Validation and Exploitation of Munition Environmental Data

David Richards MSc CEng CEnv FSEE FIMechE
Kent Engineering Services
UNITED KINGDOM

dave.richards@environmental.org.uk

ABSTRACT

Currently, a variety of data loggers are in use to monitor and record munition environmental parameters. Such loggers are typically intended to provide information for munition life assessment and to assist in munition management. However, in order to derive maximum benefit from such information, a data exploitation strategy is essential to allow safety critical munition life extension decisions to be agreed, by the appropriate weapons authorities, with an appropriate level of confidence. Any such data exploitation strategy needs to adopt a rigorous approach for verifying and assessing the munition logger data.

A programme of work to establish a data exploitation strategy was identified and funded by the UK Weapons Science Technology Centre (WSTC). A contract (WSTC0036) to undertake this work programme was awarded to a consortium led by QinetiQ Ltd and included participation from Kent Engineering Services and the University of Sheffield. The 15 month task was completed in May 2016.

The data exploitation strategy developed by the WSTC work programme, comprised two separate processes. The first process related to the data utilisation and verification approach, that effectively defined the tools and verification approach needed to provide the necessary data logger evidence base. The second process utilised the verified logger data for the purpose of making munition surveillance and life extension decisions. The exploitation strategy adopted, comprises a process by which information from a typical UK munition Safety and Suitability for Service programme, can be used to establish criterion against which remaining weapon life can be assessed.

This paper primarily focuses upon the key features of the two processes developed within the WSTC work programme.

1.0 INTRODUCTION

The purpose of the work, encompassed by the WSTC programme, was to identify data utilisation and verification strategies, which could be practically exploited by the UK weapons community, to support surveillance and life extension decisions. The objective of such strategies is to realise whole life cost savings, by preventing premature disposal or nugatory testing of munitions. The work programme, undertaken by the QinetiQ consortium to achieve the required objective, comprised four inter-related tasks. This paper primarily focuses upon two of those tasks. Although, those tasks are addressed here sequentially, in practice they are likely to be undertaken at different stages within the life of a munition and frequently by different authorities.

The first process of the exploitation strategy for environmental logger data, defines the tools and verification approach which are needed to provide the necessary data logger evidence base [1]. The strategy adopted is a general framework by which generic environmental logger data can be utilised for safety critical decisions. It is also intended to ensure logger information is reported in a reliable and dependable manner. The verification approach developed adopts criterion which are challenging, but should be achievable by the majority logger data provided it is of reasonable quality and providence. The tools and verification approach are applicable to all types of Environmental Logger data i.e. temperature, humidity, shock, vibration and pressure.

The second process of the exploitation strategy, utilises the verified logger data for the purpose of making munition surveillance and life extension decisions [2]. The approach adopted, using information from a typical UK munition Safety and Suitability for Service programme, can be used to establish criterion against which remaining weapon life can be assessed.

Both processes of the exploitation strategy, utilised a consistent set of examples to demonstrate how the various tools and processes could be applied. The examples were all extracted from a data base of "real world" measured logger data, acquired during long term operational deployment. The demonstration examples show how various commonly encountered practical issues can be addressed, when attempting to use "real world" information, to establish life extension of a weapon.

2.0 DATA EXTRACTION AND VERIFICATION PROCESS

2.1 Background

Existing environmental data loggers are able to monitor and record a variety of environmental parameters. The most commonly measured environmental parameters are; temperature, humidity, pressure, shock and vibration. However, not all of these environmental parameters are monitored and recorded for every logging application. The selection of which environmental parameters are to be measured, is usually dependent upon the anticipated degradation mechanism and "life" parameter to be established i.e. storage life, deployed life, flight life. Currently, it is not uncommon for only one or two environmental parameters to be monitored for a particular application. However, the data analysis and verification process needs to be capable of utilising each of the commonly measured environmental parameters, as if it were the only parameter measured. With that said the process needs also to consider the advantages of measuring multiple parameters when to do so could enhance the outcome of the process. Additionally, to ensure a verification process is consistently adopted, the data analysis process needs to be integrated with the verification process.

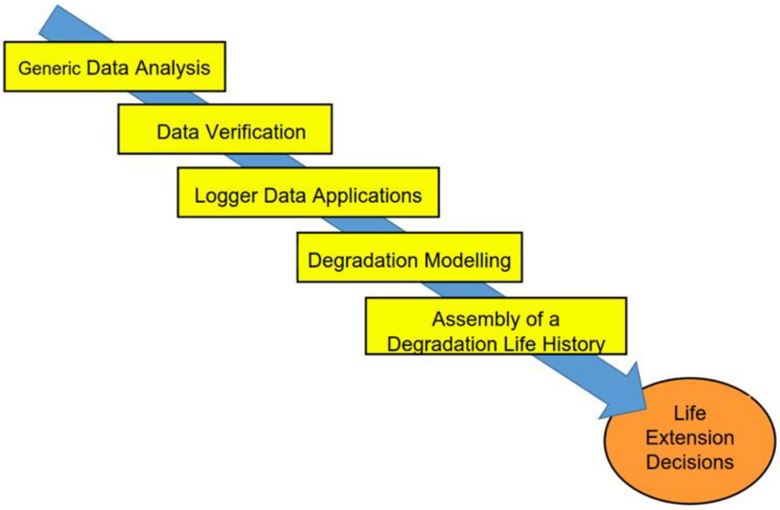

Figure 1: Overview of Data Extraction and Verification Process

2.2 Key Phases of Process

2.2.1 Generic Data Analysis.

This aspect of the process addressed generic data analysis issues associated with the utilisation of environmental logger data. The issues addressed related to; sub-dividing individual records, combining and assembling records as well as identifying erroneous and lost data. However, in order to undertake these data analysis activities, an understanding of the applicability of individual records needs to be first established. Indeed, the data analysis activities are intrinsically linked to an understanding of the conditions represented by the measurements. As a consequence, advice has been provided on issues associated with identifying the conditions represented by the measurements, from the data itself. This advice is provided specific advice on specific issues related to temperature, humidity, pressure, shock and vibration measurements.

2.2.2 Data Verification.

For the exploitation of environmental logger data to be effective, confidence in the measured data is essential. This aspect of the process extended and interacted with the data analysis aspects using a three stage verification process, from which confidence in the overall data set can be achieved. Essentially, the first stage of the verification process is to gain an understanding of the conditions represented by the measured data. The second and third stages of the verification process are to respectively compare, the measured logger data with similar data from the same acquisition process (i.e. from similar loggers on the same deployment) and with applicable information available from wider sources. The extent and quality of the data collection exercise, will dictate whether the bulk of the verification, is completed within the second or third stages.

2.2.3 Logger Data Applications.

The final two aspects of the process all effectively address the use of the environmental logger data within degradation models. However, not all logger data is acquired solely for use in degradation models. For example many shock loggers are not used to establish elapsed life but to act as munition “abuse” indicators. As a consequence, before focusing on aspects related to degradation, the process reviewed the most common uses for logger data and how the data may be used to make decisions. This aspect of the work also addressed and advised upon the potential capability of existing data loggers to measure the various environmental conditions experienced by a munition.

2.2.4 Degradation Modelling.

The quality of the degradation models adopted commonly range from; simple degradation models incorporating general and conservative numerical parameters, through enhanced simple degradation models incorporating targeted munition specific numerical parameters to verified complex degradation models used to make unsupported life predictions. Over the years a number of simple degradation models have been postulated, for munitions and energetic materials. From the viewpoint of utilising logger data, three generic approaches are commonly considered viz. chemical degradation (mostly associated with temperature and humidity), high cycle fatigue damage (mostly associated with vibration) and low cycle fatigue (mostly associated with shock, thermo-mechanical stress and pressure). In addition some consideration is given to chemical migration (mostly associated with temperature). The work associated with this aspect of the process addresses issues associated with each of the degradation models commonly used for munitions and energetic materials.

2.2.5 Assembly of a Degradation Life History.

The last aspect of the process related to issues associated with the assembling of degradation life histories for groups of munitions. It essentially considers the commonly encountered situation were information from a modest number of loggers are available. However, the need is to establish how those apply to a larger group of munitions.

2.3 Generic Data Analysis.

2.3.1 Identify Service Situations

The approach used to analyse data acquired from environmental data loggers, will largely depend upon the purpose of the exercise. The usual approach adopted in the UK is to establish the degradation, by comparison with the environmental conditions applied during the munition Safety and Suitability for

Service sequential environmental testing programme. Although this approach tends to underestimate the life of the munition, it does ensure that the munition stays within bounds of existing evaluations. Whichever approach is used, environmental logger data encompassing the entire elapsed life of the munition, needs to be assembled. This may be from a single logger or from several loggers utilised during different phases of its life. This may involve sub-dividing individual records, combining and assembling data, undertaking statistical analysis of the data as well as identifying erroneous and lost data. Gaps in the data may need to be filled with suitable information, either from facilities or suitable adopted meteorological data.

An integral part of the data verification process, for data acquired by environmental data loggers, is establishing an understanding of the conditions encompassed by each record. This is also an essential pre-requisite, before any manipulation and processing is undertaken on environmental logger data. Whilst, some knowledge is likely to be available as to the service situations experienced by a particular munition, these are unlikely to be highly detailed. As a consequence, it is usually necessary to correlate events within the environmental logger record, with likely service situations.

The ability and approach used to identify service situations from within an environmental logger record, will depend upon the environmental parameter measured (temperature, humidity, shock etc.). Within limits, identifying different service situations, from within temperature, shock or vibration logger records, is generally possible. Conversely, humidity and pressure logger records, only allow the identification of some very specific service situations. However, they may prove valuable to confirm the service situations, identified with other parameters. Generally, identifying service situations, when several simultaneously measured environmental parameters are available, is considerably easier than when only a single parameter is recorded.

The WSTC work programme supplied advice on the identification of service conditions from consideration of temperature, humidity, vibration, pressure and shock data. For the purpose of this paper only temperature logger measurements is considered. For such data it may be possible to separately identify periods in; office conditions, long term munition storage, unprotected storage, partly protected storage, conditioned storage and usually air transport. Temperature measurements alone, will generally not allow the type and periods of land transport to be identified. The predominant record discriminators, that may be used to identify Service situations from temperature records, relate to the characteristics of the diurnal temperature cycle and the mean daily temperature.

- Office conditions are usually characterised by a consistent mean daily temperature of around 20 °C and a small temperature diurnal span (daily maximum to minimum). Although the daily variations will be predominantly due to meteorological conditions, some variations due to contributions from human activity, as well as the influence of heating systems, are often apparent.

- Long term munition storage occurs within substantial unheated structures which usually also have a substantial thermal mass. As a consequence long term munition storage, can be usually characterised by a consistent mean daily temperature of typically 5 °C to 15 °C (depending upon season) usually with only a small temperature diurnal span.

- Unprotected storage, can be characterised by a large variations in diurnal temperature, especially were the contribution from solar radiation is significant. The mean daily temperature will also be consistent with the geographic location and local meteorological conditions. The characteristics of the diurnal temperature variations are typically those of the local meteorological solar radiation cycle i.e. the peak occurring a little after noon local time and has an influence only during periods of daylight.

- Partly protected munition storage, is usually deliberately arranged to limit the variations in diurnal temperature. However, diurnal temperature variations will still be discernible, where the contribution from solar radiation occurs. Partly protected munition storage will mostly still experience the mean daily temperature, which will again typically be consistent with the geographic location and local meteorological conditions. The characteristics of the diurnal temperature variations are those of the local meteorological solar radiation cycle but markedly delayed by the thermal effects of the protection. As a consequence, the peak temperature is likely to occur somewhat after noon local time, typically by several hours. Also the influence of the local meteorological solar radiation cycle may still be apparent, even after sunset (due to the influence of the thermal lag).

