limiting factors and their scientific basis and describe the methodology used for conducting whole life assessment of munitions.

2. The assessment process may include aspects other than testing, such as modelling and in-service surveillance.

3. Safety and Suitability for Service (S3) assessment is described in AOP-15 which is complementary to this AOP.

1.4 DEFINITIONS

For the purpose of this document, definitions of terms are given in the NATO Terminology Database (NATOTerm[1]) that is available by reference for all Allied Publications. Other definitions specific to this standard are presented in the following paragraphs.

1.4.1 Service Life

The Service Life is the time for which a munition, in specified storage environmental conditions and when subsequently used in its specified operational and/or training conditions, may be expected to remain safe and suitable for service. Service Life is the sum of Storage and Operational Lives.

a. For certain items, the cumulative periods of time spent in the storage or operational environments are not recorded or differentiated between and it would not be cost-effective to introduce such recording. In these instances, the term 'Service Life' may be used to define the total period of time an item may be kept in service before disposal or being expended.

b. For munitions entering service, it is often necessary to assess an initial Service Life which is subsequently subject to extension.

[1] https://nso.nato.int/natoterm

1.4.2 Storage Life

The Storage Life is the time for which a munition, in specified storage conditions, may be expected to remain safe and suitable for service.

1.4.3 Operational Life

The Operational Life is the time for which a munition, when used in specified operational or training conditions, may be expected to remain safe and suitable for service.

1.4.4 Air-Carriage Life

Air-Carriage Life is an element of Operational Life and is normally expressed in flying hours and/or sorties.

1.4.5 Standby Life

Standby Life is an element of Operational Life and is often expressed in days; it represents a period of time when the item may be exposed to conditions outside the normal storage conditions prior to being used operationally or for training. Examples include a weapon which has been fitted to a launcher and a weapon which is removed from storage and held forward ready for use.

1.4.6 Disposal Life

The Disposal Life is the period of time between the end of service and disposal in which a munition is considered to remain safe for storage and logistic handling.

1.4.7 Life Extension

The term Life Extension is used to refer to the increase of the life of a munition beyond its previously assessed life.

1.4.8 Commencement of Life

The Commencement of Life for a munition is normally the date of filling provided that any delay between manufacture of the explosive and filling or assembly is acceptable to the Approving Authority. For an assembly containing 2 or more lifed explosive items, the commencement of life of the assembly will be determined by the date of filling of the item expected to become life expired first. There are 2 exceptions:

a. Difficulties may arise with foreign weapons where the date of filling is not known or cannot be verified. In such instances, a suitable date must be chosen such as the date of acceptance by the foreign inspectorate, or earlier if it is suspected that any component has aged significantly prior to that date.

b. In some instances, the life of an explosive item may be governed by a lifed non-explosive component within the item. In such cases it may be necessary to calculate the life of the item or assembly from some date other than the explosive filling date.

1.4.9 In-Service Surveillance

In-Service Surveillance (ISS) consists of the planned withdrawal of munitions from the in-service environment for detailed examination and/or performance evaluation.

1.5 GENERAL

1. The life of a munition is a major factor of any whole life cost study to be carried out on a weapon system because the replacement of life expired munitions or components is, after the initial purchase, the major element in the whole life cost of a weapons system. Assessment of life, at least to the point where a munition is likely to be consumed in training or become obsolete, is therefore essential to the effective and economic management of operational stocks.

2. This document examines the scientific basis of the procedures used for the whole life assessment of munitions.

1.6 LIMITATIONS

This document applies to the assessment of the life of non-nuclear munitions. In addition, the information here may be applied to the assessment of munitions being considered for exchange between NATO armed forces

CHAPTER 2 LIFE ASSESSMENT OF MUNITIONS

2.1 BACKGROUND

1. Munitions are normally required to withstand exposure to a wide range of environmental conditions without becoming unsafe or unsuitable for handling, storage or transport and then function as designed when required. This may mean that the most extreme climatic environments are experienced by the munition concurrently with induced environmental conditions arising from service use.

2. The safety or suitability for service of a munition may be terminated by an unacceptable degree of degradation of components or materials when subjected to normal service environments, or after exposure to certain extreme conditions. Examples of the latter include munitions being dropped in excess of normal handling heights or experiencing very high levels of underwater shock.

3. Under these conditions the munitions must remain safe for subsequent disposal, but not necessarily serviceable. The degradation of a munition's components or materials when subjected to normal service use will eventually produce a critical failure mode which will be the life limiting factor. This may include cracking of explosive charges, bond failures, seal failures, dimensional changes and failure of a munition's structure or casing. A more comprehensive list is given in Annex A.

4. The identification of this process using theoretical models and practical environmental trials enables an appropriate life assessment to be made.

5. One of the most important considerations of a munition is the choice of appropriate energetic materials. A careful selection is vital since it has a critical effect on the safety of the munition in storage, transit and operational use. To ensure that the selected explosive material possesses the required properties which make it safe and suitable for consideration for use in a particular role, the explosive should be Qualified.

6. The principles and methodology used to Qualify explosive compositions are given in STANAG 4170. The tests to enable compliance with the methodology are given in AOP-7.

7. The assessment will cover the characterization of the explosive in terms of its physical and chemical properties, its sensitiveness to thermal, electrical and mechanical stimuli, and its explosiveness. Hazard testing of aged explosives gives confidence that they will remain safe within the anticipated environment for the required life.

8. Qualification is an intermediate stage which reduces the risk to the designer in the choice of an explosive for a particular application, although it does not include any tests of the explosive in that application. Ideally Qualification should be completed before the designer makes his choice of explosive materials. However, this may not

always be practical. In such cases Qualification needs to be completed prior to the system trials so that any potential problems regarding the explosive can then be assessed.

9. Explosive compositions may be Type Qualified when the explosive has been assessed as part of the design of a specific weapon and shown to be safe and suitable for operational or training use in that role.

10. Munition designs incorporate a wide range of materials including metals, plastics, rubbers, adhesives and explosives. It is essential that no chemical or physical interaction will occur between the materials in a munition such that its safety or suitability will be unacceptably degraded during its specified service life.

11. Any materials and explosives which will be in direct contact or are so situated that vapours from either can come into direct contact with the other, must be shown by appropriate tests to be mutually compatible. This applies also for packaging materials which shall be compatible with one another and with the contents. Test procedures by which the chemical compatibility of explosives with other materials used in munitions may be determined include vacuum stability, heat flow calorimetry and chemical analysis (see STANAG 4147).

2.2 DEFINING THE ENVIRONMENT

1. The life of a munition varies significantly depending on the severities of the climatic categories, type of storage, transport and operational conditions it must endure. Therefore, the accuracy of any estimates, confirmations or revisions of service life will depend on the knowledge of the environment which the munition will experience in service, so particular attention is given to acquiring the data.

2. To obtain the information, an environmental questionnaire is required to be completed as described in AOP-15. The answers to the questionnaire will state the manner in which the store will be used, transported, stored (including timescales) and the Climatic Categories for service use. This information then enables appropriate Life Cycle Environmental Profile to be developed which will represent these conditions which will be experienced in service.

2.3 BUILD STANDARD

1. The hardware used during development testing may have many differences compared to the build standard of the final product. However, when safety authorities advise on the safety and suitability for service of a munition the advice relates to a defined design build standard from a particular manufacturer, manufacturing site and manufacturing process.

2. Changes to the above, including changes in the source or type of raw materials or components or break in production could affect the validity of the original

assessment. Of particular significance are any changes to the energetic materials used in a munition which could affect the safety, performance or ageing characteristics.

2.4 MUNITION PACKAGING

1. The majority of munitions spend most of their service life in storage. The period spent in operational use will be shorter and packaging (if used) may be much lighter. Adequate protection is required during all these periods. Therefore, suitable packaging of munitions is essential to maintain safety, serviceability and reliability by protecting the munition against extremes of temperature, humidity, vibration, shock and other environmental hazards.

2. The packaging should be constructed of compatible materials which do not affect or contaminate the munition. Trials of packaged munitions are essential to confirm that adequate protection is afforded to the munition from the environmental effects and rough usage likely to be encountered during its service life.

2.5 DEGRADATION MECHANISMS

The materials used in munitions may deteriorate in a variety of ways. The deterioration may be sudden or gradual and it may be reversible or irreversible. Failure modes may be classified under the following categories.

2.5.1 Thermal (Chemical)

1. These failure modes may be defined as changes occurring in the chemical composition of materials resulting in unacceptable degradation of safety or functioning characteristics. Certain explosive compositions are inherently unstable and are continually undergoing slow decomposition even at ambient temperature. The decomposition reaction rate is altered by temperature and sometimes by other factors such as humidity.

2. Examples of chemical failure modes include decomposition reactions of nitric ester propellants, (even when modified by the presence of stabilizers), corrosion of metals, incompatibility between materials and also the degradative effect of solar radiation on natural and synthetic organic materials such as rubbers and plastics.

2.5.2 Mechanical

1. Two principal mechanical failure modes can be identified. The first of these is fatigue where under the action of cyclical loading a crack is initiated and propagates leading to failure of the component. The second principal failure mode is due to the applied stress exceeding a threshold and breaking the component.

2. Specifically, in the case of the energetic material, friction or fretting failures occur by contact movement causing two types of problems i.e. loss of material and heating.

Loss of material may cause structural weakness or looseness between mating surfaces. The occurrence of fretting under these conditions between exposed explosive surfaces can lead to the possible formation of “hot spots” with subsequent ignition and/or explosive events. Explosive material in the form of dust may also occur under these conditions and can have a higher sensitiveness than the parent bulk composition and lead to a hazardous condition. The infiltration of the dust to parts of the munition where nipping of the material can occur may lead to an ignition and provide a flame path back to the bulk of the explosive.

2.5.3 Thermomechanical

1. This term applies to mechanical stresses in materials that are induced by thermal effects resulting in mechanical failure. A change of temperature in systems containing materials with different thermal properties, thermal diffusivity and coefficients of thermal expansion produces stresses within the materials and particularly at bonded surfaces. Coefficients of expansion of metals are much smaller than those of plastics and rubbers.

2. Such problems are often encountered in case bonded rocket motors between propelling charge, liner and case or, in motors with loose charges, between charge and inhibitor. Bond failure at such interfaces commonly leads to catastrophic failure on functioning. The results of differential thermal expansion and contraction of materials in munitions leading to dimensional changes can cause problems such as cracked explosive fillings or seal failures, the latter permitting ingress of moisture or exudation of explosive material. Cracking of TNT based compositions in the main fillings of munitions occurs due to thermomechanical stressing and is more severe when such fillings are bonded to the case material thus restricting volume contraction of the explosive on cooling. These effects are all likely to be exacerbated by rapid changes in temperature, for example caused by a swift change in altitude during air-carriage.

2.6 DESIGN ASSESSMENT AND HAZARD ANALYSIS

1. It is essential to carry out a design assessment and hazard analysis review against agreed design principles prior to practical tests on all munitions as part of the life assessment programme. The review should ensure that potential hazards and failure modes are detected, hazardous conditions identified and should establish whether a failure will affect safety or suitability for service of the munition. Assessment techniques include Failure Modes and Effects Analysis (FMEA), Failure Modes Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA).

2. FME(C)A is a bottom up analysis which examines low level components and considers the systems failures that result from their different failure modes. Benefits of the analysis include:

   a. Providing an understanding of the structure of the system and factors influencing reliability.

b. Identifying components that are reliability sensitive or of high risk.

3. The FME(C)A assess for each failure mode:

a. The effect on subsystems to a system level.

b. Likelihood of occurrence.

c. Severity and criticality (for a criticality analysis).

4. The FME(C)A may be quantitative or qualitative or a mixture of the two.

5. FTA compliments FME(C)A in that it is a top down analysis, starting with a system fault and analysing the fault in terms of subsystem faults. This has the effect of identifying all possible causes of the system fault. For a system with little or no redundancy FME(C)A is best but for a complex system FTA is better. For further discussion see Annex B.

2.7 LIFE ASSESSMENT PROCEDURE

1. A realistic appraisal of life assessment requires accurate detailed knowledge regarding the design, materials used and functioning aspects of the munition plus the environment and conditions the store might experience in service. It is essential that the build standard, which may be of a complex design, is thoroughly documented and understood and that the materials used in the construction and the energetic compositions employed are critically assessed. A detailed design and hazard assessment exercise identifying possible failure modes and their effect on the system is essential. The anticipated service environment including the transportation, storage, handling and operational use over many years is complex, varied and difficult to establish with complete accuracy. Equally the precise thermal and mechanical conditions which the munition will encounter can only be a best estimate.

2. For life assessment programmes to achieve their prime aim of maximizing service lives of munitions at minimum cost, they must be tailored for each munition. Whole life assessment should be treated as an integral process in which adequate provision of required munitions for planned in-service testing, firings, life extension trials etc. is made. Earlier prediction of service lives can be confirmed and as appropriate extended until the required life of the munition is met.

3. The assessment for relatively simple, low cost munitions only requiring a short in-service life where the consequences of munition failure presents little hazard to life or equipment may comprise a design assessment and little or no, practical testing. The large number of rounds used in service provides, through defect reporting, adequate confidence of the safe and serviceable condition of the munition. No further in-service testing would normally be required for such natures of munitions.

4. For the most complex munitions where a long service life is required, the number of test assets is limited and the consequences of failure present a hazard to life and equipment a programme consisting of design/hazard assessment, modelling and extensive practical trials is more likely to be appropriate. For such a munition an assessment programme is carried out in 5 phases (see Figure 1).

a. Phase 1 consists of carrying out a design assessment in order to identify potential failure modes of the system (Annex B). The assessment addresses the overall system configuration, components and constituent materials. In parallel the MTDS is reviewed and also the environments seen by the munition.

b. In Phase 2 all the potential life limiting failure mechanisms are identified.

c. Phase 3 constitutes a decision process where the techniques to be used for assessing the life of the munition are identified, i.e. a combination of modelling, testing, condition monitoring and in service surveillance.

d. In Phase 4 trials are performed in the form of a combination of sequential and safety tests.

e. The fifth and final phase involves utilizing all the evidence accumulated during the process and making an assessment of the life for which the munition remains safe and suitable for service.

5. Details of the baseline data information needed for life assessment and the factors to be considered to justify the award of an initial service life are given in Annexes E & F. A brief overview of testing, modelling, in service surveillance and condition monitoring is given in Sections 2.8, 2.9, 2.10 and 2.11.

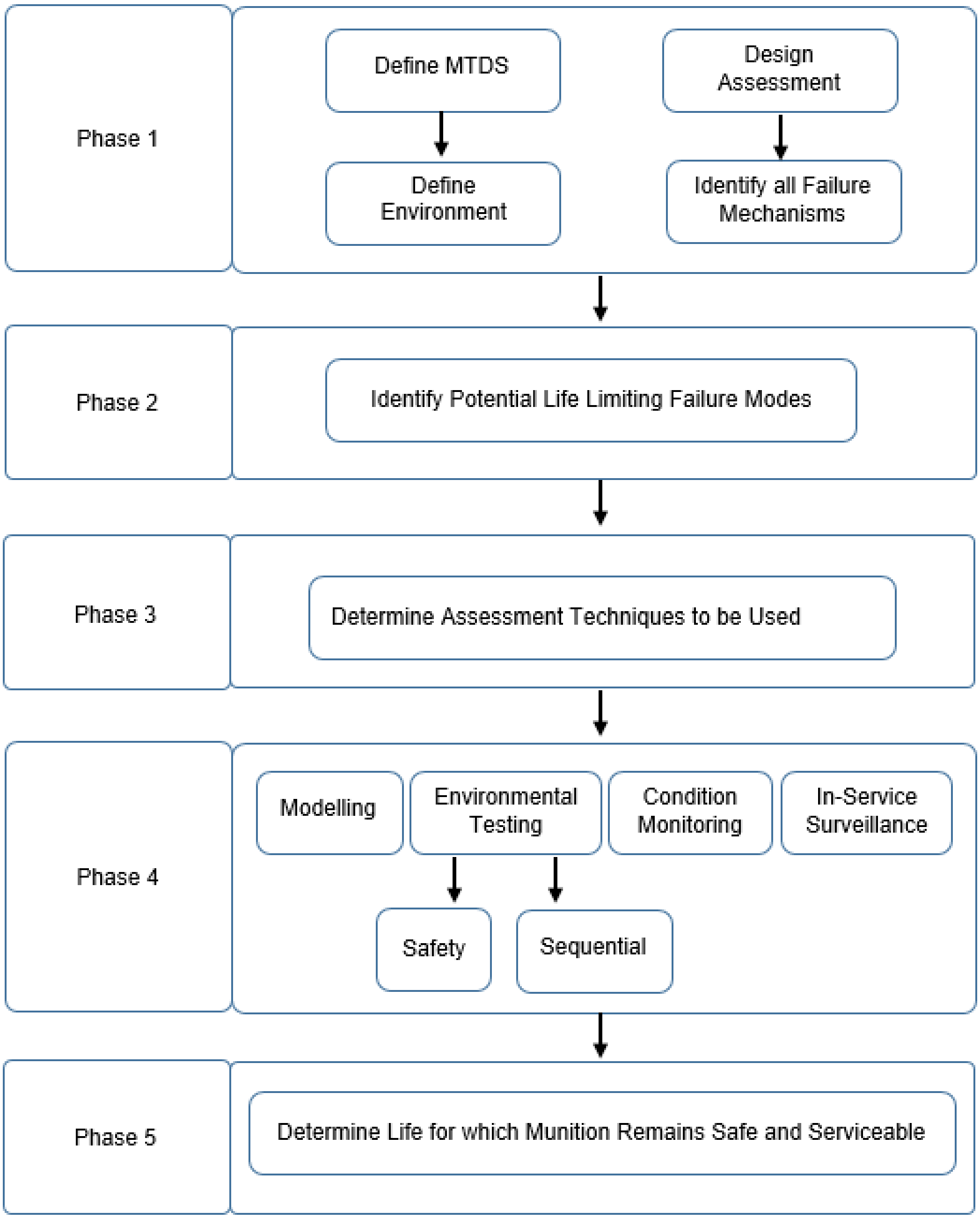

Figure 1: The five stages in the life assessment procedure.

2.8 TESTING

1. If environmental trials are deemed necessary as part of the life assessment procedure, they should wherever possible follow a sequential program. A typical sequential testing programme will follow the MTDS for the munition and will comprise periods of time in transit, in storage, in the operationally ready state and in delivery to the target.

2. In essence, munitions are artificially aged by subjecting them to a sequence of climatic and other environmental tests prior to critical examination and firing. These include diurnal cycling, vibration, shock and handling tests which are adjusted in length and severity to ensure that the resultant ageing adequately represents the anticipated service life of the munition.

3. The use of accelerated testing enables, in a relatively short time, an assessment of the response of a munition to its expected environments. The acceleration factor is the ratio between the deterioration occurring when the munition is subjected to an accelerated test compared to the degradation caused by the worst expected real time service environment. The conditions of the accelerated test should not exceed the extreme values, or rates of change of values, likely to be encountered in the defined service environment.

4. It must be recognized that any departure from the service environmental conditions relating to the munition involves a loss of realism and some degree of confidence in the results of the test. The acceleration of the degradation may be achieved by increasing the time spent at the most severe conditions during testing. Predictions based on accelerated tests are considered to be more realistic than those derived from aggravated tests where the test conditions can exceed those expected in the service environment. However, to reduce test durations it can be acceptable for benign environments to increase test severities.

5. A significant factor in the life assessment trials programme concerns identifying and evaluating the state of the munition. At the commencement of the trial, visual inspection to detect obvious defects such as cracking or corrosion of exterior components, radiography and any electrical measurements required would be normally carried out.

6. For munitions that have completed the required amount of the trials programme, comprehensive examination and functioning at the correct limiting temperatures would be needed to establish the effect of the trials upon the state of the munitions. Radiography and ultrasonics are widely applied assessment techniques to establish the physical states of the munition. For those munitions which are disassembled further, physical and chemical inspection of components and ingredients is possible. Physical characterization can be carried out to determine dimensional measurements, densities, bond strength and mechanical properties of the energetic and non-energetic materials, whilst a wide range of techniques is available for characterizing the energetic material compositions. Techniques such as Dynamic Mechanical Spectroscopy, Chromatography, Thermal Analysis and Molecular Spectroscopy are commonly employed. It must be emphasized that the value of the critical examination is greatly enhanced if the properties of the explosive charges are known at the time of the compositions being filled into the components. This “zero time” requirement for information on the explosive changes should be stipulated whenever possible in contracts for new munitions.