- Conditioned storage is usually characterised by a very consistent mean daily temperature, of typically around 20 °C (although temperatures of up to 26 °C has been observed). These temperatures will be accompanied by either no temperature diurnal span or one which is very small. Not infrequently, conditioned storage is used during the local summer months only. It may be switched on, early spring and switched off again in early winter. Conditioned storage, when the conditioning system is not operating, may give rise to conditions equivalent or worse than partly protected storage. This is commonly because the packing density, within the conditioned storage, is frequently high and consequently no cooling airflow occurs.
- Air transport of munitions, normally occurs in unconditioned aircraft holds and hence occurs at low temperature. The low temperature cycle will be related to the duration of the transport flight and will not relate to the meteorological diurnal temperature variations at the departure or arrival locations. Further confirmation that air transport has occurred can be that, the peak temperature of the meteorological diurnal temperature cycle occurs at different times before and after the air transport, provided transportation is to another time zone. Generally, air transport and its duration, can usually be clearly identified with considerable confidence from a temperature record.

Generally a minimum of two parameters should be used by a user to be able to reliably identify most service situations. The most useful pair of parameters is temperature and shock/ vibration. Together these have the potential to permit most service situations to be identified. In some situations, temperature and shock logger data has been utilised as a means of verifying, a contracted transportation logistics chain, was actually followed.

2.3.2 Erroneous and Defective Data

Once the service situation encompassed by an individual logger record has been identified, a number of tasks on the data record can be performed. The most important task at this stage is to identify obviously erroneous and defective data. Some manipulation of the record may also be undertaken, for example, to extract specific service situation for further consideration, to include logger records from other service situation or to make-good defective data. These aspects are addressed later within this section.

Identifying service situations from within an individual logger record, goes hand-in-hand with the preliminary identification of obviously erroneous and defective data. Quite a number of defects can be detected at this stage, although some may not be visually apparent in a single logger record. Defective operation, of the logger itself, can frequently be identified from inspection of individual records. Identifying such conditions is important. This is because, whilst, environmental data loggers are robust and reliable, they are also usually low cost devices, intended to operate for over long periods, using only low levels of power. These requirements usually mean that logger data measurement quality is unlikely to be as good, as would occur in laboratory conditions. This can give rise to measurement issues, which should not be ignored when utilising the derived data.

Defective operation of the logger may arise for several reasons. As with most measuring devices, the logger sensor and its associated conditioning equipment have the potential to be influenced by parameters other than that intended to be measured. Such unintended influences may appear superimposed upon the measured parameter, as uncorrelated noise or (more problematically) correlated to the measured parameter. Unintended sensor influences are well documented for most types of sensor technology, and it is important to understand the type of sensor technology utilised by a particular logger. Moreover, the low power and low cost requirements for loggers may make some logger designs prone to unintended sensor.

For example, some shock and vibration sensors can be sensitive to thermal effects. A number of commonly encountered sensor issues are set out below.

- Temperature. Most temperature sensors used in loggers are reasonably robust and not unduly influenced by extraneous influences. They usually have greatest accuracy at laboratory ambient, becoming progressively more inaccurate at high and low temperatures. Defects with the sensor (or the cold junction in a thermocouple) usually result in apparent step changes in the measurements which may appear at the upper or lower limits of the measurement range, with the step change persisting for a protracted period. Any step change in temperature measurement is worthy of review, especially if it does not coincide with daily metrological temperature variations. In some instances step changes which occur daily, but do not coincide with daily metrological temperature variations, may be due to manmade influences or peculiarities of the storage arrangement.
- Humidity. A variety of humidity sensor technologies are in use with logger. Due to the demands of loggers of small size, low cost and low power, many are not particularly accurate and may not be fully corrected for temperature and pressure variations. Humidity sensors used in loggers may not measure Relative Humidity directly, but rather measure dew point or absolute humidity. The conversion to Relative Humidity is usually not accurate, which can result in apparent Relative Humidity values of greater than 100% and less than 0%. Some humidity sensor technologies can become saturated at high Relative Humidity values, resulting in erroneous high measurements for the considerable period they require to recover.
- Pressure. Pressure sensors used in loggers are robust and not unduly influenced by extraneous influences. Pressure measurements can be slightly influenced by temperature but the sensors are more likely to be sensitive to severe vibration and shock conditions. Nevertheless, a well-engineered pressure logger should mitigate the sensitivity of the sensor to vibration and shock conditions.
- Shock and Vibration. Shock and Vibration sensors used in loggers are likely to be low cost devices operating in conjunction with low power signal conditioning equipment. Such sensors are likely to have a much greater sensitivity to extraneous parameters than would be the case for conventional vibration and shock sensors. Specifically, they are likely to show sensitivity to cross axis motions, base strain, temperature and temperature change. Anti-aliasing filtering is likely to be non-existent or of limited capability (commonly a simple mechanical filter). As a consequence, the occurrence of higher frequencies may result in aliasing errors, in which the higher frequencies are reflected as low frequency contributions. Shock loggers may be repeatedly triggered in a vibration environment if the shock threshold levels are set inappropriately. Although such an occurrence can be determined from inspection of the shock waveform, this may not be possible with some loggers. Conversely, vibration loggers may be overloaded in the presence of shocks. Such overloads may be indicated by clipping of the vibration waveform, but can also appear as a low frequency oscillatory motion lasting many seconds.

In addition to the above sensor issues, the WSTC work programme [1] supplied advice on the sensitivity of batteries to temperature, poor physical retention of the battery, interference from electro-magnetic influences as well as the ingress of dust and water. The work programme also addresses how such faults can be identified from the characteristics of the measured data.

2.3.3 Data Manipulation

Sub-dividing individual logger records is probably the most commonly utilised preliminary manipulation undertaken. It is also one of the simplest operations to implement and undertake. Logger records may be sub-divided for a variety of reasons, but one of the most common, is to extract specific periods of the same service situation. This is usually to allow comparisons and statistical computations to be undertaken. Sub-dividing the record may also be undertaken to remove periods of the record, which are not of interest or to remove defective data. If the intent is to remove defective data from a logger data record, it is likely that the extracted data will need to be replaced. Approaches for incorporating data into an existing record are addressed in detail hereinafter. Another reason for sub-dividing the data is to facilitate the alignment of climatic information to permit a comparison across season and/or time of year. Whilst, sub-dividing individual logger records into diurnal data can be undertaken, it is usually more convenient to re-align (or pivot) the entire data record into a sequence of individual days.

Sub-dividing the data to facilitate the alignment of logger data across season and time of year can be particularly important for temperature information. This is because temperature induced degradation rates can vary significantly over the course of a year, in all climatic zones. This is especially the case for munitions deployed in the hot dry as well as the warm wet climatic zones. There is no current consensus as to how the yearly data are sub-divided. However, the most commonly utilised categories are, by month or season. Sub-dividing by calendar month allows direct comparison with world-wide meteorological databases of monthly average information. Sub-dividing by season is often more practical and relevant to users. In such cases, the actual sub-division periods, are usually best identified by inspection of the data records.

Combining and assembling logger records is almost entirely undertaken when historical information is used to determine the elapsed life of a munition. It is a process which can be fraught with difficulties and has the potential to result in erroneous and misleading life estimates. The most straightforward combination of logger data is to facilitate the assembly of information from several different stages of a munition's life. This is commonly needed when the environmental data loggers is changed during the life of the munition. This is commonly necessary to facilitate battery replacement and the downloading of data before the available logger memory is exhausted. Provided the loggers are similarly located and the exchange takes place straight away, then the two data sets can practically be assembled into a single record.

The most common issue, when exchanging loggers located with a specific munition, arises when one logger is removed but is not replaced for several days or sometimes weeks. This usually occurs because operational and procedural constraints prevent a simple exchange of loggers. In such cases it may be necessary to make good any resultant gap in the data. This may be particularly relevant if the environmental conditions during the data "gap" are severe i.e. during the summer months for climatic data. Several approaches are available to fill such data "gaps". However, if the data "gap" is relatively short, then the usual approach is to undertake a linear interpolation between the end of one record and the start of the next. Experience suggests this works reasonably well for climatic data, but no realistic solutions are available for the loss of vibration and shock data. As loggers are commonly exchanged when the munition is in storage, the likelihood of severe vibration and shock conditions occurring is generally low. A caveat to this would be that some manual munition handling may be required to access the logger.

2.4 Data Verification.

2.4.1 Overview of Process

For the exploitation of environmental logger data to be effective, confidence in the measured data is essential. To this end a three stage frame work verification process has been adopted from which confidence in the overall data set can be achieved.

The verification approach adopted is essentially that published in PD IEC/TR 62131-1 "Dynamic field data including validation - Process for validation of dynamic data" [3]. With that said, the three stage validation process is not unique to that publication; rather it comprises a set of logical steps that most assessors of environmental data would work through prior to utilising any measured information. The intent is that each phase should build on those preceding it and are normally undertaken in order. The three phases of the process are described in more detail below.

- Phase 1 - Data Source and Quality. This phase undertakes a review of each individual record, to establish that it appears sound. The main tools in this are; the visual appearance of the data and consideration of its likely measurement and analysis errors.

- Phase 2 - Intra Data Comparison. This phase is undertaken on a data ensemble, to establish that the data set is self-consistent. This usually involves verifying that any trends and characteristics are consistent across the data set.
- Phase 3 - Inter Data Comparison. This phase is undertaken on several data sources, to establish that the data set is comparable with other similar data sets or (failing that) with expectations.

2.4.2 Phase 1 of Verification Process

The purpose of Phase 1 of the verification process is to review each individual logger record, to establish that it appears consistent. The main tools to achieve this have been discussed earlier. Nevertheless, as a check list, assessment of the data quality of each data item would normally include consideration of the following aspects.

- Association. A data item is only of use if it is possible to identify the measurement location (and axis for vibration and shock data) with respect to the munition, as well as an understanding of the service conditions to which the measurements relate. Whilst association information is unlikely to be entirely adequate, the data user should not be in a position of having to make significant judgements as to the conditions and locations to which the data refers.
- Appearance. The characteristics of many measurement faults can be identified from the appearance of the data alone. Whilst, the identification of such trace characteristics may not be conclusive, as they are often “warning signs” of problems justifying further appraisal. Aspects related to “Identifying Erroneous and Lost Data” were addressed previously. As a minimum the data user should be confident that the characteristics under investigation have not been unduly modified by measurement noise and errors.

2.4.3 Phase 2 of Verification Process

The purpose of the Intra Data Comparison (Phase 2) of the verification process is to establish that the data from a group of loggers are consistent. This usually involves verifying that any trends and characteristics are consistent across the group of logger records. The extent to which trends exist within the data will depend upon; the parameters measured, the conditions under which the measurements were made and knowledge of how local conditions could influence the measurements. In most cases, the initial identification of trends, within a data ensemble, will arise as a consequence of the work to identify service usage situations. The work described previously, should already have identified different periods when each logger is experiencing environments arising from; office conditions, long term munition storage, transport, unprotected deployed storage, partly protected deployed storage or conditioned deployed storage. Each of these service situations will generate different characteristics which can be compared across a group of loggers.

The identification of trends, within a data ensemble, is commonly initially achieved by plotting all the different records comprising the data ensemble, against a common time base. This is illustrated in Figure 2, where data from eleven temperature loggers are overlaid. This example shows that, for the majority of the logged period, the eleven loggers were experiencing very similar temperature conditions. That is the case, whether the data are considered daily, weekly or seasonally. A few loggers do show slightly different characteristics during the winter period, but with quite similar underlying seasonal temperature conditions. This would suggest that some of the loggers, were at the same geographical location, but were (less well) stored within different facilities over the winter.