7. A significant factor in any life assessment programme applies to the accelerating ageing method used. Chemical and thermomechanical degradation may be accelerated by the use of elevated temperatures (either using constant temperature or the 1% diurnal cycles given in AECTP-230). It is considered that the application of diurnal cycling subjects the store to a more realistic regime than that of constant temperatures. The effect of temperature cycling produces a more realistic determination of failure modes in the munition, for example, of cracking and debonding of explosive materials, joints and seals becoming ineffective and simulates real conditions where moisture ingress can occur. The application of a combination of constant temperature ageing and diurnal cycling may be valid for certain types of MTDS.

8. The application of the Arrhenius equation (or Berthelot's Law) in calculating the acceleration factor involved when subjecting a munition to higher testing temperatures compared to the anticipated average service temperature needs careful attention. The values of the reference service temperature and the activation energy assigned to the identified critical failure mode are highly significant regarding the figure obtained for the acceleration factor used to predict interim service life from MTDS trials. Relatively small changes in the activation energy assigned can lead to large differences in the acceleration factor. It is shown in Annex C, Paragraph 6 how the activation energies vary considerably for failure modes even in a given material such as a propellant.

9. The simulation of the vibration environment that a munition will encounter throughout its service life is not always possible so there is invariably a degree of uncertainty. Unless real time data is available, most vibration tests tend to be a little more severe than the service environment. The satisfactory completion of these tests gives confidence in the munition's ability to survive the real environment. Any acceleration of vibration testing must be used with caution. Miner's hypothesis (Reference 1) is used to relate test levels and times to measured levels and desired service life times. The hypothesis is based on fatigue failure in mild steel items only. It should therefore be applied with caution to munitions which are largely made from other materials. For a more complete discussion on fatigue analysis and fracture mechanics see Annex C.

10. On completion of an environmental test programme an assessment of the condition of the munition is made to establish the effects of the trial. The factors that affect the safety of a system are much more important than those which only affect suitability for service. The acquisition of a comprehensive data base of similar munitions, which have been in service under analogous condition to the subject munition, can assist in the overall appraisal of life assessment.

11. Details of the methodologies for determination and assessment of the three types of degradation defined in section 2.7, which may lead to failure of munitions, are given in Annex C. See AOP-15 for further discussion on testing.

2.9 MODELLING

1. Modelling is increasingly being used to support safety assessments. This is because fewer assets are generally available for testing than was historically the case, leading to a shortfall in the confidence achievable through testing alone. Modelling is increasingly being used to compensate for this shortfall. Moreover, environmental constraints are increasingly restricting the use of tests such as the Standard Liquid Fuel Fire Test. Models are now available which accurately predict the time to reaction under slow heating conditions. Equally modelling can provide valuable information on likelihood of penetration by low and high-speed threats. In addition, modelling can be used to assess stress levels introduced by thermal and mechanical environments.

2. Models for high velocity impact leading to prompt shock initiation are well advanced. However, the intermediate and lower velocity impact scenarios still present problems to researchers in predicting the consequences of the event, due to the difficulty of modelling a coupled thermal and mechanical scenario with processes such as deflagration to detonation transition (DDT) possible. A similarly mixed situation exists regarding the modelling of slow and fast heating scenarios, with the time to an event predictable but not the consequences of the event.

3. In the areas of dynamic modelling and thermal transfer the technology is more advanced enabling the performance of analyses such as heat transfer, modal analysis. These applications are significant for many munition related scenarios, such as the dynamic response of a munition under vibration loading and the differential thermal loads introduced by a thermal shock during air-carriage. Such models are already enabling the performance of advanced fatigue and fracture calculations.

4. Computer power is increasing in inverse proportion to hardware costs. Moreover, national and international collaboration on data exchange and model development and verification is helping to ensure further progress in modelling capability, and the next few years will see the balance between practical trials and theoretical modelling swing towards the latter, but not to the elimination of the former.

5. The munitions assessment process is such that it is unlikely that a model will replace a test on a one-for-one basis. The process requires that outputs from modelling, like test results, are used to support an assessment that demonstrates that the environmental and safety requirements have been met. The assessment process is therefore likely to include a combination of both testing and modelling.

6. The progressive incorporation of modelling techniques will tend to change the nature of testing from mainly conditioning tests to tests for the validation of models. Characterization tests tend to be less expensive than conditioning tests.

7. Details of some of the computer models used for service life prediction are given in Annex D.

2.10 IN SERVICE SURVEILLANCE (ISS)

1. The primary purpose of ISS is to monitor the condition of in-service munitions and to demonstrate that the munition will still function safely and reliably after exposure to the service environment. The ISS programme should allow validation and confirmation of the natural ageing effects predicted from the environmental trials programme. Unfortunately, ISS can only provide real time results so that should unacceptable degradation be identified, then such deterioration may be widespread amongst the population. In order to minimize the impact of this, the munitions selected for surveillance testing will normally be those from very early production that have experienced worst case service conditions. ISS programmes may also be used for extending the life of munitions having simpler designs and for which no unexpected safety failure is likely.

2. The ISS programme should include critical examination involving non-destructive testing techniques, chemical/physical analysis and testing of materials and functional testing. Firings should be carried out at extreme service temperatures. For complex munitions such as missiles or torpedoes, the number that can be selected for an ISS programme is very limited. It is therefore essential that the maximum information is extracted from the investigation. When the store is simple, cheap and abundant then relatively large sample sizes can be taken allowing a high degree of confidence in the results.

3. The ISS philosophy is applied extensively by the U.S. authorities to extend munition life but with a significant difference from the UK approach. On the successful completion of an environmental acceptance programme a munition is assigned an indefinite life by the U.S. authorities. This means that a munition is not given a definite life duration but is considered to remain acceptable for service until results from ISS type programmes indicate otherwise. The importance of maintaining an effective ISS programme using this approach must be clearly recognized. The disadvantage of the ISS process is that any failure mode which occurs over a relatively short period of time and is not identified by regression analysis allows a short lead time for any corrective action or new purchases. Further guidance on life extension processes can be found in AECTP 600.

2.11 CONDITION MONITORING

1. The use of condition monitoring is an important step to understanding the real environment seen by the munition. This information adds confidence to the assessment process by confirmation of the actual through life conditions. Clearly implementation of any monitoring system must provide adequate information relating to the physical parameters affected by the degradation process. Furthermore, sufficient sensitivity to change will be necessary to allow detection of the onset of failure in time to take remedial action.

2. Monitoring records the response of the munition to environmental conditions. It can be used for the validation of the environmental requirements specification, to provide input parameters to assessments and for condition monitoring. Many parameters may be measured but those of most interest for munitions include; temperature, displacement, stress/strain and acceleration.

3. Monitoring through life provides the historical data (e.g. using data loggers) necessary to reassess the design and establish the life fraction. This is an essential factor in the strategy of incremental life assessment.

CHAPTER 3 SUMMARY

1. Confidence in the assessed life of a munition comes from a wide spectrum of information acquired from predictive modelling, hazard analyses and practical trials carried out on production standard munitions, read across from similar stores and subsequent ISS/ISE programmes.

2. The methodology employed to produce evidence that the munition is safe and suitable for service requires the potential failure modes to be identified. This is initially accomplished during the design assessment and hazard analysis review. Mathematical modelling studies are an important technique in understanding munition behaviour. The amount of practical tests necessary in a life assessment programme can be significantly reduce with considerable savings in cost and time by the use of appropriate modelling techniques.

3. The accuracy of any life assessment is dependent upon the knowledge of the environment which the munition will experience in service. Careful attention is needed to ensure the correct necessary information is obtained.

4. The MTDS programme is based upon induced stresses provided by accelerated ageing and mechanical (dynamic) trials. The application of the Arrhenius equation for the acceleration of chemical degradation modes is considered to be the most appropriate method. The identification of the critical failure mode and the assignment of realistic activation energy in the Arrhenius equation is of paramount importance in the assessment of the life of a munition. Particularly where there is uncertainty in the value of the activation energy the degree of acceleration of the trial should be kept as low as reasonably possible, consistent with keeping its cost and length within acceptable bounds.

5. The use of amelioration methods such as controlled storage conditions, use of high-quality packaging, dual-inventory policy will significantly extend the life of munitions.

6. The storage life of a munition can be significantly affected by the storage temperature and humidity experienced. Where thermal degradation is the main factor in munition ageing, maintaining storage temperature of 15 °C instead of 20 °C (or higher), will provide considerable cost benefits in increased munition life. Temperature monitoring of service storage facilities is recommended in order to acquire realistic data for munition life assessment purposes.

7. The use of data logging systems capable of delivering accurate records of the environment actually experienced by the munitions will make important contributions to a more accurate life assessment evaluation and the development of predictive modelling techniques.

8. The application of Miner's hypothesis (Reference 1) for the acceleration of vibration degradation rates is accepted but extreme care is required to ensure that levels more severe than the munition design limits are not applied. Anticipated shock pulses experienced by a munition must be reproduced in real time.

9. The significance of determining and evaluating the state of the munition prior, during and on completion of a life assessment programme is recognized. Appropriate non-destructive testing techniques and the full range of chemical and physical analysis methods must be applied to the munition's components and materials in order to establish their condition.

10. Life extension of munitions where safety failures are unlikely beyond the interim 10-year assessment can be achieved by undertaking ISS or ISE programmes including firings at extreme service temperatures and critical analysis. The frequency of sampling may vary from 1 to 5 years and continue until the munition is used operationally, in training, or is disposed of.

11. Life extension of other complex munitions beyond the original 10-year assessment is achieved by undertaking life extension programme trials. Extensions of up to 10 years can be achieved with each programme so that the whole life of a munition may be extended beyond 25 years.

3.1 REFERENCES

1. Miner M A, "Cumulative Damage in Fatigue" J Appl Mech. 12, 159-164, 1945.

ANNEX A THE EFFECTS OF THE ENVIRONMENT ON MUNITIONS

1. The following paragraphs illustrate some of the ways in which the environment, which includes transportation, rough usage and climatic conditions, can affect the safety and suitability for service of munitions.

2. Transport and rough usage may:

a. Break seals.

b. Cause fatigue or fracture.

c. Induce fissures in explosives.

d. Reduce explosives to powder.

e. Shake explosives into cracks or screw threads.

f. Cause local heating by shaking particles against one another or by friction with package furniture or mountings.

g. Involve impacts or cause distortion, thus compressing explosives either in bulk or in cracks or screw heads.

h. Break or damage mechanical parts of arming mechanisms, thus producing an armed or blind store.

i. Make or break electrical circuits by damaging wiring or components, either directly, or indirectly through the production and movement of swarf.

j. Cause damage which is undetectable until an attempt is made to use a store or until a further event exploits the original damage and an accident results.

3. Climatic conditions and changes may:

a. Result in explosives being heated to such a temperature that they melt or flow plastically, even though below the melting point. This can lead to explosive being trapped in screw threads or in cracks in metal where it may later be impacted or subjected to friction and detonated. Characteristics of shell with molten fillings or fillings which have flowed and re-solidified may be different from those with normal fillings.

b. Cause sensitisation or desensitisation through overheating for too long a period.

c. Induce air to be sucked in and out through broken seals. This can cause water vapour to be drawn in. Most explosives are adversely affected by water. They may become inert or more sensitive. Sensitive products of decomposition may, through reactions in the vapour phase, be deposited elsewhere in the store and cause accidents during subsequent handling.

d. Lead to the formation of ice internally and externally. If this is formed in joints, it exerts a powerful disruptive force. Ice formed on surfaces may affect functioning and aerodynamics.

e. Result in damaging aerodynamics heating effects.

f. Cause cracks in explosives.

g. Change the properties of materials. It should be noted that some physical changes occur, or have maximum rates, at low temperatures. Therefore, rubber crystallises most rapidly at about -25 °C. Some materials stiffen or reach a glassy state at severe arctic temperatures. Similarly, the electrical properties of materials may be altered.

h. Produce differential expansions and contractions between materials of differing properties, causing broken seals, cases and components.

i. Lead to corrosion as a result of exposure to damaging vapours from packages or materials and moisture (fresh, salt or chemically contaminated). Some alloys, particularly magnesium, are especially susceptible to saltwater corrosion.

j. Cause condensation on electrical components resulting in short circuits or altered characteristics.

k. Promote electro-chemical action at junctions of dissimilar metals.

l. Cause reactions to occur between incompatible materials.

m. Cause gassing of explosives, setting up high internal pressures and introducing a risk that explosive gas may be released.

n. Involve extremes of pressure which can damage sealed stores and may involve alteration of functioning characteristics.

o. Produce effects which are not apparent until an attempt is made to use a store.

4. Rocket motors are particularly susceptible to climatic changes. Besides changes in ballistic performance, other serious and sometimes dangerous effects can occur, such as degradation of the bonding and inhibitor systems, changes in mechanical properties, changes in stabilisers and plasticisers, gas evolution leading to

cracking, degradation in ignition characteristics and degradation in the igniter system itself.

5. The lists given above are not exhaustive, but they indicate the variety of ways in which trouble may arise and the close inter-relationship between mechanical and climatic damage. Some of the effects may be on safety, others on suitability for service, while some effects will have a bearing on both. Although these effects are often simulated by separate tests, the interrelationship between them must always be borne in mind when deciding upon a test programme.

INTENTIONALLY BLANK

ANNEX B DESIGN ASSESSMENT AND HAZARD ANALYSIS

1. A design assessment and hazard analysis should ensure that potential hazards and failure modes are detected, hazardous conditions identified and establish whether a failure mode will affect safety or suitability for service of the munition. Hazard analysis applies to new systems and systems undergoing modifications.

2. The initial phase in any design assessment is to establish and clearly understand the overall system design and structure and correct functioning principles. The latest issue of drawings of the selected build standard is essential.

3. As part of the assessment a Failure Modes and Effects Analysis (FMEA) is carried out to consider all identified failure modes of components. The failure mode of each component is considered in isolation and the effect of that failure in the system is analysed. The output from a FMEA enables:

   a. Identification and assessment of high-risk items and areas.

   b. Identification of where special inspection, test or maintenance requirements may be needed.

   c. Establishment of any operational constraints imposed by the design.

4. A FMEA study may be undertaken in conjunction with a Criticality Analysis (CA). The combined exercise is then termed a Failure Mode and Effect Criticality Analysis (FMECA), details of which are given in Reference 1.

5. The purpose of a CA is to rank each potential failure mode identified in the FMEA according to the combined influence of the probability of occurrence and the severity of the failure effect. When a criticality analysis is performed the evaluation of the criticality of each failure mode should be assessed in terms of worst-case conditions.

6. A further essential design assessment technique uses a Fault Tree Analysis (FTA) programme. This technique provides a means of showing the logical relationship between a particular system failure mode and the basic failure causes. The technique can be applied between any levels, from system to assembly or component level and considers all credible failures, degradations, environmental factors and operational modes and is the main technique for assessing the causes and probability of accidents (Reference 1)

B.1 REFERENCES

1. IEC 60812:2018, Failure modes and effects analysis (FMEA and FMECA)

INTENTIONALLY BLANK

ANNEX C ACCELERATION OF FAILURE MODES

C.1 THERMAL (CHEMICAL) FAILURE MODES

1. For chemical reactions the dependence on temperature is defined by the activation energy. The Arrhenius rate equation in a slightly modified form shows the relationship between the rates of reaction at different temperatures:

$$F = \frac{k_1}{k_2} = e^{\left(-\frac{E}{R}\left\{\frac{1}{T1} - \frac{1}{T2}\right)\right)}$$

where	F	=	Acceleration reaction factor
	k_1, k_2	=	Reaction rates at temperatures T_1 and T_2 separately
	T_1	=	Test temperature (K)
	T_2	=	Reference temperature (K)
	E	=	Activation energy (J mol^{-1})
	R	=	Universal gas constant (8.314 $mol^{-1}K^{-1}$)

2. It is assumed that more than one thermal (chemical) degradation process is occurring as the munition ages. The design assessment will have determined which failure modes may possibly occur. The process leading to each failure mode is represented generically as a sequence of chemical reactions:

$$A + B \xrightarrow{E_1} C$$

$$C + D \xrightarrow{E_2} E$$

$$E + F \xrightarrow{E_3} G$$

where E_n represents the activation energy for the nth step in the reaction sequence. Each sequence will have one step which controls the overall rate of the sequence. The activation energy for this rate controlling step must be measured or estimated for each potential failure mode. The lowest activation energy is then used in the Arrhenius rate equation to determine F, the minimum ratio (which equates to the overall “acceleration” factor) between the length of the accelerated diurnal cycling and the life it represents.

3. This is straightforward when comparing two constant temperatures. When stores are subjected to varying temperatures, however, such as the daily climatic temperature cycles quoted in AECTP-230, (Reference 1), calculation becomes more complicated and it is then necessary to calculate a “weighted average” temperature for the cycle and the particular activation energy for the critical step. Each cycle represents

the most severe storage conditions likely to be encountered in the given climatic category. The maximum temperature of the storage temperature cycle is the air temperature which is likely to be exceeded in temporary unventilated field storage, exposed to direct solar radiation, in the hottest part of the region for about 7-8 hours only per year on average. Since this cycle clearly does not represent the average storage conditions experienced throughout the year it can be used to accelerate the normal chemical degradation processes by virtue of the higher temperatures employed, compared with that encountered in service during most of the year. Cold environments do not normally influence chemical failure modes since the reduction of temperature generally reduces the rates of physico-chemical processes. Exceptions to this are phase changes and the crystallization of amorphous materials such as rubbers.

4. The reference temperature (T_2) is preferably an average value obtained from actual measured storage condition data. Where this information is not available T_2 is taken as 20 °C for UK storage conditions, or the “averaged” year-round temperature calculated from AECTP-230 data for other regions of the world.

5. The values of T_1, T_2 and E significantly affect the calculated values of F due to the exponential nature of the equation. The effect of using different values of activation energies on the acceleration reaction factor for given values of T_1 (60 °C) and T_2 (20 °C) is shown in Table C-1 (Reference 1). For a particular activation energy, the effect on the value of F when the test temperature remains at 60 °C but the reference temperature is varied is shown in Table C-2. The importance of using accurate values for inputs into the Arrhenius equation is paramount in obtaining realistic service life predictions based on accelerated ageing trials.

Table C-1: Relative rates at 60 °C and 20 °C for different activation energies.

Ea (kJ mol^{-1})	Relative Rate (F)	Approximate Life (Years) at 20 °C for 15 weeks at 60 °C
50	11.7	3
60	19.2	5
70	31.4	9
75	40.2	12
80	51.4	15
90	84.1	24
100	137.6	40

Table C-2: Relative rates at 60 °C and various reference temperatures for an activation energy of 70 kJ mol^{-1}.

Temperature T_2 (^{0}C)	Relative Rate (F)	Life (Years) at T_2 ^{0}C for 15 weeks at 60 °C
20	31.6	9
25	19.5	6
30	12.2	4
35	7.8	2

6. Activation energies normally encountered in explosive systems lie in the range of 40-200 kJ mol^{-1} covering first order thermal decomposition of explosive materials and pseudo unimolecular reactions typified by the interaction of moisture with pyrotechnic compositions. In cases where the ingress and subsequent reaction of moisture represents a likely failure mode, the value of E will be dependent upon its rate of diffusion through seals etc. Table C-3 gives some useful values whilst section C.3 provides a more detailed study of material failure modes and activation energies. For materials used in weapon systems, reactions with low values of activation energy proceed more rapidly at 20 °C than those with high values. Even closely related materials such as propellants from a particular family may exhibit significant variations in activation energies, so extreme caution is advised.

Table C-3: Activation energy values for rate determining steps of some failure modes.