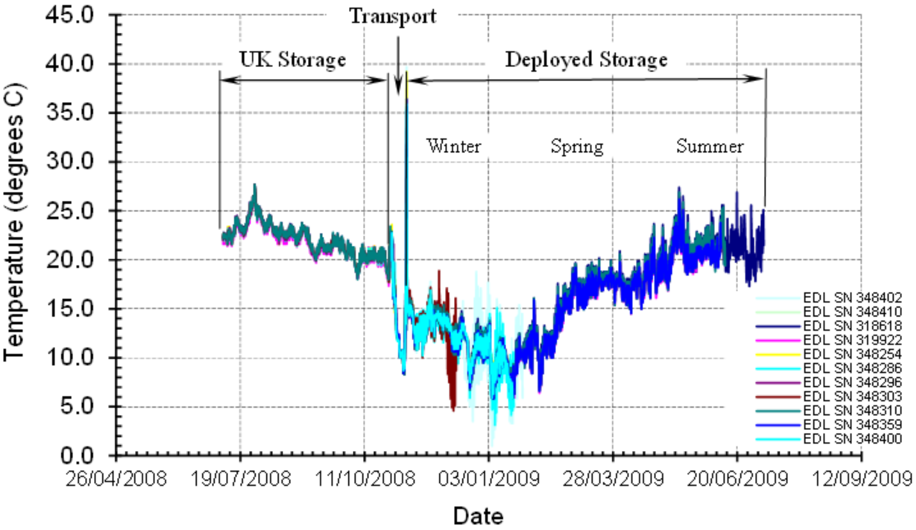

Figure 2: Overlaid Temperature Data from Eleven Loggers

Whilst plotting all the different records together on a common time base gives a good visual comparison, it can sometimes be difficult to interpret the outcome. Moreover, the approach does not quantify the comparison. One approach, which can be used to support the visual comparison, is to undertake a pairwise comparison of the measured records. Using two of the temperature records, from the previous example, a pairwise comparison is illustrated in Figure 3 and Figure 4. Those figures show the temperature data from one logger, plotted against temperatures data from another logger. This approach is only viable if the data from the two loggers are available at coincident time points. This is because each point in the figures represent temperatures occurring at the same time.

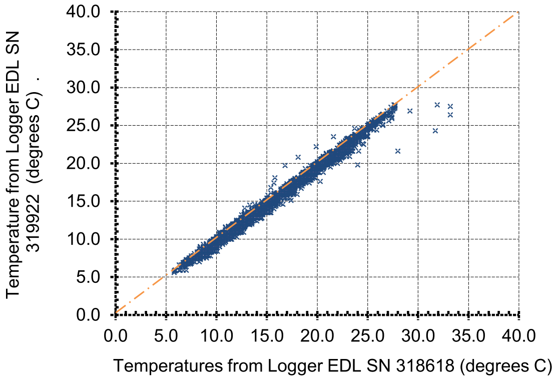

Figure 3: Comparison of Logger Data

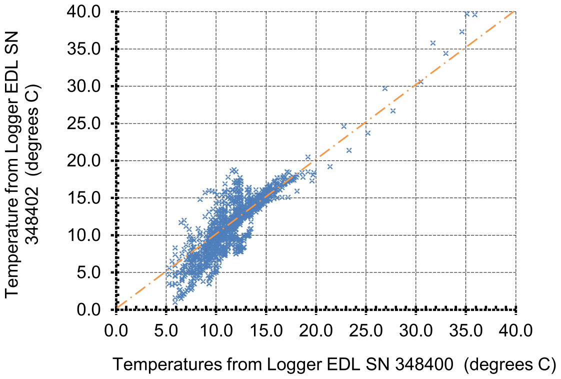

Figure 4: Comparison of Logger Data

In the example shown in Figure 3, the vast majority of the temperature values, from the two loggers, follow essentially a straight line. This indicates that the records from the two loggers are highly correlated. If required, a statistical correlation coefficient could be computed to quantify the relationship. A second example is shown in Figure 4, which compares two of the loggers, which appeared to be stored in different facilities over the winter period. In this case, the correlation between the temperatures from the two loggers is not as good as that shown in the previous figure but the underlying correlation is reasonable.

In addition to the identification of trends within a data ensemble, plotting all the different records against a common time base can also be useful to identify defects in the data. This is illustrated in Figure 5, where data from three temperature loggers, are overlaid. This example shows that although the loggers are clearly at the same deployment site, for several periods the munitions associated with the loggers were stored differently. Of particular interest here, is that for several periods, the records from the loggers show distinct discrepancies which could indicate faulty data.

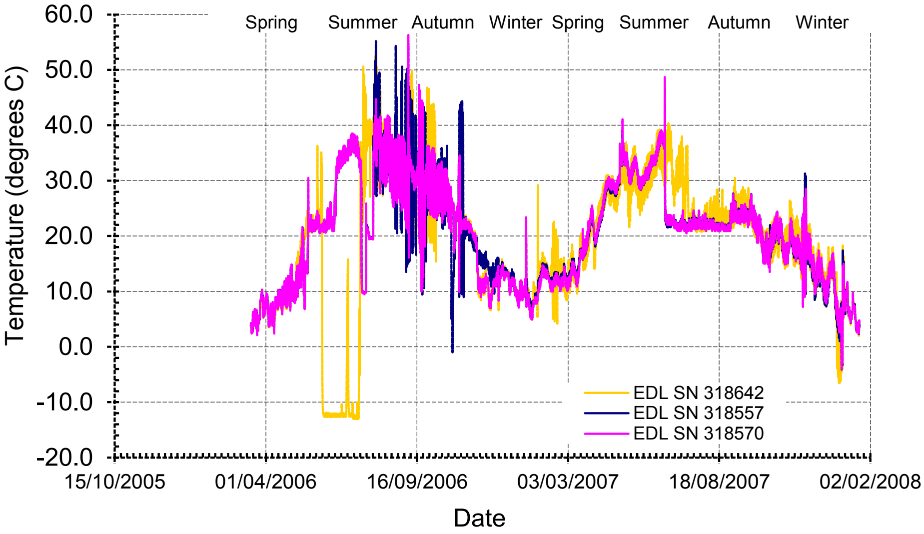

Figure 5: Overlaid Temperature Data from Three Loggers

2.4.3.1 Temperature.

Of the commonly acquired climatic conditions (temperature, humidity and pressure), temperature can often prove to be the most useful for the purposes of intra data comparison. Meteorological temperature generally applies to a reasonably broad geographic area, but has temporal characteristics which can be unique. This can readily allow the identification of temporal characteristics across a group of loggers, which may be deployed to a similar location, but are not necessarily in close proximity to each other. An example of such a comparison is shown in Figure 2. The temporal characteristics that may be used for this purpose are the daily (diurnal) temperature cycle, the temperature variations that occur day to day and the underlying seasonal variations. Even when loggers and munitions are deployed at the same location, but stored differently, the underlying temporal temperature signature can often still be compared, provided some limited analysis is undertaken.

2.4.3.2 Pressure.

Pressure is influenced by altitude and meteorological conditions. Meteorological pressure conditions apply to a large geographic area and have temporal characteristics which vary over relatively long periods (days). Although these temporal characteristics can be used for the purposes of intra data comparison, a larger data set than for temperature is usually required. Pressure does have the advantage that its influence, is difficult to modify by different storage methods. As a consequence, a common pressure signature can usually be detected even when loggers are deployed at the same location but stored differently. The exception to this is when the munitions are protected against nuclear, biological and chemical warfare conditions as such protection usually involves a degree of deliberate over pressure. This is typically the case with munitions stored on ships (and submarines but for different reasons).

2.4.3.3 Humidity.

In some instances humidity can be a used for the purposes of intra data comparison. The signature of any underlying meteorological humidity levels can be used as the basis for comparison. However, the underlying meteorological humidity may well be relatively modest compared to local variations in humidity that can occur due to storage condition and due to the effects of any humidity control (desiccant and similar devices). It is also worthy of note, that humidity measured by a low cost logger may be significantly different to that measured by good quality meteorological instruments.

2.4.3.4 Vibration.

The vibration signature, arising from land transportation, can be used for the purposes of intra data comparison. That is provided that the different loggers/ munitions are transported together. If land transportation occurs at different times, different vibration signatures will be experienced, even when using the same class of vehicle and route. It may be possible to use the vibration signature, arising from air and sea transportation, for the purposes of intra data comparison. However, such methods of transportation usually generate low levels of vibration which may not be sufficient to trigger vibration data logging.

2.4.3.5 Shock.

The shock signature, arising from handling, can have some limited use for the purposes of intra data comparison. However, it only has value if a common handling shock signature can be discerned.

2.4.4 Phase 3 of Verification Process

The purpose of the Inter Data Comparison (phase 3) of the verification phase is to establish that the data set is comparable with other similar data sets or, failing that, with expectations. The approach is to establish the consistency of the underlying severities and significant features. The process used within this phase, is similar to that of the previous phase. However, on this occasion, the logger data will be compared with related data sources which may not be entirely comparable. For example, the previous phase made a comparison between the data from several temperature loggers associated with munitions stored in either the same or adjacent facilities. In this phase, the logger data could be compared with; temperature data collected in the same adjacent geographic area at the same time, historic temperature records for the area, or with expected features from available publications. All of these can be used to confirm overall trends and broad features are comparable, but not that specific details are correct.

This third verification phase becomes particularly important when the data ensemble, contains relatively few records. In such cases it is recommended that to establish working confidence, data should be compared with at least three separate data sets. In this case, as a general rule-of-thumb, a logger record should be positively compared with a minimum of three other independent data sets, before it is used for decisions which may have safety and operational implications. For decisions concerning the life of munitions, which have safety implications, logger records should be compared with as many independent data sets as is reasonably practical. Establishing the consistency of data sets, permits verification that the assumed operations conditions, used to certify and accept the munition into service, are actually applicable.

The extent to which this verification phase can be completed will depend upon the parameters measured, the conditions under which the measurements were made and knowledge of how local conditions could influence the measurements. The WSTC programme provided advice on a variety of approach which could be adopted in this verification phase.

An example of the implementation of this verification phase, is shown in Figure 6. This uses the same data as shown in Figure 5, but compared with “independent” temperature logger data acquired by another agency, from three loggers located on a different munition which was fully exposed to meteorological conditions including full solar radiation. In this case, the “independent” logger data exhibits a much larger daily temperature variation (due to the effects of direct solar radiation. The “independent” temperature data was only concurrent with the logger data of Figure 5, for a period of sixteen weeks, part of which was when the Figure 5 loggers, had operational temperature conditioning. Despite these differences, comparison of the figures would suggest that the two groups of loggers were located in the same broad geographic location. This is because there is a clear commonality of the underlying meteorological temperature signature.