Failure Mode	Activation Energy (kJ mol^{-1})
Moisture diffusion through seals	70
Propellant plasticiser migration	50-75
Ageing of rubbers	85-95
Thermal decomposition of HE	150-200
Thermal decomposition of primary explosives	90-120
Propellant gas cracking	100

7. Berthelot's Law has also been used to predict the safe life of propellant. Measurement of the stabilizer consumption at various temperatures will provide data that enables graphs of temperature (T) verses log time (log t) for different consumption of stabilizer. If these plots result in straight line graphs, then the process follows Berthelot's Law, which can be expressed as:

$$T = -\frac{1}{a}\log t + \frac{1}{a}(\log c - b)$$

where a and b are coefficients characteristic of the product under study and c is the concentration of stabiliser. The slope of the lines can be defined by a coefficient γ_{10} corresponding to the increase in the reaction rate for a temperature change of 10 °C.

8. It can be shown (Reference 2) that the equation above can be rewritten as:

$$\frac{t_1}{t_2} = y_{10}^{\frac{T_2 - T_1}{10}}$$

and this leads to:

$$D_x = \left(\frac{a_x y_{10}}{365}\right)^{\frac{T_2 - T_1}{10}}$$

where α_x is the time, in days, necessary for obtaining an x% decrease in stabilizer content at T_2; γ_{10} is the increase of the rate of reaction for a 10 °C temperature change and D_x is the prediction of safe life expressed in years to obtain an x% decrease in the stabilizer content at T_1.

9. More information on the use of Berthelot's Law can be found in References 3 and 4.

C.2 MECHANICAL FAILURE MODES

1. Mechanical failure modes can be summarized as follows:

   a. Brittle Fracture. This occurs in a material when the crack driving force at the tip of a crack becomes greater than the toughness value. Rapid crack extension then occurs.

   b. Fatigue. Under the action of cyclic loading defects can grow until a predefined crack size is reached which is taken as failure of the component.

   c. Plastic collapse. Occurs when a crack is of sufficient size that the remaining ligament of the cracked section cannot sustain the stresses introduced during the life cycle.

   d. Failure by leakage. This is a failure condition of a containment vessel where the safety and suitability for service of the vessel is compromised by providing a path from interior to exterior.

   e. Corrosion, erosion, corrosion fatigue, stress corrosion. Arises due to environmental factors which may cause failure themselves (e.g. corrosion) or may contribute to failure in another form.

f. Buckling. This arises when the total aggregate area and position of defects causes the buckling strength of a component to be exceeded by the applied load conditions.

g. Creep. This corresponds to the slow stable extension of a macroscopic crack. Interaction between creep and fatigue has been recognised but in the absence of experimental data it may be difficult to prove structural integrity.

h. Failure from initial imperfections. Initial imperfections can cause stress concentrations resulting in accelerated or enhanced likelihood of failure from defects located within these regions.

i. Wear. Wear is a surface phenomenon which involves progressive loss of material and reductions of dimensions over a period of time.

2. Other modes of failure which are a combination a. to i. can occur.

C.2.1 Fatigue

1. To produce fatigue requires a cyclic strain which includes a tensile component. At a microstructural level this gives rise to cumulative damage, which can involve the initiation and propagation of a crack. A convenient way of characterizing the fatigue behaviour of a material is via an S-N curve, where S is the applied stress amplitude about zero mean stress and N is the number of cycles to failure. For many materials such as metals the S-N curve can be described by the following relationship:

$$N\,S^b = C$$

where b and C are characteristic of the material. In addition, a threshold stress amplitude below which no fatigue occurs exists.

2. If the mean stress is increased from the usual zero the curve drops to a lower stress level, i.e. less applied cycles of a particular stress are required to fatigue the material. S-N curves can be normalized for this effect using a Goodman diagram.

3. Life prediction under loading at different stress amplitudes can be predicted using Miner's hypothesis (Reference 5) which simply adds the proportion of life used at the different stress amplitudes until they reach 1. In particular the damage incurred by the material during application of n_i stress half cycles with amplitude s_i is given by:

$$d_i = \frac{(n_1 s_i)^b}{2C}$$

4. This approach is most usually implemented using specialist Rainflow range counting software to sum the cumulative damage, although other software exists which counts individual cycles thereby taking into account the order of the peaks.

5. Munitions are made of a variety of different materials, and to fully utilise this approach the stress at a location of interest, such as a stress concentrating feature, under dynamic loading is required. This can be evaluated using a finite element model to predict a time history of stress due to dynamic (or thermal) loading of the munition.

6. This approach to fatigue assessment represents an improvement over the traditional approach in the munitions industry of using Miner's rule for mild steel based on overall input grms. The latter approach is used for comparing the relative severity of different environments such as a test and the true environment and relies on the assumption that mode shapes induced within the munition are similar in the test and deployment scenarios. In this approach the equation used is:

$$\frac{t_2}{t_1} = \left(\frac{R_1}{R_2}\right)^{2.5}$$

where: t = time

R = Test severity in terms of acceleration spectral density

The application of simulated shock pulses must be carried out in real time.

C.2.2 Fracture Mechanics

1. Fracture mechanics lifing is based on a pre-existing crack, either measured or assumed. The fracture mechanics equivalent of stress range Δσ is stress intensity factor range, ΔK. The stress intensity factor depends on the applied stress, the geometry and the crack size. Paris et al (Reference 6) demonstrated that K is a useful parameter to characterise crack growth by fatigue. For a crack under cyclical loading the crack growth rate is a function of ΔK and K_{max} and K_{min}.

2. For many materials, such as metals at low values of ΔK, a threshold is noticeable, below which no crack growth occurs. At intermediate values of ΔK a linear variation in crack growth rate da/dN is exhibited according to the Paris law:

$$\frac{da}{dN} = C.\Delta K^m$$

where C and m are constant for the material. At higher values of ΔK rapid failure occurs as K_{max} approaches the fracture toughness of the material K_{IC}. The crack length as this situation is reached is known as the critical crack size.

3. Knowledge of the fatigue and fracture behaviour of a material can enable a 'defect tolerance' approach to be developed in some mechanical and thermomechanical stressing applications. Existing cracks are monitored and a life to failure is estimated based on the perceived duty cycle. This approach is usually supported by a finite element model.

C.2.3 Thermomechanical Failure Modes

1. In general, thermal stresses are minimized by the use of materials having similar coefficients of thermal expansion and high thermal diffusivities (thermal conductivity divided by the product of the specific heat and density).

2. The quantitative acceleration of degradation caused by thermomechanical effects, as defined in section 2.5 of AOP-46, is difficult to achieve. Testing over a larger temperature range than anticipated in service leads to increased severity and earlier identification of failure modes, but there is no guarantee that these failures would have occurred in real life. Similarly increasing the rate of change of temperature will increase the severity but this may also result in failures that would not have occurred in the real environment. It is therefore preferable not to exceed in ageing tests the temperatures or rates of change of temperature which may be experienced in service.

C.3 MATERIAL FAILURE MODES AND ACTIVATION ENERGIES

C.3.1 General

The identification of critical failure modes and the associated activation energies of energetic and non-energetic materials is vital in life assessment studies. Failure modes, particularly those occurring in energetic materials can lead to catastrophic occurrences. Information on the cause and effect of some failure modes with appropriate values of activation energies is considered.

C.3.2 Moisture Ingress

1. One of the most common failure modes resulting in the munition becoming unsafe or unsuitable for service is the contamination of the internal environment of the weapon system by moisture, i.e. interactions/reactions of water with explosive, electrical, mechanical and electromechanical components. The rate controlling step in this sequence of chemical reactions is believed to be the diffusion of moisture, present in the weapon system at manufacture and/or in the external environment, through seals, or other non-metallic components. The ingress of moisture from external sources after manufacture can occur via two different mechanisms; through direct leakage paths or by moisture vapour transmission via gaskets and seals. This latter moisture penetration mode is relative to the water vapour pressure differential across the gasket and seals.

2. In general, the diffusion of moisture in polymeric materials such as propellants, liners and adhesives is considered to follow Fick's second law:

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2}$$

where x = distance normal to surface

c = concentration of water at x

t = time

D = diffusion coefficient

3. Solutions of this equation have been derived assuming the system is one dimensional and that the sample is isotropic. By evaluation of D over a range of temperatures the activation energy of diffusion for a particular material at a given relative humidity can be calculated using the Arrhenius expression.

$$D = D_0 exp^{\frac{-E}{RT}}$$

where D = diffusion coefficient

D_0 = pre-exponential factor

E = activation energy

R = gas constant

T = temperature (K)

The majority of information available on diffusion of moisture is with respect to epoxy resins where experimentally measured activation energies are in the range 40-70 kJ mol^{-1}

4. Absorbed moisture will tend to plasticise an adhesive or polymeric structure, thus decreasing the glass transition temperature, the stress will decrease, and the failure strain may either increase or decrease. Moisture can also displace the adhesive from the interface with the adherend. In particular, it affects joints involving metals which may react to form hydroxides or oxides, reducing joint strength.

C.3.3 Colloidal (Nitrate Ester Based) Propellants

1. Nitrate esters in colloidal propellants decompose very slowly at normal ambient temperatures, but more rapidly as the temperature increases. However, the reaction is autocatalytic and therefore a stabiliser is required to react with the decomposition products and prevent autocatalysis. Historically, end of life has been associated with a drop in stabiliser level to a particular fraction, often one half or one third, of its original content. With modern propellants stabiliser loss is unlikely to be the major life limiting factor. Activation energy values for stabiliser loss in colloidal propellants vary depending upon the nature of the stabiliser and propellant composition, but values around 85 kJ mol^{-1} have been measured.

2. The mechanical strength of colloidal propellants is provided by the nitrocellulose (NC) and any degradation of this ingredient such as chain scission, the shortening of the NC polymer chain, will result in strength reduction and possible loss of charge integrity. At elevated temperatures the compositions tend to soften and lose strength whilst at low temperature hardening and brittleness can occur with an accompanying higher propensity to crack. Activation energy values for this degradation process vary widely with propellant composition.

3. Propellant degradation produces gases which dissolve in the propellant to varying degrees creating an internal gas pressure which diffuses to the atmosphere at exposed surfaces. The production of the decomposition gases is a chemical effect governed by the Arrhenius equation. The solubility/diffusion processes are physical phenomena which are substantially less temperature sensitive. During accelerated ageing, gas accumulates in the propellant creating an internal gas pressure which can exceed the propellants cohesive strength leading to cracking of the material. In the real service environment, periods spent at high temperatures are relatively short and are interspersed with long periods at relatively low temperatures. Therefore, any gas produced at the higher temperatures has time to diffuse through the propellant at the lower temperatures. Obviously, consideration of inducing artificial, unrepresentative, failure modes, such as gas cracking, must be given due care when accelerated ageing trials for propellants are used. Activation energy values of about 100 kJ mol^{-1} are appropriate for gas cracking failure modes (Reference 7).