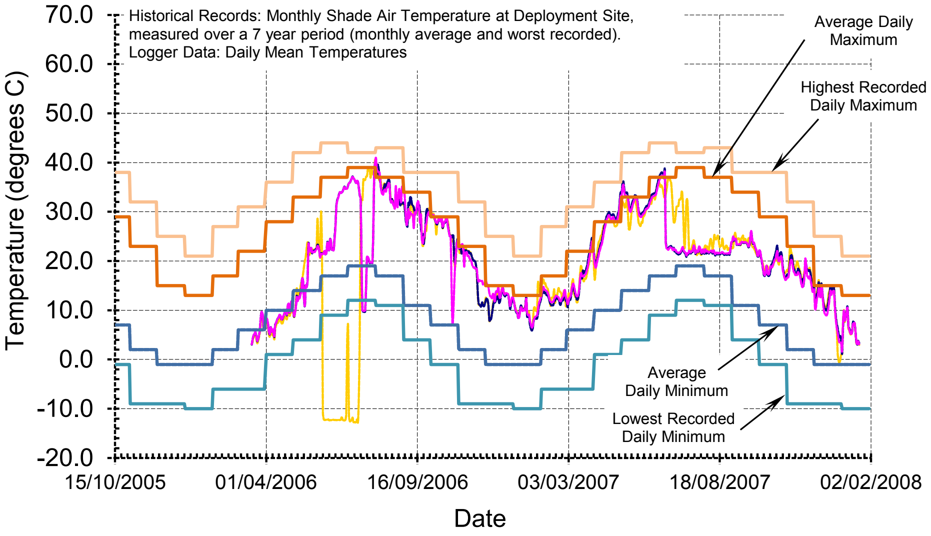

Figure 6: Inter data Comparison with Independent Logger Data

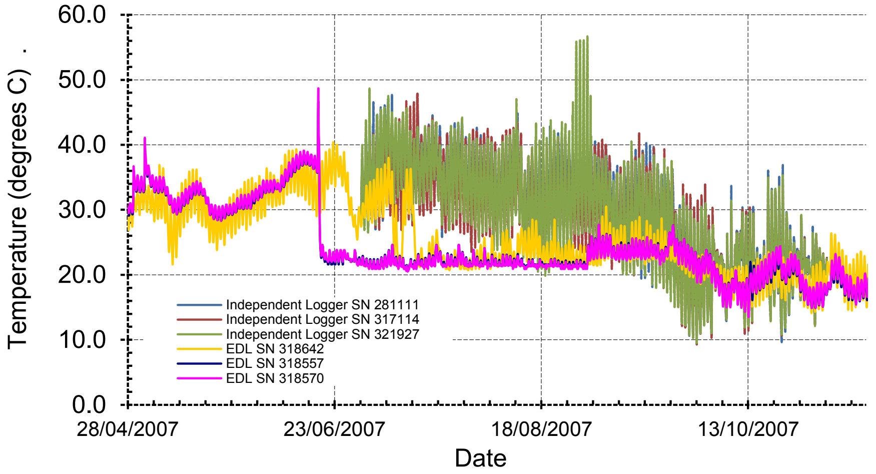

Figure 7: Inter data Comparison with Historic Meteorological Data

Continuing with the examples, the logger data of Figure 5 can also be compared with historical World Meteorological Organisation (WMO) data [4] related to a site adjacent to the deployment zone. In this case the information relates to 7 years of three hourly measurements of shade air temperature made from within a Stevenson screen. In this case, monthly information is available, comprising daily maximum and minimum averaged for each month, over the 7 year period. The worst case monthly maximum and minimum temperature values are also available related to the 7 year measurement period. In order to undertake a comparison using this historic data, it was necessary to compute the mean daily temperature for the logger data. The resulting comparison is shown in Figure 7. That figure indicates the logger data compares well with the historic meteorological data. That is excepting for two periods when temperature conditioning was operational. However, it will be observed that for much of the deployment period, the daily mean logger data is close to the average daily maximum. This is almost certainly because solar radiation is having a greater influence on the storage facility than on the temperature sensor in the Stevenson screen. It is also worthy of note that the low temperature "drop out", discussed hereinbefore, is significantly below the lowest temperature recorded for the appropriate month.

This would further support the hypothesis that that particular low temperature "drop out" is erroneous.

Yet a further inter-data comparison can be made with the Figure 4 logger data. That is to compare measured daily temperature cycles, with those from publications such as STANAG 4370 AECTP 230. For the purpose of illustration the monthly diurnal temperature cycles for August (the most severe months for high temperatures) are shown in Figure 8. Although only one month is illustrated here, comparison across the entire calendar year and between loggers is also viable. The main difficulty in undertaking diurnal comparisons is that the data has to be reformatted into daily "blocks". Such reformatting is well worth the effort, as daily statistics and daily equivalent damage can be subsequently computed. Those parameters form the basis for degradation modelling, which is addressed later in this report. It should be noted that the logger data, in Figure 8, are in Coordinated Universal Time (UTC) and are not adjusted to local time. Hence, the peak temperatures for the August data are occurring several hours earlier, than would be expected from the effects of peak solar radiation. For the purposes of this illustration, the diurnal cycles, from STANAG 4370 AECTP 230, have been adjusted to represent local time.

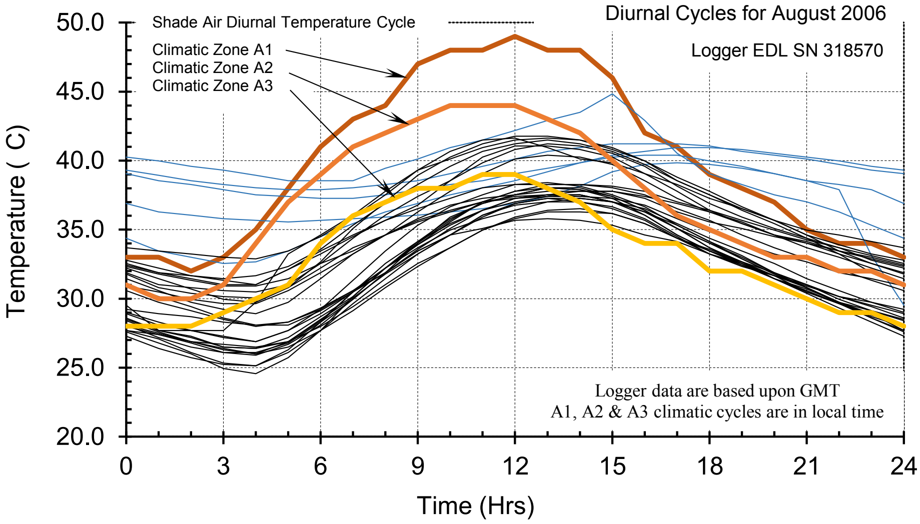

Figure 8: Inter data Comparison against Diurnal Cycles for Climatic Zones A1, A2 & A3

2.5 Degradation Modelling.

2.5.1 Overview

Although, Environmental Logger Data is able to provide information on actual usage conditions, the data needs to be evaluated against the failure modes and degradation rates, before it can provide useful comparative information on munition life. Over the years, a number of degradation models have been postulated, for munitions and energetic materials. Moreover, a number of on-going studies are currently looking at specific degradation models related to failure modes of energetic materials. The simple as well as the enhanced degradation models are well document and it is not intended to reproduce that information in this paper. However, the practical issues associated with utilising such simple degradation models are briefly addressed.

A primary limitation on the use of any of any degradation models is knowledge of its applicability. Essentially the choice of a particular degradation model needs to be based upon knowledge of the potential critical failure mechanisms that may limit the life of a particular munition. Within the UK, the identification of potential critical failure mechanisms is initially based upon the extensive safety and suitability for service environmental testing programme undertaken on munitions before they enter service. Such programmes subjects both energetic material samples and complete munitions, to sequential environmental testing programmes. These programmes are intended to generate aging and degradation of the munitions and specifically, the energetic material. Following such exposure the material samples and complete munitions are subject to extensive investigatory work to identify potential life limiting damage, failure modes, degradation and if applicable degradation mechanisms.

2.5.2 Chemical Degradation Models

Thermal or chemical degradation can produce changes in the chemical composition of materials resulting in unacceptable degradation of safety or functioning characteristics. Energetic materials are inherently unstable and continually undergoing slow decomposition even at ambient temperature. The decomposition reaction rate is altered by temperature and sometimes by other factors such as humidity. Examples of chemical failure modes include decomposition reactions of propellants, (even when modified by the presence of stabilisers), corrosion of metals, incompatibility between materials and also the degradative effects of solar radiation on natural and synthetic organic materials such as rubbers and plastics.

The chemical degradation model traditionally used for initial life assessments of virtually all munitions and energetic materials, is that due to Arrhenius. A model based upon Arrhenius [6] is almost always used to establish design life and the initial service life of munitions. The Arrhenius chemical degradation model is also used as the basis for establishing the thermal exposure necessary for the Safety and Suitability for Service environmental testing programmes. As a consequence, when using Environmental Logger temperature data to evaluate the life of a munition, the initial exercise almost always adopt a simple Arrhenius chemical degradation model.

The most common form of the Arrhenius based relationships, used with logger data, is that which allows the calculation of “Equivalent Temperature”. The equivalent temperature is that which would generate the same degradation damage if the material was at a constant temperature.

The calculation of equivalent temperature from the logger measurements can utilise any number of individual temperature measurements. However, there are advantages, if equivalent temperature is computed on the temperature measurements when partitioned into daily groups. Daily equivalent temperature is usually computed from diurnal temperatures (such as those previously used to verify the temperature data). Calculating daily equivalent temperatures, at the same time as other diurnal parameters, is a relatively straightforward process. Moreover, it can also be used as an additional verification parameter. As daily equivalent temperatures are an indicator of chemical degradation damage, the derived values can be used to identify and categorise the conditions experienced by the logger and its associated munition.

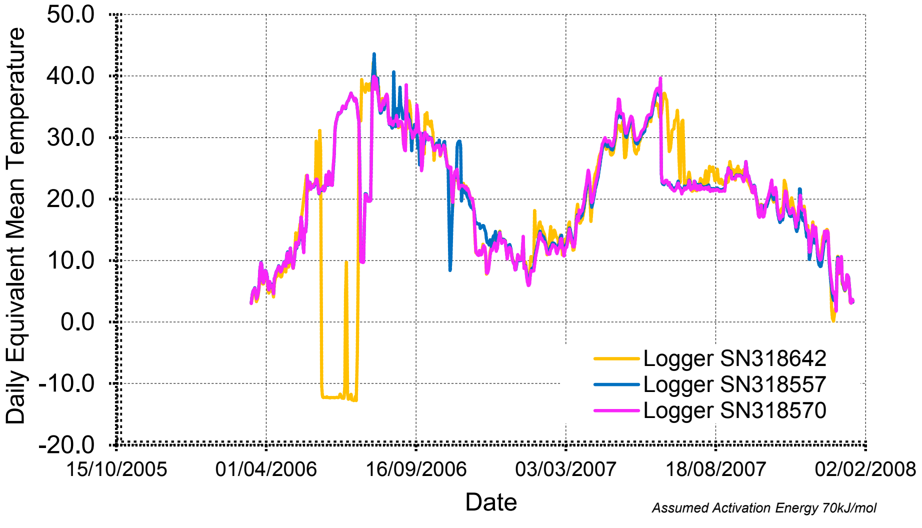

Figure 9: Example of Daily Equivalent Temperature

The daily equivalent temperatures, for the same three loggers used in previous examples, are shown in Figure 5. In this example, daily equivalent temperatures provides a much better understanding of the chemical degradation potential, than would be achieved from consideration of daily maximum temperatures. Specifically, some of the largest daily temperatures, apparent from the direct temperature measurements in Figure 9, are indicated to be of lesser significance, when viewed as daily equivalent temperatures. This is because peak daily temperatures may only occur for a relatively short period. It has to be said that, for this particular example, daily equivalent temperature provides little advantage over average daily temperature when used solely as a validation tool. However, this is not always the case, as daily equivalent temperature takes into account the degradation damage that high temperature exposure can generate. Also daily equivalent temperatures can be easily manipulated further to establish elapsed life and used to establish degradation rates for life extension purposes.

Daily equivalent temperatures are a useful starting point, for further manipulation to establish elapsed life and degradation rates, for life extension purposes. Daily equivalent temperatures can also be used, as the basis for establishing factors of accelerated degradation. It is also relatively straight forward, to transform daily equivalent temperatures into values which can be compared against the testing of samples of energetic materials or the complete munition in the Safety and Suitability for Service environmental programme.

Figure 10 shows, for the three loggers used in previous examples, the result of converting the daily equivalent temperatures, into the equivalent number of days that would give the same damage as the diurnal temperature test cycle representing the A1 Storage and Transit (S&T) climatic zone (as defined in STANAG 4370 AECTP 230 [5]). The A1 Storage and Transit diurnal cycle, is commonly used in the testing of the associated munition within its Safety and Suitability for Service environmental testing programmes.

Another way to view the information of Figure 10 is as the cumulative days of A1 Storage and Transit diurnal cycle, which is shown in Figure 11. The first piece of useful information revealed by that figure, is that the total two year deployment accumulated the equivalent of 47 days of A1 S&T diurnal cycles. The munition associated with this logger data was subject to a 120 days of A1 cycles during its Safety and Suitability for Service environmental testing programme. As a consequence, these three munitions have experienced due to this deployment, around 40% of the thermal damage imposed during Safety and Suitability for Service testing.