4. The migration of ingredients within the propellants can cause serious problems. This is particularly relevant to the migration of nitroglycerine or other plasticizers into inhibitors or insulants, where not only are the propellants ballistics affected but also the flame resistance of the inhibitor is reduced. Swelling of the insulant or inhibitor from this migration can occur and cause high stress concentrations with consequent bond failures. The inhibitor may also become mechanically weak and softened due to plasticizer absorption. The migration of nitro-glycerine, or other plasticizers, into inhibitors has E values of 50-90 kJ mol^{-1} (Reference 8). Migration of nitro-glycerine may also occur between boost and sustain charges where these are in close proximity and particularly when these are bonded together causing a failure to meet the motor performance requirements.

5. Extruded propellants tend to change their dimensions on storage as the molecular chains relax slightly from their as extruded orientation. For motors where initial dimensions are critical, the reduction in length, increase in diameter and decrease in central conduit size that occur may result in erosive burning and pressure increase, or to double obturation of the charge leading to cracking and failure. No quantitative information for the variation of the rate of this process with temperature is known.

C.3.4 Composite Propellants

1. Composite propellants offer improved properties over colloidal propellants in that they can be highly loaded, possess good mechanical properties at low temperatures and they can be case bonded. These qualities are directly related to the rubbery properties of the binder which is generally hydroxyl-terminated polybutadiene (HTPB).

2. The degradation of composite propellants based on ammonium perchlorate (AP) with a polymer binder is most likely to be as a result of the presence of moisture and/or oxygen. Moisture causes AP crystal growth and agglomeration which leads to a hardening of the propellant and sometimes to a reduction in the burning rate. Moisture contamination can also reduce the ignitability of the composition.

3. Polymers used in composite propellants, such as the commonly used HTPB are susceptible to oxidative cross-linking. This can lead to hardening and embrittlement of the propellant with associated loss of extensibility and an increased propensity for cracking. This deterioration of the mechanical properties can be critical in determining the life of the motor. The activation energy for the rate of cross linking in air of a particular HTPB composition propellant is approximately 90 kJ mol^{-1} (Reference 2). The value of the activation energy for the oxygen reaction means that the ageing of the propellant varies quite rapidly with temperature. The expected life of the motor will therefore vary significantly for modest changes in storage temperature. The rate of ageing is reduced considerably by lowering the oxygen concentration above the propellant surface. If an atmosphere of nitrogen can be preserved above the propellant the cross-linking ageing mechanism will be greatly reduced.

4. Other factors to be considered with composite propellant include inhibitor and case bond failures. Inhibitor degradation may be caused by plasticizer absorption leading to inhibitor swelling and high stress concentrations with consequent bond failures. In solid rocket motors the coefficient of thermal expansion for the composite propellant can be 2 or 3 times higher than for the metallic or composite case materials. On thermal cycling, the motor case may act as a rigid restraint. The resulting stresses that accumulate in the propellant and at the propellant case interface will ultimately lead to cracking within the composition or case bond failure.

5. High performance low vulnerability gun propellants use nitramine loaded compositions with binder system with good rubbery properties. One such system based on a commercially available polyester cured with an isocyanate and containing an energetic plasticizer has been investigated, (Reference 9). The work showed that ageing is relatively rapid under both wet and dry conditions leading to a softening and eventual breakdown of the binder. The degradation of the binder on ageing is caused by a chain scission process. The apparent activation energies are unusually low at about 28 kJ mol^{-1}, without the presence of the energetic plasticizer, and somewhat higher at 33 kJ mol^{-1}, when the plasticizer is included.

6. Studies have shown that two propellants when subjected to standard constant temperature ageing may show minimal change in mechanical properties. However, if the same two propellants are bonded to form boost and sustain sections of a rocket motor, the mechanical properties may well change with age more extensively than for individual propellants. The change in mechanical properties has been shown to be caused by migration of plasticizer from one composition to the other when the initial plasticizer ratios are different. Values of activation energies for the process are in the order of 70-90 kJ mol^{-1}.

7. A comprehensive study concerning the service life of composite propellant rocket motors (CPRMs) is given in Reference 10. The document contributes to the progress of selecting appropriate methods in determining a safe life. This is achieved by providing a comprehensive description of the composition, ingredients and manufacture of the component parts of a composite propellant rocket motor, a description of the loads applied from Service use, and the relevant behaviour and failure modes of the components, especially the propellant charge. The four broad categories of propellant main failure modes of CPRMs were considered to be cracking, debonding, slumping and combustion instability.

C.3.5 Primary and Secondary Explosives

1. High Explosives are metastable substances and will decompose at velocities dependent upon the temperature. These reaction rates are negligibly small at normal service ambient and storage temperature the munition is likely to encounter. This is due to the high values of E_a, 150-200 kJ mol^{-1}, for the thermal decomposition process. It is only when the temperature is increased above ca 100 °C that the thermal decomposition rate becomes significant.

2. Different secondary explosives have varying degrees of thermal stability. It appears that there is no simple relationship between thermal stability and chemical structure of an explosive. The critical temperature of an explosive, defined as the lowest constant surface temperature at which a given material will self-heat catastrophically, is dependent upon size, shape and confinement. Changes in shape are not so important as are changes in size and confinement. Critical temperatures can be predicted using the Frank-Kamenetskii equation (Reference 11). This equation provides the relationship between size, shape, chemical properties, and physical properties including thermal conductivity to the critical temperature of the material.

3. For TNT based secondary explosive compositions a potential failure mode is exudation. The intentional use of certain additives can reduce the exudation point to about 60 °C. At temperatures of about 70 °C the eutectic between TNT and the isomers of mono- or di-nitrotoluenes present will become molten. At 80 °C TNT will itself melt and if the whole of the filling reaches this temperature there will be a volume increase due to the phase change of +10.8% of the TNT solid volume. Unless this increased HE volume can be accommodated in some way, seals will be subjected to pressure with a high risk of molten TNT exuding.

4. Some of the modern HMX/RDX/TNT type fillings contain plasticizing agents in order to reduce cracking problems at low temperatures. The plasticizers are only present in small amount, less than 0.5%, but they can present additional exudation problems because of the mobility of the formed eutectic at temperatures well below the melting point of TNT. Similarly, if certain waxes are present in a composition mobility resulting in exudation may occur at temperatures only marginally above normal ambient.

5. Increasingly polymer bonded high explosives (PBX's) in which the energetic material commonly is bound in a rubbery binder are used in missile warheads. Polybutadiene binders (such as HTPB) are commonly used and these can degrade in the same way as composite propellants, resulting in embrittlement and cracking of the composition.

6. Primary explosives are mostly ionic compounds having high melting points, so exudation is not a problem. The main potential failure modes are due to material incompatibilities and moisture ingress. The former should be eliminated by standard screening tests and choice of materials. The reaction of moisture with initiatory substances such as lead azide can lead to non-functioning failure. It is essential that primary explosives are contained in well-sealed containers to ensure long term stability. A value of 70 kJ mol^{-1} for the failure mode activation energy is appropriate for moisture degradation.

C.3.6 Pyrotechnic Compositions

1. Pyrotechnic compositions work by the oxidation of a fuel to release energy in the form of heat, light or sound. Traditional pyrotechnic compositions, in comparison to the organic nature of the other types of energetic material, are physical mixtures of mainly inorganic ingredients. However, several oxidizers (e.g. sodium nitrate) used in service compositions are hygroscopic and some fuels are readily hydrolyzed by moist air. The adsorption of moisture can also lead to physical changes due to the partial solution of ingredients of the compositions, changes in the density or shape of the consolidated product, cracking and crystallization of salts on the surfaces of the composition. Pyrotechnic compositions such as MTV (magnesium, Teflon, Viton) contain no compounds of oxygen and degradation can occur via the transfer of one or more electrons from one constituent to another which is nevertheless classified as an oxidation-reduction reaction

2. With the chemical degradation of pyrotechnic fuels, two fundamental stability processes need consideration. The first is the stability of the composition with the non-explosive with which it is in contact. The second process, which accounts for the major proportion of ageing problems is the ingress of moisture into the pyrotechnic item from the atmosphere, even in “hermetically” sealed items. In the few components in which there is little or no exchange of gases between the outside atmosphere and that inside the item, there is generally little or no chemical degradation by moisture of the pyrotechnic compositions.

3. There are however stores in which the pyrotechnic fuel reacts with residual moisture from within the composition. Three examples are now given.

a. Decoy flares containing MTV compositions have been found to outgas during storage. Analysis of the gas produced showed the main constituents to be the solvents used in the composition’s manufacturing process plus hydrogen. It is generally accepted that hydrogen is produced by the reaction of moisture with metal fuels.

$$M_g + 2H_2 0 \rightarrow M_g OH_2 + H_2$$

b. Hexachlorethane smoke ammunition can also suffer from outgassing. This generation of gas is also due to the reaction of the filling with its inherent moisture content. This defect manifests itself, when the ammunition filling or container is hermetically sealed, by bulging or splitting the seams of the store or by bulging the inner ammunition containers. Under certain conditions, hexachloroethane will condense as a white deposit within the store. This state does not affect performance and the deposit disappears when exposed to the atmosphere.

c. Red phosphorous filled smoke ammunition can produce gas. The reaction of phosphorus with oxygen and moisture produces the very toxic phosphine gas. The phosphine can also corrode copper components.

4. Physical degradation failure mode can take place in two main ways dependent on the in-service form of the pyrotechnic composition.

a. In any ignition train it must be ensured that at each interface, whether between the same composition or between different compositions/components, complete and uniform transfer of the combustion zone occurs. The interface between different compositions, whether pressed incremental filling, component interfaces or air gaps, are the most likely to be the sites of failure or malfunction in the transfer of the ignition stimulus. Failure at interfaces is usually due to the inadequate pairing of the donor and acceptor composition. Reliability margins must be provided to ensure reliable ignition transfer throughout the required temperature range and to allow for changes in air gaps and degradation of the pyrotechnic(s) during service life.

b. With consolidated pyrotechnic pellets or candles, loss of binding/adhesion between the candle and its casing or cracking within the candle itself, can lead to either uneven burning or to failures on functioning.

c. With compositions used in loose powder form, such as propellant igniter compositions, segregation of the ingredients can give rise to unreliable functioning. This failure mode, often showing itself by changes in pressure/time profiles, can be accentuated by the effects of chemical degradation. The end of service life for such pyrotechnic devices should however be determined by testing of individual donor/acceptor pairs (e.g. propellant igniter and propellant charge).

C.3.7 Polymers

1. The use of polymers in composite propellant compositions has been discussed in Paragraph 5. Natural and synthetic materials such as rubbers, adhesives and polymers deteriorate in a variety of ways in different environments. Small changes in composition can lead to considerable changes in the ageing behaviour of the materials. In general, they are more or less sensitive to temperature, moisture and solar radiation, particularly the ultra-violet, however they can be quite sensitive to the order of exposure to different environments. The deterioration of rubbers in natural exposure can vary depending on whether they are exposed early to strong solar radiation which forms a protective skin or whether there is regular rainfall which may wash away autocatalytic products of composition. The ageing (oxidation) of rubber is represented by E_a values of about 90 kJ mol^{-1} whilst for the degradation of fluoro-elastomers, values of about 5 kJ mol^{-1} are appropriate.

2. Adhesive joints are sensitive to temperature, time, moisture and stress. Exposure to low temperatures can have significant effect due to brittleness. Adhesive bond properties are degraded by moisture at the pre-bond surface in the adhesive film and by its ingress during service. The degradation of the bonded joint through moisture is dependent upon the pre-treatment given. When bonding dissimilar metals or non-metals to metals large thermal stresses can be generated during cooling after a hot cycle which will reduce the joint strength. The maximum strength reduction will occur at the lowest temperature experienced. The effects of impact or rough handling are important as joint failure can occur particularly for rigid adhesives which are more vulnerable than the flexible types. Some adhesion failures caused by moisture penetration have an activation energy value of 70 kJ mol^{-1}.

C.3.8 Composite Materials

1. Composite materials consist of a mixture of two or more materials of which one is usually in the form of fibres embedded in a matrix of the other material. The fibres are often ceramics, which are strong, whilst low density polymers form the matrix. This combination optimises the mechanical properties so that the material has greater fracture strength than a solid piece of the fibre material of the same total volume. The presence of cracks is limited to the fibres in which they exist and do not readily run from one fibre to another.

2. Composite materials suffer from two main damage mechanisms. The first is through moisture absorption by the matrix which can lead to a rapid decrease in strength. Secondly, in service use composite materials can be damaged by impact with the damage not being apparent without detailed critical examination.

C.3.9 Metals

The corrosion of metals is usually accelerated by increasing the temperature, but the amount of acceleration varies considerably. Examples exist in which further corrosion is inhibited by protective oxide films formed at elevated temperatures. Atmospheric corrosion of metals is greatly affected by small quantities of gaseous impurities and water vapours. If the metal is in contact with soil a great variety of additional corrosive agents come into play including acidity/basicity of the soil, aeration, impurities and micro-organisms, all of which can affect the rate of corrosion. Electrochemical effects are also important. The type of corrosion is dependent on many of the above factors and also on the characteristics of the metal or alloy, protective films etc. Quantitative acceleration of corrosion is difficult if not impossible to achieve.

C.3.10 Electronic Components

The correct functioning of electronic components is vital to the safety and suitability of munitions which incorporate electronics in such areas as guidance or fuze mechanisms. Degradation is primarily through the effects of temperature and humidity. A standard test involves exposure of components/sub-assemblies to 85 °C/85% RH. The acceleration factors for this test are not well understood. The E values which have been reported by various researches vary between 29-221 kJ mol^{-1}.

C.4 REFERENCES

1. Bunyan P, Cunliffe A V, Davis A, Tod D "Input Data for Predictive Models for Lifetimes of Propellants", ADPA Predictive Technology Symposium, Orlando, USA, 22-24 June 1993.

2. Garman N, Picard J, Polakoski S, Murphy J, "Prediction of Safe Life of Propellants", Technical Report 4505, Picatinny Arsenal

3. Tranchant J, "Contribution a L'Etude des Proprietes Chimiques et Physico-Chimiques des Poudres", Memorial des Poudres 44, Annex (1962)

4. Tranchant J, Brun J, "Etude Genereale de la Stabilite Chimique des Poudres", Memorial des Poudres 41, 189 (1959)

5. Miner M A, "Cumulative Damage in Fatigue", J Appl Mech. 12, 159-164, 1945

6. Paris P C and Erdogan F, "A Critical Analysis of Crack Propagation Laws". Journal of Basic Engineering, Vol 85, 1960 , pp 528-534.

7. Healey M H “The Shelf Lives of Solid Propellant Rocket Motors”, PERME, Waltham Abbey, Essex, March 1979.

8. Cunliffe A V, Davis A, Kirby F A, Tod D A, “Life Prediction of Composite Propellant Motors”, DRA, Fort Halstead, Kent, March 1992.

9. Cunliffe A V, Davis A, Kirby F A “The Long Term Stability of Diorez Binder with and without K10”, RARDE, Waltham Abbey, Essex, 1989.

10. Sqn Ldr Maxey I H “Aspects Concerning the Service Life of Composite Propellant Rocket Motors”, MOD(PE) Ordnance Board, 15 May 93.

11. Frank-Kamenetzky D N, Acta Physichemica I.R.S.S 3, 365, 1939.

ANNEX D MODELLING AND MODAL ANALYSIS

D.1 MODELLING

1. The impact response of materials varies according to strain rates. For example, at low strain rates (e.g. 10^{-1}), corresponding to impacts velocities of a few ms^{-1}, the response is in general primarily elastic. At higher strain rates (10^2 to 10^3) corresponding to impact velocities of the order 500 ms^{-1} material strength becomes important with plastic deformation occurring. At higher strain rates still such as 10^8 vaporisation of colliding solids occurs.

2. For modelling purposes, the motion of the continuum is described by conservation of mass, momentum and energy, with boundary conditions imposed and models for material behaviour. The problem domain is usually discretized into a set of discrete cells.

3. For the solution of these impact problems the use of a hydrocode is advisable employing a choice of processing techniques such as Lagrange and Euler. In the Lagrangian method the material flows with the cells. Good definition of material boundaries is achieved but grid tangling can occur in highly non-linear situations. The Eulerian technique employs a fixed grid with material flowing through cell faces and is normally used for modelling fluids and gases.

4. The finite element and finite difference methods are mathematically equivalent numerical techniques within hydrocodes. The former represents the geometry with a set of interconnected elements with interpolation functions used to represent the variation of variables across an element. The resulting equations are solved to obtain a piecewise approximation to physical parameters. The latter represents the geometry with a grid of nodes and replaces derivatives in the differential equations with difference equations. The resulting equations are solved to obtain the values of physical parameters over a cell.

5. An equation of state is required to express the relationship between pressure, volume and internal energy. This accounts for compressibility effects (changes in density) and irreversible thermodynamic effects such as shock heating. For low velocities pressure varies linearly with compression based on bulk modulus. A further requirement is a constitutive model which permits the stress to be a function of strain, strain rate, internal energy and damage. The deformation behaviour is generally divided into volumetric and deviatoric parts.

6. Specifically, in the case of energetic materials, the JWL model (Reference 1) is often used to represent explosive reaction products. More specific models of initiation of detonation have also been developed and incorporated into a number of hydrocodes, including the Forest Fire and the Lee and Tarver.

7. Explicit time integration is used in hydrocodes whereby the variables at a new time are found using existing values. Implicit time integration is used in structural response calculations or heat transfer calculations, where significant changes occur over timeframes which are orders of magnitude longer than microseconds. Such codes are often referred to simply as finite element codes and are widely used in industries as diverse as defence, offshore, nuclear and aerospace to model effects such as thermal stressing, fatigue and fracture.

8. Considerable effort has been applied to modelling stress-strain mechanisms for munitions. Propellant material experiences various stresses and strains during its storage as a result of diurnal and seasonal thermal cycles. Any cracks which are inherently present in the propellant are subjected to a cyclic fatigue environment which causes them to propagate, subsequently resulting in degradation of the propellant with time. A technique is available which uses field data to determine the time dependent statistical variation of stress and strain as a function of temperature. The service life of propellant can be predicted using probability analysis to determine at which point in time the cumulative effects of induced stress and strain exceed the strength of the propellant.

9. At a higher level of abstraction, lumped mass and beam element models are widely used in dynamic analysis, for example to assist in fixture design and evaluation. The beam element approach is particularly useful in evaluating the modes of vibration of a system, such as a long slender missile.

D.2 MODAL ANALYSIS

1. The purpose of modal testing is the measurement of vibration modes of a system and the generation of a mathematical model of the system. One method of performing a modal analysis is to excite the system at a single point, in its most simple form by using a hammer, and to measure the response around the structure using an array of transducers. Other methods of excitation include using a shaker.

2. The responses and the input can then be analysed using a spectrum analyser. A major part of the analysis consists of curve fitting a theoretical expression for an individual frequency response function to the actual measured data. Three types of system model can be evaluated:

a. Spatial model (mass, stiffness and damping properties).

b. Modal model (comprising natural frequencies and mode shapes).

c. Response model (typically consisting of a set of frequency response functions).

3. The results can be used to validate a finite element model of the system, enabling engineering activities such as fatigue analysis, design modifications, rig design etc. to be performed. For a fuller discussion see Reference 2.

D.3 REFERENCES

1. Kury J, Hornig H C, Lee E L, McDonnel J L, Ornllan D L, Finger M, Sirage F M and Wilkins M L. 1965 Fourth Symposium on Detonation Preprints Vol 1, p A109 US Naval Ordnance Laboratory

2. Modal Testing: Theory and Practice. Ewins D J, Research Studies Press Ltd 1984.

INTENTIONALLY BLANK

ANNEX E BASELINE DATA FOR LIFE ASSESSMENTS

1. In order to make an assessment of the life of a munition it is necessary to generate the initial information required to form the baseline data against which that life assessments will be made. The baseline data may consist of the chemical and physical properties of the energetic materials; the specifications used during manufacture; the results of initial characterisation undertaken on materials; Type Qualification firings; and the identified critical design and life-cycle loads.