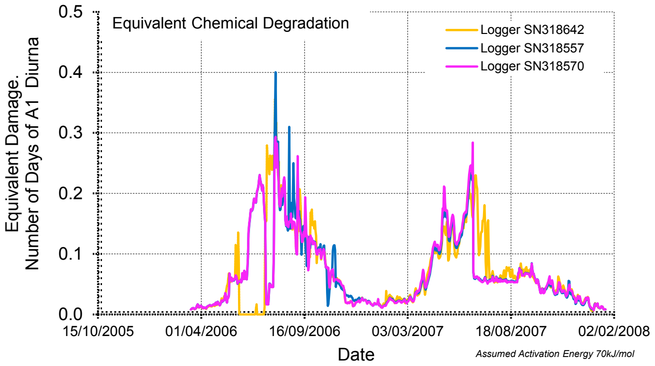

Figure 10: Daily Equivalent Temperature

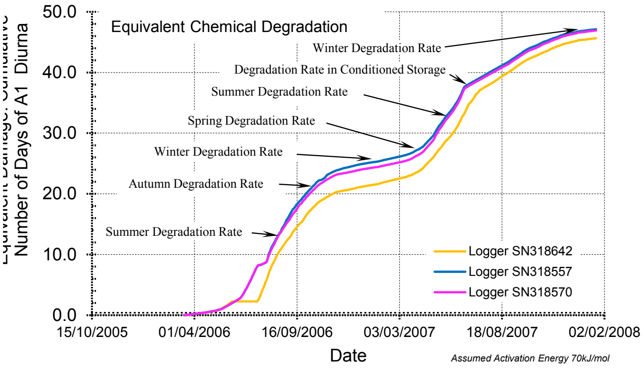

Figure 11: Cumulative Days of A1 Cycles

Figure 11 can be used to quantify the rates of degradation, experienced during the different seasons and (in this case) during conditioned storage. As can be observed, the rates for summer and winter can be clearly identified and are essentially constant for three to four months. However, the rates for spring and autumn do vary, essentially transitioning between the summer and autumn rates. Once established, these degradation rates can be used to establish predictions of munition thermal damage, in similar deployment conditions, for life extension purposes.

2.5.3 Thermo-Mechanical Degradation Models

Thermomechanical degradation relates to mechanical stresses in materials that are induced by thermal effects, resulting in mechanical failure. A change of temperature in equipment 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 the plastics and rubbers. 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 can lead 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, can occur due to thermo-mechanical 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.

The simple model associated with thermomechanical degradation is based on the equation of Whetstone Sheath and Manson [7 and 8]. This relationship corresponds to a model of fatigue with low number of cycles if the plastic deformations dominate (i.e. negligible creep). By considering the plastic deformations proportional to the variations in temperature of the thermal cycles, the factor of acceleration resulting from the Coffin-Manson relationship can be developed. The Coffin-Manson relationship has significant similarities to the Palmgren Miner linear damage hypothesis, used in the evaluation of high cycle fatigue.

As thermo-mechanical damage is related to changes in temperature, for consideration of potential damage, it is useful to consider the daily temperature differences within the logger data. That is the difference between the maximum and minimum temperature occurring daily. Figure 12 shows, for the three loggers used in previous examples, the daily temperature differences. As can be seen, the daily temperature differences for the three loggers do not show the same degree of consistency as was observed when considering for chemical degradation. Moreover, the majority of the larger differences occurred on discrete days rather than for protracted periods. These are probably a result of discrete munitions handling events.

In a manner similar to that used for chemical degradation, the Coffin-Manson relationship can be used to compare the thermo-mechanical damage with that imposed during its Safety and Suitability for Service environmental testing programme. The cumulative daily equivalent thermo-mechanical damage, for the three loggers used in previous examples, are shown in Figure 13. In this case the comparison has used the temperature difference produced by the diurnal temperature cycle representing the A1 Storage and Transit (S&T) climatic zone (38 °C) and fatigue parameter “n” of 2.

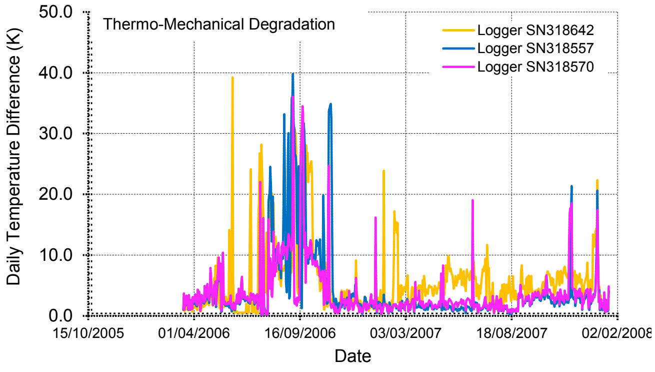

Figure 12: Daily Temperature Differences.

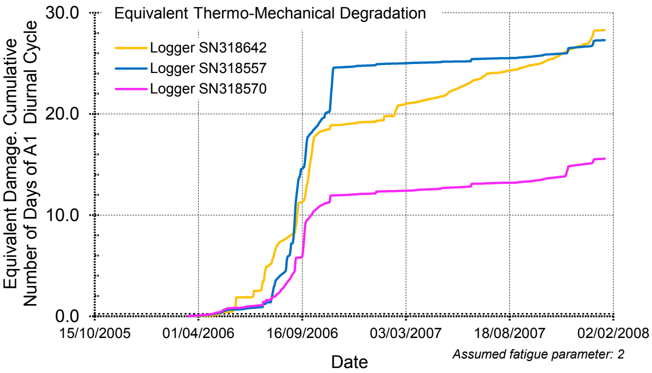

Figure 13: Cumulative Daily Temperature Differences

A question that often arises, is whether thermo-mechanical damage is occurring at a faster or slower rate, than thermo-chemical damage. The comparison is usually undertaken in terms of cycles of diurnal testing, undertaken as part of the Safety and Suitability for Service environmental test programme. In this case, the question can be answered by comparison of Figure 11 and Figure 13.

2.5.4 High Cycle Fatigue (Vibration) Degradation Models

The most common degradation mechanism, associated with mechanical vibrations, is fatigue arising from the cyclic stresses induced within a structure. The cyclic stresses have the potential to initiate cracks, propagate cracks as well as to induce friction and fretting between adjacent surfaces. However, fatigue is not the only mechanism by which vibration can induce damage. Friction or fretting, within energetic materials, may cause loss of material, powdering and heating. These conditions can lead to the formation of “hot spots” with the potential for ignition. Powdered explosive material may penetrate other parts of the munition which can increase the likelihood of ignition and provide an explosive path to the bulk of the energetic material. Mechanical vibrations may induce structural failure as a consequence of the induced stress exceeding a threshold, the occurrence of velocity exceedances or high relative displacement. These latter conditions may occur due to the build-up of resonant responses in lightly damped structures or packages. However, they are also likely to be apparent as a result of shocks.

The most commonly used approach to establish the life of materiel against vibration conditions is by means of the Palmgren Miner linear damage hypothesis. The Palmgren Miner [9, 10 & 11] linear damage hypothesis was originally based on empirical data and established a relationship between the ratio of the number of cycles at a given stress level to the number of cycles at another stress level. As a fatigue damage algorithm, it facilitates an estimate of fatigue damage accruing from different stress or strain cycles, by summing their effects for a linear elastic material. The Palmgren Miner linear damage hypothesis traditionally uses, stress level and the number of applied stress cycles, to establish cumulative damage. Used in this manner the algorithm has a basis in material science.

The Palmgren Miner hypothesis is commonly used in the assessment of vibratory service life, by using the algorithm to aggregate individual vibration periods of operational usage. The resultant aggregation can be used to establish elapsed life by comparison to a known exposure capability. To achieve this loggers mostly measure vibrations in terms of acceleration levels as well as the duration of applied vibration. In essence it is assumed that vibratory acceleration levels and material stress levels are related by a fixed (and unknown) constant. In practice stress would be more appropriately related to displacement rather than acceleration. It is also assumes, that the number of applied stress cycles, is directly related to the period of application of the vibrations. The vast majority of the vibrations experienced by munitions are composed of some form of broadband random vibration. As such the number of applied stress cycles can only be directly related to the period of application of the vibrations, when the spectral content of the broadband random vibration remains constant over a relatively long time period.

When using the Palmgren Miner linear damage hypothesis as originally intended, it is only applicable to a single material type and for a single failure mode i.e. fatigue. However, when assessing vibration damage from logger data, the Palmgren Miner linear damage hypothesis is used to estimate damage, from a variety of failure modes as well as for structures comprising many different and mostly nonlinear materials. Therefore, used in this manner the algorithm has only a tenuous basis in material science. This link is weakened even further, because when assessing vibration damage from logger data as the measurements cannot be directly related to material stresses of the number of applied cycles.

Currently, the type of vibration information acquired by environmental data loggers varies significantly. This is because of the large processing and storage capacity requirements, needed to measure and record the actual vibration waveforms. Currently no commercially available Environmental Data Logger is capable of continuously recording vibration data over the protracted periods required for a full munition deployment. Some prototype and high cost Environmental Data Loggers do allow the measurement of the full vibration waveforms, but have limitations either in storage capacity, battery life or period of operation. Others allow the intermittent measurement of vibration either at discrete intervals, for example recording one block of vibration data every five minutes. Typically, such loggers are able to store several hundred blocks of vibration data. Alternatively, such loggers may be set to record the most severe conditions, by overwriting any with a lower amplitude.

The above notwithstanding, a number of commercially available, mid-priced, vibration loggers, are capable of making reasonably good vibration measurements for some applications. However, such loggers only record a sub-set of the full information. Typically such loggers are capable of recording the r.m.s. of the vibration amplitudes, measured over a predefined period. In some instances, the r.m.s. amplitude may be augmented with the peak amplitude occurring in the same predefined interval. Nevertheless, such measurements can be effectively used to establish vibration fatigue damage, albeit with some limitations. Measured r.m.s. vibration amplitudes can be used with the Palmgren Miner equations and compared to the equivalent vibration fatigue damage established, for example, during a comparable laboratory vibration test. For most methods of transportation, comparison of the r.m.s. vibration amplitudes with the equivalent value, from the laboratory vibration test, is both practical and reasonable. This is because, for most methods of transportation, the fatigue generating aspects of the vibration can be reasonably well described by r.m.s. values.

In order to use r.m.s. information as the basis for assessing elapsed fatigue life, it is important to identify the type of transport or deployment platform involved. This is because the Palmgren Miner equations, as used with vibration conditions, necessitates that the spectral distribution of the vibrations, remains constant. Different transportation and deployment platforms (wheeled vehicles, rail vehicles, jet aircraft, propeller aircraft, helicopter, tracked vehicles etc.) all have different vibration spectral distribution characteristics. As a consequence, it is necessary to identify the type of transport or deployment platform utilised, in order to facilitate any comparison of measured vibration data with its appropriate laboratory vibration test severity. For example, vibration damage cannot be established by comparing logger measurements from air transport with the vibration test severity for road transportation. The necessary task of identifying the type of transport or deployment platform, from the logger data, was addressed in some detail within the WSTC work programme [1]. That work indicated that information from suitable mid-priced loggers can be used to identify different types of transport.

An example of measured peak and r.m.s. values which could be used to establish a measure of equivalent vibration fatigue damage is shown in Figure 14. This example is from a single two hour flight of a transport aircraft. The flight was made specifically for measurement purposes and consequently, contains far more changes of flight condition that would be found in a typical transport flight. An example of the use of r.m.s. values to establish elapsed vibration fatigue damage. The cumulative values of the factor of accelerated degradation have been used to compute the (un-factored) fatigue index shown in Figure 15. Fatigue index is essentially the percentage of flight life consumed, by the measurement, compared to the appropriate vibration test. The fatigue index values shown in Figure 15 should, to be technically correct, have incorporated a suitable margin. It was omitted in this example to better illustrate the process. However, the incorporation of a typical margin would increase the values of fatigue index shown in the figure by a factor of 5 [12]. That is the flight measurement would have consumed a total of 0.185% of the flight life set by the vibration test for transportation by jet aircraft.

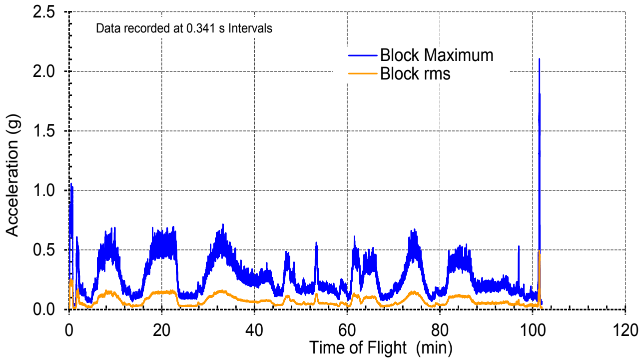

Figure 14: Example of r.m.s. and Peak Data

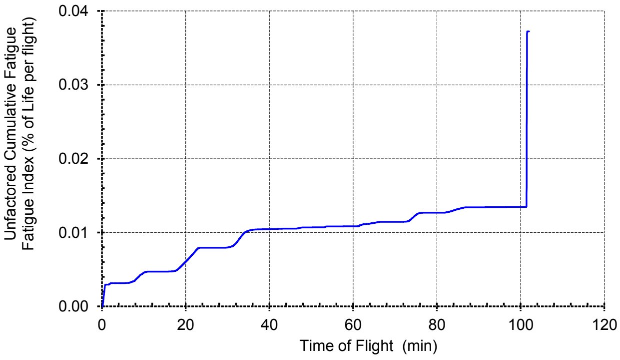

Figure 15: Example of Un-factored Fatigue Index

None of the methods, based upon the Palmgren Miner linear damage hypothesis, permit the use of logger data, representing one type of usage condition, to be compared against testing undertaken for a different type of usage condition. This is because they usually do not have comparable frequency characteristics. The similarity of frequency characteristics is essential to ensure similarity of stress levels and cycle count. It is only with similarity of stress levels and cycle count, can fatigue life be established. The only approaches that allow comparison between different types of usage condition methods, are those that directly relate the vibration conditions with stress levels and cycle count.

It is sometimes suggested that the Fatigue Damage Spectrum [13 and 14] can be used to establish elapsed life, even with different frequency response information. This is a myth, which arises because the Fatigue Damage Spectrum can give the impression they account for variations in frequency response characteristics. Fatigue Damage Spectra are based upon exactly the same assumptions as Palmgren Miner and do not relate vibration directly to stress and cycle count.

2.5.5 Shock Degradation Models

Munitions can experience shock environments due to a variety of causes. The most obvious are the shock and impacts that arising from the handling, or more commonly mishandling, of the munition. Shocks also arise from transportation in wheeled or tracked vehicles both on public roads and, to a greater extent, during degraded and off-road operations. In addition to those shocks, which can arise at any time during normal deployments, there is another group which arise from specific operational conditions. Such conditions include the shocks from parachute delivery, firing of shells, ammunition, adjacent guns and the launch or firing of other munition. Such conditions could also include the operation of pyrotechnically operated devices, such as valves, pin pullers, vee-band separation devices, bolt cutters and pyrotechnic cutting cords. Lastly there are shocks that can occur due to hostile operations, ballistic impact and blast.

Mostly environmental data loggers are concerned with the handling / mishandling shocks and, to a lesser extent, those arising from transportation in wheeled (or tracked) vehicles. Shocks arising from many operation conditions cannot credibly be measured by environmental data loggers. This is because Environmental Data Loggers simply do not have the sample rate capability to quantify such events. However, loggers could be used as a simple indicator to the occurrence of such events.

Shocks can cause a range of damage to munitions, but the most usual are; distortion, deformation and structural failures. However, from the view point of munition life, crack initiation is probably of the greatest concern. For the majority of munitions there is a level of damage after which subsequent shocks and/or vibration may result in those cracks growing or (for when in energetic materials) generating powdering or heat. These subsequent damage mechanisms are analogous to fatigue and are usually handled in a manner essentially identical to those discussed previously for fatigue.

Simple shock indicators (both mechanical and electronic) are commonly used to identify the occurrence of mishandling. Mechanical shock indicators are typically only capable of identifying the occurrence of a shock and its approximate severity. Low cost electronic indicators are typically able to identify the occurrence of shocks, the date & time each event occurred and provide an indicator of the peak severity of each shock event. Mostly these types of indicator are set to indicate event(s) occurring above a “safe” capability of item they are monitoring. For munitions, such criteria could be established from the shocks and impacts undertaken as part of the safety and suitability for service evaluation. Typically those severity levels are those at which the munition is; safe and serviceable, safe to use but not necessarily serviceable or only safe for disposal.

The common issue with simple shock indicators is that they can, in a number of circumstances, give false alarms. In such cases the information supplied by simple shock indicators is mostly inadequate to allow credible investigations to be undertaken into the validity of the indicated event. For that reason, it has becoming increasingly common to utilise more sophisticated shock devices, which are able to record the shock waveform arising from the most severe shock conditions.

If the shock logger, is able to measure shock and impact waveforms, a greater level of evaluation of the shock events can be achieved. The availability of measured shock waveforms permits a number of parameters to be computed. Those parameters can be subsequently employed to evaluate the shock as well as to quantify its damage potential. The various shock evaluation tools that may be utilised, are well documented and are summarised in [15].

2.5.6 Humidity Degradation Models

Humidity and moisture can be major physical and chemical agents of deterioration. Moisture may stimulate attack by other agents and may also act in conjunction with other atmospheric components in the degradation processes. Generally, the more severe the moisture conditions, the more rapid the degradative effect. However, moisture is not always harmful to materials and may be essential to the useful properties of some, for example wood and paper. The physical effects of moisture can be seen in the shrinking and swelling of wood, paper, hydrophilic plastics and textile fibres, as water is desorbed and absorbed with changing humidity. Moisture also acts chemically, as in the corrosion of metals and the deterioration of some organic materials, including energetic materials. Changes caused by moisture in the electrical and mechanical properties of materials may affect the function of equipment, of which they form a part. The moisture content of materials is dependent both upon their hygroscopic characteristics and the humidity of the environment. All materials tend towards an equilibrium where the partial pressure of the water vapour contained in or on the material, balances the partial pressure of the water vapour in the surrounding air. Under the right conditions, moisture vapour from the air can condense onto the surface of materials as liquid water.

Although, the monitoring of humidity levels within a munition or its package is already commonly undertaken, mostly this is by means of a relatively simple device. These are typically used to indicate when the level of humidity (inside a package) approaches an unacceptable level. A variety of design and control measures are then normally adopted to either, limit these conditions or to mitigate the effect of them. If Environmental Data Loggers are used to establish humidity conditions, the current primary use, is to perform the same simple humidity level exceedance checks.

The materials of most munitions are selected and designed to withstand a reasonable exposure period to high humidity (typically 30 days to 90 days at 95% RH). This is mostly established at component and material level, with any weaknesses mitigated by good design practice. For this reason, the second most common use of Environmental Data Loggers is to record time at high humidity levels. That information is mostly compared to the materials and component databases, established during the design process.

Whilst, humidity can be a major physical and chemical agent of deterioration, it mostly occurs in conjunction with other atmospheric components. As a consequence there are many different mechanisms by which humidity may influence the life of a munition. Conversely, little information is deliberately derived in in munition test programmes which allow the identification of suitable humidity degradation models or the values to use in it. In the cases were a humidity degradation model is used, the degradation mechanism usually considered is that arising from absorption of moisture into materials.

Eyring proposed a model which relates degradation to associated environmental constraints, which takes a similar form to the general model of Arrhenius. Practically, the model of Eyring can used only to take into account the combined effect of the temperature and another constraint (moisture, electric constraint, mechanical constraint, radiation etc.). The Eyring model has been further developed [16, 17 and 18] to encompass the combined empirical degradation effects of humidity and temperature. The reason that a number of empirical humidity models exist is a consequence of the various humidity degradation mechanisms possible. Nevertheless, the most commonly utilised variant of the basic Eyring model is that by Eyring Peck.

An example of the use of the Eyring Peck model to compare conditions measured by an environmental data logger with the number of B1 diurnal cycle [5] applied during testing is shown in Figure 16. In this example the cumulative damage (Figure 17) superficially appears as relatively high, in comparison to the testing durations normally undertaken (7 to 14 days). However, it should be remembered that humidity sensitive material would normally be protected from humidity and would not experience eighteen months of repeated high humidity exposure. A typical design period, for humidity sensitive material, would be in the order of ninety days. In this example, that would correspond to around five days of exposure to the B1 constant temperature and humidity conditions. This would compare reasonably well with the testing durations normally undertaken.

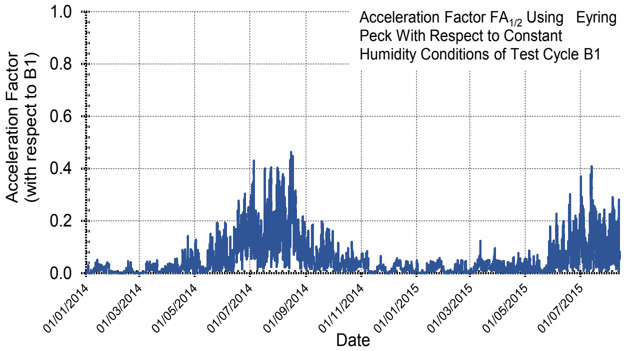

Figure 16 Hourly Degradation Factor

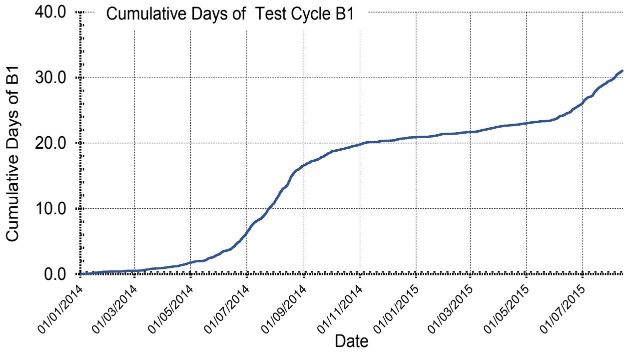

Figure 17: Cumulative Humidity Degradation

2.5.7 Pressure Degradation Models

The monitoring of pressure is usually not a priority, for most munitions, as few pressure related damage modes having an influence on munition life. Excessive, high or low, atmospheric air pressure can give rise to failure of seals, or in extreme cases, structural failure. However, virtually all munitions are designed to withstand operation at altitude as well as low air pressure arising from unpressurised air transportation. Munitions intended to be stored or operated under pressurised conditions, are also specifically designed against such conditions. Mostly, pressure conditions induce loadings, which are only very modest, in comparison to other structural loads that may be experienced.

One of the most vulnerable munition components, with regard pressure, is often the thin foil seals used to prevent moisture ingress into energetic material. Such seals are typically fitted across rocket motor nozzles to prevent moisture ingress, but are deliberately insubstantial to prevent debris damage when the motor is fired. Excessive (high or low) pressure may prematurely rupture such a seal or a sufficient number pressure cycles may result in fatigue degradation. There is little evidence of such degradation, most probably because insufficient pressure cycles can occur in the life of a munition. However, the appropriate degradation model would be that of low-cycle fatigue. The issues associated with modelling low cycle fatigue have already been addressed in this report and those issues would apply to pressure induced loading also.

2.6 Assembly of a Degradation Life History.

This aspect of the WSTC work programme [1] addressed issues associated with the assembling of degradation life histories, for individual and groups of munitions. It particularly it addressed issues associated with using information from a small group of loggers to establish elapsed life of a larger group of munitions, which have experienced broadly similar conditions. Broadly, two approaches for the use of environmental logger data, in establishing munition life, are commonly claimed.

The first approach is as a means of tracking the elapsed life of a single munition with a logger installed either with or within a munition. This approach is usually stated to be the ideal future scenario and is gradually becoming the preferred option, for high value munitions. To establish the remaining life of a specific munition, the approach requires that environmental data logging occurs continuously. Should gaps exist in the data, there are a number of acceptable approaches, already discussed, which can be used to fill small voids. Larger voids may need to be filled, using the same assumed degradation rates, used to establish initial in-service capability.

The second approach is to track the elapsed life of a group of munitions with a loggers installed within a subset of those munitions, rather than the entire population. This approach is currently commonly used and is likely to become the pragmatic option for medium and low value munitions. Provided the sample of munitions, having associated loggers, is reasonably large, this approach can form the basis for predicting the likely remaining life of the entire population. The primary issue, in this case, is ensuring that the available logger data encompasses credible variability in the handling and usage conditions experienced by the designated population. This implies that additional consideration needs to be given to estimating and quantifying the variabilities which may exist. It also invariably means that some form of statistical analysis and factoring will need to be applied to the data.