2. The data will need to be generated from a combination of read across; design and development tests; and models. The extent of information, and the need to generate further data, will be dependent on such factors as:

a. If the energetic components are known from other roles or uses.

b. If the characterisation stage has provided sufficient detail of the energetic materials to assess the likely failure modes.

c. Whether material properties ageing details are known.

d. Whether hardware components reliability and failure modes are known from similar roles.

e. Whether static and fatigue strength details of hardware, especially pressure vessels, have been established and whether the results of analysis by modelling (e.g. finite element analysis) are provided.

f. What is the build standard of the energetic materials and all components being assessed.

g. Whether empirical data on service conditions are available.

h. If performance firing and critical examination is being conducted at an appropriate level in order to achieve Type Qualification.

i. Whether data from production proof testing and firing is being made available.

INTENTIONALLY BLANK

ANNEX F INITIAL SERVICE LIFE ASSESSMENT

In most projects the DA will have been contracted to provide assurance of an initial life by the time of entry into service. Even where the munition is bought off the shelf or from overseas it will be necessary to use data provided from the Contractor. In all cases, an assessment will be needed of such data against the requirement for an initial Service Life. This will need to consider such factors as:

a. If all likely failure modes have been identified and if their hazard criticality/consequences are assessed to be tolerable.

b. If the environmental conditions in the MTDS likely to cause degradation of the munition have been identified. Have sequential environmental trials been conducted to show that the munition can withstand those conditions for the period of Service Life required.

c. If sufficient evidence has been gathered from component tests and qualification trials in order that the probability of occurrence of failure in the expected service life cycle is acceptable.

d. If the initial Service Life meets the needs within the planned programme of whole life assessment and service acceptance.

e. Whether the build standard which has been assessed is the same as that which will enter service or are changes acceptable without further evidence being required.

f. Whether it is planned to validate the initial life by ISE and/or ISS.

INTENTIONALLY BLANK

ANNEX G INITIAL SERVICE LIFE ASSESSMENT

G.1 GENERAL

By adopting a whole life assessment (WLA) approach it is possible to identify the measures which can be taken to preserve or optimise the life of the munitions. These measures should ideally be identified before introduction to service; however, it may not be possible to identify some until the munition has been exposed to its service environment and its effects noted through in-service experience (ISE) or in-service surveillance (ISS). Amelioration is the use of these measures to preserve or conserve the life of the service environment. Amelioration should provide the information to allow the Project Managers to optimise the best approach for a particular weapon system, to ensure its inherent safety in service and at the best value for money.

G.2 BENEFITS OF AMELIORATION

The benefits of amelioration are:

a. Amelioration can be used to extend the life of munitions beyond that which would be possible without such techniques.

b. If amelioration can be planned in advance then the increases in life of the whole inventory can be significant.

c. In cases where amelioration could not be, or was not, planned in advance then introduction of these measures mid-life can still have a significant effect on life, particularly for munitions which are younger than the fleet leaders both in terms of service life and operational life.

d. By the careful use of amelioration measures it is possible to reduce the life-cycle costs of the munition. This may be achieved by reducing the need to replace short life items and by reducing the degree of testing required to maintain confidence in the life of the munition.

e. The introduction of amelioration measures will lead to improved confidence in predicting the munition’s whole life.

G.3 AMELIORATION OPTIONS

1. Amelioration can be achieved by several measures which may be applied individually or as part of an overall policy designed to reduce the ageing effects of the environment on the particular munition. These measures include:

a. <u>Controlled Storage.</u> Explosives degrade at a faster rate in conditions of elevated temperature and high humidity. Controlling storage conditions may both defer the onset and abate the speed of this degradation. This may be achieved in a number of ways such as:

(1) Use of high-quality storehouses with effective temperature and humidity control.

(2) Use of a dual-inventory policy where small numbers of munitions are in training or operational use, while the main stock remains in controlled storage conditions.

(3) Application of the All Up Round where complete munitions are held in good quality containers, and particularly when most of the stockpile is held in Depots.

(4) Use of high-quality packaging.

b. <u>Recording.</u> The information required for munition life management includes not only the environmental extremes experienced, but also a complete history of the munition’s life. Therefore, it is necessary to maintain records of;

(1) The temperature and humidity of the storage area and of each individual munition, through a data logging system.

(2) The extent of exposure outside normal, specified controlled storage conditions, such as periods on standby. These should include meteorological conditions and duration at least, and ideally should be recorded by data logger.

(3) Duration, type and details of operational and training sorties, e.g. air-carriage vibration levels, and their associated temperature and dynamic pressure levels. Data logging systems capable of monitoring and recording shock and vibration levels for selective application would be invaluable in this respect.

(4) Transportation, duration and type (rail, wheeled vehicle, tracked vehicle etc.)

c. Refining service life calculations from the records of the temperature, solar radiation and humidity for the storage area and for each individual munition.

2. If the conditions of storage and use of a munition can be monitored - by storehouse, batch, unit load, or even individually for high value stores - then the actual percentage of the service life consumed may be determined. This will invariably be less than the current worst-case assumption, and in most cases a considerable saving

may be made. Until recently the task of acquiring and processing this data would have been unmanageable, but the advent of compact and cheap data-logging equipment and stores management software now makes it feasible.

3. Some ISMs have already introduced elements of environmental recording in order to gain or confirm their knowledge of the actual conditions experienced. To make full use of this information they will require an algorithm or model that can relate it to the amount of life consumed (this would be similar to the way in which an aircraft's fatigue-life index (FI) is incremented according to the amount and severity of "g" loading recorded by on-board accelerometers.) This in turn calls for a quantifiable understanding of the cause-effect link between environment and life-limiting failure.

G.4 EFFECTIVENESS OF AMELIORATION OPTIONS

1. It may not be possible to determine accurately the effectiveness of amelioration at the beginning of a project. However, many of the options can be effectively used from introduction into service, providing that careful consideration of the cost benefits is taken into account. Storage under controlled conditions of items which are most affected by temperature and humidity, such as rocket motors and pyrotechnics, can be a very effective option. In many cases the packaging will provide the necessary controlled conditions at a relatively low cost.

2. One of the main aims of WLA of munitions is to build up models of the ageing characteristics of the explosives which can be used in the life assessment process. Often the worst-case extremes have to be used in these models as the actual environmental exposure of the munition is not known.

3. The feedback of accurate and reliable data on the climatic and mechanical environment in service is therefore an important element in achieving the maximum life for a munition. Feedback enables the model to be refined and the degradation rate which has been assumed to be adjusted to the actual levels experienced by the munitions.

4. This is particularly true where a dual inventory has been used as selective part of the inventory may be extended if they have not experienced the predicted average or extremes of thermal ageing but some lower level. Therefore, a combination of amelioration measures and the recording and feedback of data which should go with it can provide an improvement which outweighs the cost of implementing such a policy.

INTENTIONALLY BLANK

ANNEX H SERVICE LIFE EXTENSION

1. In many projects, the DA will have been contracted to provide assurance that the service life will be met, often after entry to service. The initial life is likely to be insufficient. It may therefore be necessary to reassess life, perhaps more than once, before the full design life can be underwritten. The Service sponsor may also need to extend the life above that certified by the DA. When considering extending the Service Life of a munition.

2. In addition to deciding whether extensions are cost-effective, there are a number of other factors that need to be considered when determining the way to extend service life:

a. What length of extension is essential and what is desirable to avoid re-procurement penalties?

b. Do the predictions of the likely failure modes which have been made during development, Qualification, ISE, ISS and earlier life assessment programmes remain accurate and valid? Do they preclude life extension?

c. Have any new failure modes been found and do these limit the life of the store to below the Design Life?

d. Have the environmental effects caused greater degradation than predicted?

e. Is the build standard which was assessed at entry to service the same as all service stocks?

f. Will adequate structural safety margins remain throughout the period of the extension?

g. Are the munitions which have been included in any ISS representative of the service stocks? Do they include the fleet leaders and has ISE backed up this data?

h. Have any additional life reassessment trials been carried out and were they representative of the operational and logistic environments taken from the MTDS and modified in the light of experience?

i. Has the life extension programme provided evidence to ensure that the munition will remain safe and suitable for service including:

(1) The operational and logistic environments such as storage, transport and handling conditions?

(2) Climatic environments for the storage, operational and stand-by conditions?

(3) Sufficient artificial ageing to give the extension of life required with confidence?

j. How much ISE and ISS will be required to confirm that the life remains valid throughout the period of the extension?

k. If the life is being extended on the basis of ISE and ISS without further accelerated ageing, has sufficient evidence been gathered over the life of the munition, including any ageing carried out in development and Qualification, to permit an extension of life?

3. Further advice on the methodology to be used for assessing service life extension can be found in AECTP-600.

ANNEX I END OF LIFE

There are a number of factors which must be considered when justifying the end of service life for a munition. These cover safety, cost of ownership and data gathering as follows:

a. Is some of the munition inventory remaining in service or is the entire inventory to be removed from service use?

b. Do the explosive components of the munition have re-use, alternative use, sales or export potential?

c. Has the original Design Life of the munition been reached?

d. Does the evidence gathered from the WLA programme, ISE and ISS indicate that the munition has reached the end of its service life due to safety failures or is it due to performance degradation alone?

e. Does the evidence available indicate that the munition has deteriorated to the extent that it must be disposed of within a specified period of time, or by a particular method?

f. Are similar stores still in service and can useful data be obtained by critical examination and firing of some of the munitions?

g. What are the elements of the MTDS (e.g. storage, logistic transportation or use) that the munition will experience before a final end life point is reached and before it needs to be finally sent for disposal?

INTENTIONALLY BLANK

ANNEX J DOCUMENT MODIFICATION HISTORY

J.1 AOP-46 EDITION B VERSION 1

1. The changes from AOP-46 Edition 1 to Edition B Version 1 include only minor grammatical and wording changes throughout, an update to references where applicable and an update to the document's format to align with current NSO standardisation requirements.

2. A future revision of AOP-46 is planned in order to update the technical content in accordance with modern best practice, latest policy and to reflect and incorporate the development of other related standards.

AOP-46(B)(1)