Pragmatically, there is actually a third approach which regularly arises. That is tracking the elapsed life of a group of munitions with a logger installed with only a single logger. This approach represents a far more difficult problem than the other approaches, as it can be virtually impossible to understand the likely variability in usage and degradation that may have occurred. Adopting the verification process, set out within this report, will significantly increase confidence in the validity of the single set of data. However, confidence is never going to be high, as a single record can never give a credible understanding of the conditions that a single munition has experienced. In reality, a single logger, used to track the conditions experienced by a group of munitions, is only ever likely to supply confidence that the assumed conditions and generic degradation rates are not being exceeded. Although, this can be useful information, confirming good munition management is been employed, it is unlikely to be sufficient to permit life extension.

The WSTC work programme addressed issues associated with the assembling of degradation life histories, for all the different degradation mechanisms. However, for the purpose of this paper, only the assembly of chemical degradation rates is addressed.

The outcome of the validation and degradation modelling processes is typically a set of cumulative degradation, of the type shown in Figure 18. Seasonal degradation rates can be derived directly from the slopes of the cumulative degradation curves as illustrated in Figure 18. In order to ensure worst case degradation rates from different handling and usage conditions are encompassed, statistical parameters, such as the Statistical Upper Tolerance Limit or the Normal Tolerance Limit, could be calculated to produce generic seasonal degradation rates. Typically this would represent the 95% probability of occurrence at a 50% level of confidence. This could be undertaken seasonally and annually. However, such statistical parameters are only valid if the distribution of values comprises a broadly normal distribution, which would appear to be the case here. If the distribution of values was not broadly normal distribution, or insufficient values were available, then the use of the credibly largest value may be more appropriate, than the use of a statistical approach. In such cases, the use of an addition factor may be required to encompass potential variabilities not actually observed.

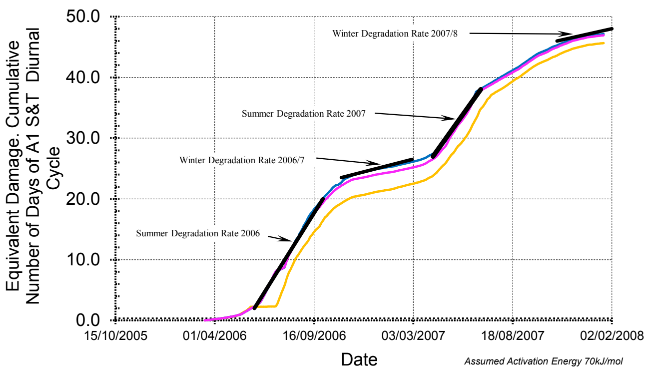

Figure 18: Seasonal Degradation Rates

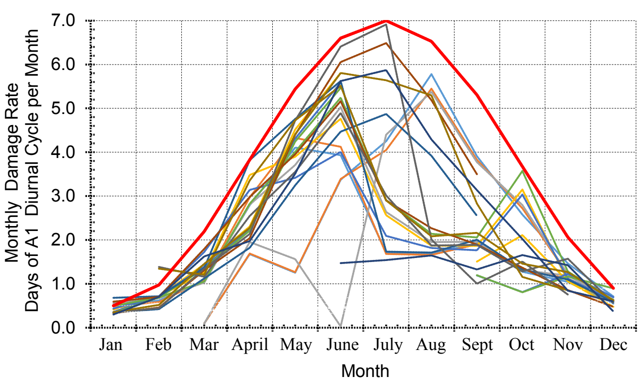

Figure 19: Monthly Degradation Rates

If a reasonable quantity of information were available, an alternative approach could be to compute the monthly equivalent degradation rates. Indeed, this is a useful alternative way of presenting the data. Such an approach is shown in Figure 19, where information from eleven loggers encompassing a period of three years are superimposed. In this case, the monthly degradation rates are effectively monthly averages. In order to establish a worst case degradation, representing the entire group, an envelope has been fitted to encompass the various monthly degradation rates. The use of statistical parameters, such as the Statistical Upper Tolerance Limit or the Normal Tolerance Limit, could again be used. However, in this example a sinusoidal based enveloping approach has been used. With sufficient logger data over a sufficient duration, such a model is that which would be broadly expected from temperatures largely arising from meteorological conditions. The enveloping model can be subsequently used to set monthly degradation rates for establishing elapsed thermo-chemical life and potentially for predicting future life capability in similar conditions.

In some instances, it may be necessary to combine data from several loggers or use several combined sources of data, such as individual logger data from deployment and long term storage from historic. When this is necessary, it can be generally good practice to statistically combine the measured data and then compute degradation rates as well as computing degradation rates of each sub-divided record and then to compute a statistical representation. Although requiring greater effort, such an approach can allow the sensitivity of the result to individual records to be identified.

3 PROCESS FOR EXPLOITATION

3.1 Safety and Suitability for Service Environmental Evaluation Programme.

The vast majority of weapons are subject to some form of safety and suitability for service environmental evaluation programme, prior to been taken into service. Within the UK, a typical programme would subject a number of complete weapons to a sequence of environmental tests. Those tests are intended to replicate the environmental stresses that the weapon is likely to encounter during its intended service life. Essentially, the aim is that the, sequentially applied, environmental tests induce damage and degradation, equivalent to that likely to be experienced by the weapon during its planned life.

Following the sequence of environmental tests, some of the weapons are usually subject to inspection and disassembly, accompanied by appropriate mechanical and chemical analysis. This work is undertaken to identify any potential failure modes of the weapon, induced damage as well as mechanical and chemical degradation. Disassembly is necessary to permit inspection and analysis of individual weapon component parts and particularly the energetic materials. This work allows degradation to be established in a qualitative and in some cases quantitative manner. Suitably interpreted, this qualitative and quantitative information provides a baseline against which the life of service weapons can be assessed. In certain instances some of the weapons will be subsequently functioned. Generally, such weapons provide little useful information against which the service life of a weapon can be established.

As well as the inspection and disassembly of environmental stressed weapons, it is usual also to undertake similar work on some weapons which have not been environmental stressed. This provides baseline qualitative and quantitative information against which damage and degradation can be established. That work is often accompanied by so called “small scale” tests [19] on the various constituent energetic materials of the weapon. These “small scale” tests on the energetic material also provide qualitative and quantitative information on degradation.

The aim of the safety and suitability for service environmental evaluation programme is induce damage and degradation, equivalent to that likely to be experienced by the weapon during its planned life. However, it is not uncommon to limit the effective service period to between 7 years and 10 years. Subsequently, this initial life, can be extended by either; an additional safety and suitability for service environmental evaluation test programme undertaken on naturally aged weapons or by surveillance using in-service weapons. Surveillance on in-service weapons would normally comprise the same inspection, disassembly and mechanical and chemical analysis, that was undertaken following initial environmental testing.

Regardless of whether additional environment testing or in-service surveillance approaches are adopted, selecting a suitably aged weapons on which to undertake such work can be problematic. This is because it is necessary to select weapons which have experienced either representative or worst case natural environmental stresses. Such natural environmental stresses may arise entirely from storage but may also include periods of deployment. The use of environmental data loggers is now starting to allow a more informed selection of weapons to utilise for such additional testing.

It is possible to establish the elapsed life of a weapon by comparison with a single safety and suitability for service environmental evaluation programme. Nevertheless, during the course of a weapons life, it is not uncommon to subject a number of weapons to several such programmes. Establishing a measure of the degradation, from several differently aged weapons, has the benefit that it may be possible to identify trends, even in the presence of variations in degradation. The identification of such trends was addressed in a separate work package of the WSTC programme undertaken by Sheffield University [20]. Essentially that work considered the use of Bayesian prognostic technique to identify trends in the various weapon parameters quantified during the life of a weapon.

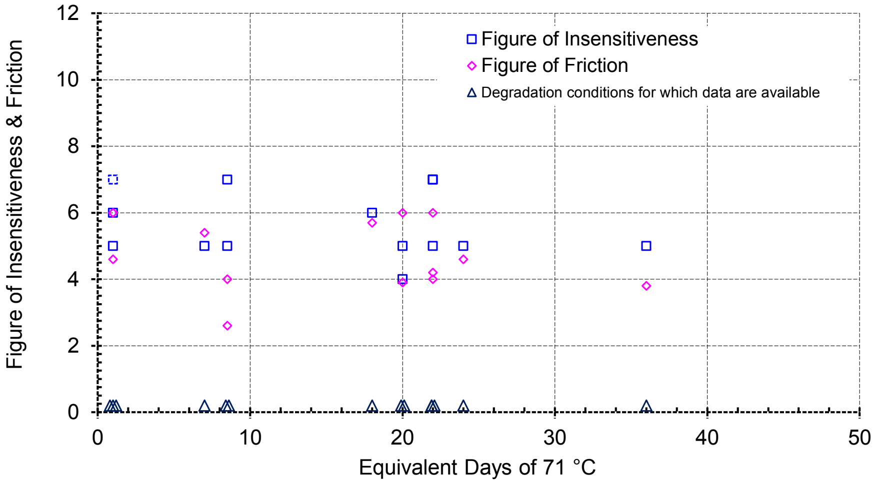

Figure 20: Example of use of Degradation Parameter to Compare Results from Different Evaluation Programmes

An example of an ensemble of results, established from a number of different weapons subject to different sequential test conditions, is shown in Figure 20. The figure shows the effects on two commonly measured hazard assessment parameters (Figure of Insensitiveness (FOI) and Figure of Friction (FoF) [19]). In this case the parameters were measured on samples of energetic material taken from 14 separate weapons of which; 3 are control weapons which had not been subject to any sequential testing, 2 are weapons which had been subject to sequential test programme representing only two years of operation use, 6 are from weapons which had been subject to sequential test programme representing ten years of operation use and 3 are from weapons removed from service for surveillance purposes.

3.2 Deriving Degradation Conditions Testing Programmes.

Within the UK, the accepted approach for establishing the elapsed life of a weapon is to compare the actual environmental conditions experienced by the weapon, with those it experienced during its various safety and suitability for service environmental evaluation programmes. This approach has historically used estimates, derived by the service user, of the actual environmental conditions experienced by a weapon. The same approach can be used when environmental logger data are available. Indeed the availability of such data has the potential to considerably increase the confidence in any estimate of elapsed weapon life. Whether logger data is used or not, in order to undertake such a comparison the environmental degradation, imposed during the sequential tests of the evaluation programmes, need to be quantified.

If a weapon is accompanied by a suitably positioned environmental data logger, throughout its safety and suitability for service environmental evaluation programme, establishing the conditions imposed on the weapon is relatively straightforward. In such cases, the logger data can be assessed in exactly the same way, as would be used with logger data from service weapons.

Unfortunately, it is currently rare for a weapon to be accompanied through the safety and suitability for service environmental evaluation programme, with a suitable environmental data logger. As a consequence, use has to be made of other information generated by the evaluation programme to establish the conditions imposed by the sequential tests. In most cases this information will be from manually generated documentation. Utilising manually generated documentation to quantify the conditions imposed does give have a number of issues and uncertainties. A number of these were addressed in detail within the WSTC work [2], although are not fully reproduced within this paper.

One commonly encountered issue is that associated with establishing the actual temperatures conditions within a weapon during laboratory testing. In particular establishing the relationship between monitored chamber temperature and the temperature within key components, such as energetic material. A separate work package within the WSTC programme [2] addressed this issue. That work indicated a simple one degree of freedom model could generally be used to represent the thermal attenuation and lag effects of typical munition packaging and the outer skin of a weapon. This approach may also be useful when Environmental Data Loggers are located outside a weapon. An illustration of the differences in temperatures that can arise, between the use of chamber temperature and actual packaged weapon temperatures is shown in Figure 21.

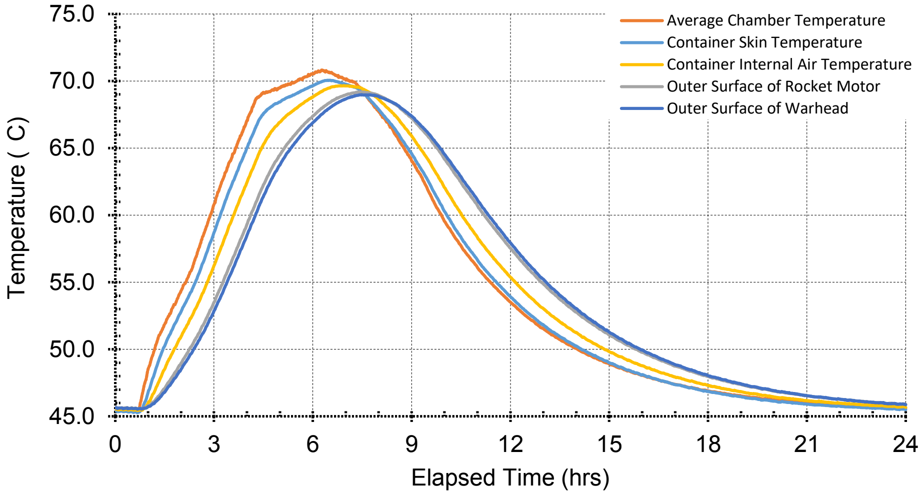

Figure 21: Illustration of the Differences Between Climatic Chamber Air Temperature and Packaged Weapon Temperature

Another common issue encountered is that during a safety and suitability for service environmental evaluation test programme a weapon may be subject to both diurnal temperature cycling and periods of elevated constant temperature. The latter may arise, for example, when the weapon is been subject to mechanical vibration conditioning applied at high temperature. In such cases the relative effects of varying and constant temperature conditions need to be aggregated. In some cases it may be appropriate transform the varying temperatures into equivalent constant conditions and in some cases the reverse may be more appropriate, depending upon which generates the greatest degradation. The equivalent constant temperatures for the STANAG 4370 AECTP 230 climatic diurnal test cycles [5] are shown Figure 22. The equivalent constant temperatures apply for a period of 1 day for each diurnal cycle.

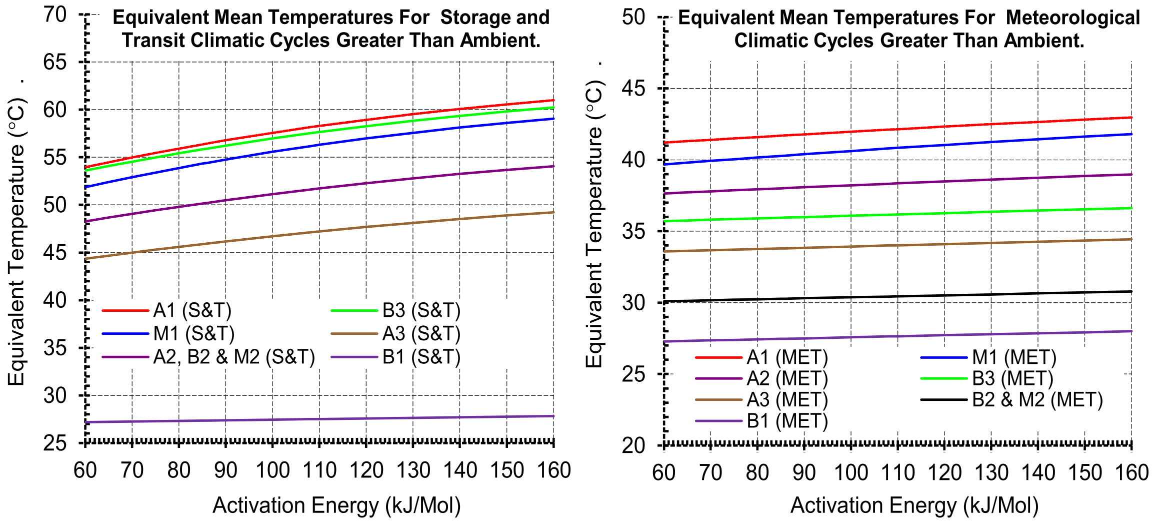

Figure 22: Equivalent Temperatures for STANAG 4370 AECTP 230 Climatic Diurnal Test Cycles

3.3 Establishing Remaining Weapon Life

This portion of the WSTC work programme, addressed out how the verified environmental data logger evidence base can be used to establish the remaining life of a weapon. For the purpose of establishing the remaining life of a weapon, the degradation information generated by the safety and suitability for service environmental evaluation programmes is compared with degradation indicated by the verified environmental logger data. Although such an approach may superficially appear to be overly prescribed, it is nevertheless the effective criterion currently used to set the service life of a weapon within the UK. Moreover, as a starting point for setting the life capability of a weapon, it is an essentially safe position, only taking the munition up to a life capability, which has already been demonstrated.

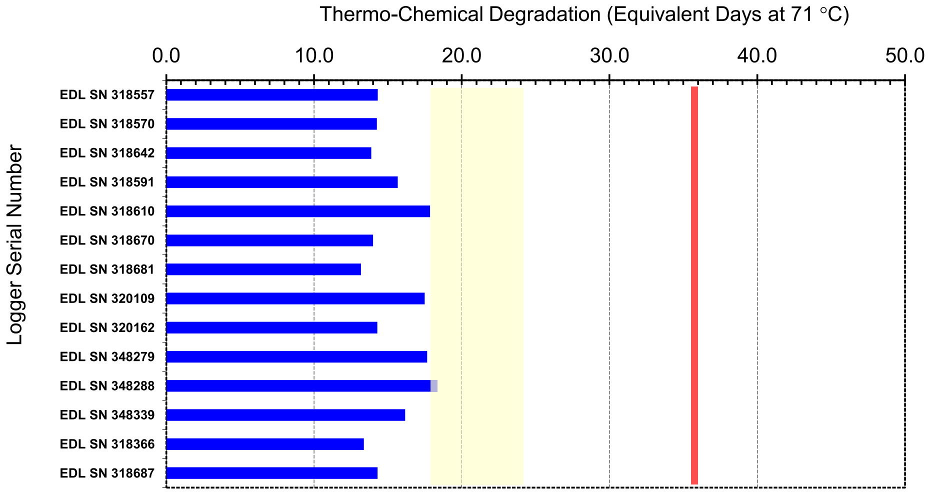

Figure 23: Example Comparison Of Logger Data (Quantified In Terms Of Thermo-Chemical Degradation) With Environmental Evaluation Programmes.

For demonstration purposes, thermo-chemical degradation from fourteen environmental data loggers have been compared to that imposed by four separate weapon safety and suitability for service environmental evaluation programmes. The demonstration utilised data, from fourteen environmental data loggers, as they indicate the greatest (thermo-chemical) degradation experienced by a larger grouping of munitions over a two year deployment period. The comparison, shown in Figure 23, is in terms of thermo-chemical degradation as equivalent days at 71 °C. Superimposed onto the figure is a marker representing the most severe degradation imposed from the weapon safety and suitability for service environmental evaluation programmes (the red marker at 36 equivalent days at 71 °C). In addition a (yellow) band (between 18 and 24 equivalent days at 71 °C) is included which corresponds to degradation observed on a group of munitions from weapon evaluation programmes and from surveillance work. This band is included as it represents a level degradation for which considerable confidence exists in the state of the munition.

3.4 Estimating Life Extension Capability

Having established the remaining life of a munition for all the degradation parameters of concern, the next objective is usually to establish whether a life extension capability is viable. In the previous example only around half the proven thermos-chemical damage had accrued. This had occurred over a period of around two years. As a consequence, provided the environmental conditions remained consistent, the indications are that the munitions could remain in service and deployed, for at least another two years. Although this is a reasonable conclusion, there are a number of caveats that need to be considered before a munitions life is extended in this way.

- Confirmation is needed that the degradation model used to establish the elapsed life is appropriate as the prime degradation modes of the munition. For complex munitions it is not credible to consider only a single degradation mode exists. As such it will almost always be necessary to consider a broad group of degradation models as well as a range of measured parameters which may indicate degradation.
- The quoted life extension period needs to encompass potential future conditions. Degradation based upon logger data only reflects conditions that have occurred, it does not necessarily represent what may occur in the future. As a consequence the estimated period of life extension would need to consider the effects of future variations in the conditions of use. For example, future conditions may be different to the historic records, because of year to year variations in climatic conditions. However, variations arising from change of storage and usage are likely to have a more significant impact.
- If the logger data utilised to establish the elapsed life of a group of munitions, represents a subset of those munitions rather than the entire population, the proposed life extension capability will need to include consideration to the variably which may exist with regard the entire population. This approach is currently used, for some munitions during deployments, and is likely to become the preferred and pragmatic option for medium and low value munitions. Provided the sample of munitions, having associated loggers, is sufficiently large, this approach can form the basis for predicting the likely remaining life of the entire population. The primary issue, in this case, is ensuring that the available logger data encompasses credible variability in the storage, handling and usage conditions experienced by the designated population.
- All life extension estimates should take into account the period necessary to arrange disposal of a weapon. An allowance of two years good storage has traditionally been considered necessary, in the UK, to allow for disposal of weapons to be arranged.

For this particular example, sufficient logger data existed to give a reasonable confidence that correct storage and usage procedures were been followed, despite regular changes of staff. As such there was reasonable confidence that the rates of degradation would not change significantly during the remainder of the deployment. Nevertheless, there are a number of issues which should be considered when setting the potential period of life extension.

- The assumptions, concerning conditions and usage, for a proposed period of life extension, should be clearly set out. This should be the case even if the assumed usage conditions are not necessary being reflected, in their entirety, in any subsequent usage limitations. Experience indicates that, unless the conditions and usage assumptions are clearly understood, there is a tendency to adopt optimistic interpretations which may have unintended implications on degradation.
- For degradation dominated by climatic conditions, if the life extension is not specified as full

years, it will be necessary to consider the effects of seasons.

- If different storage / usage options are available it may be necessary to set out the life extension options using different storage/deployment possibilities. Again even if some of these are not ultimately used, it can assist the end user to balance operational demands with maximising weapon availability.

4 CONCLUSIONS

The adoption of a rigorous approach for the verification and assessment of munition logger data is essential, if safety critical munition life extension decisions are to be made with an appropriate level of confidence. The tools, verification approach and exploitation strategy, set out in this paper, are intended to provide such confidence. Although the process set out, may need some adaption for specific situations, it forms a generic framework which is intended to ensure logger information is reported in a reliable and dependable manner. The process described is applicable to the various different types of environmental logger data that are commonly acquired.

The verification criterion proposed by this paper is for the logger data to be verified by three separate sources. When information from a large number of loggers is available, this verification may be achieved by comparison of the data from those loggers, partitioned according to storage or usage conditions. When information from fewer loggers is available the verification may need to call upon information from other sources of local information such as loggers related to other equipment, information acquired local for other purposes or databases of historic information. The verification criterion proposed is challenging. Nevertheless, it should be achievable by the majority environmental logger measurement exercises provided they are undertaken with a reasonable degree rigor.

Munition environmental logger data is only of value, in establishing remaining life and life extension capability, if it can be related to the various degradation modes applicable to that munition. To that end a number of degradation models are addressed within this paper. The degradation models addressed are those regularly used to establish the initial design service life of munitions and energetic materials. They encompass the vast majority of degradation models currently utilised to assess the life of in-service munitions. Moreover, each of the degradation models presented, provides a basis for more sophisticated degradation models and the consideration of munition specific failure conditions.

The degradations models include; chemical degradation (mostly associated with temperature), high cycle fatigue damage (mostly associated with vibration) and low cycle fatigue (mostly associated with thermo-mechanical stress). In addition, consideration is given to approaches for assessing humidity degradation (mostly moisture permeation) and the interpretation of shock events. The paper addresses issues associated with the assembling degradation life histories for a single munition as well as for groups of munitions. This includes consideration of the commonly encountered situation, were information from a modest number of loggers are available, but need to be applied to a larger group of munitions. In such cases, it is necessary to considers how variability, between the conditions experienced by a group of munitions, can be included within the degradation estimates.

The second stage of the exploitation strategy, addressed by this paper, is to utilise the verified logger data for the purpose of making munition surveillance and life extension decisions. For this purpose, the paper compares the verified logger data with the degradation information generated by the safety and suitability for service environmental evaluation programmes. This approach is the effective criterion currently used to set the service life of weapons within the UK. Moreover, as a starting point for setting the life capability of a weapon, it is an essentially safe position, only taking the munition up to a life capability which has already been adequately demonstrated.

The use of degradation information, generated by safety and suitability for service environmental evaluation programmes to set the demonstrated life capability of a weapon, does necessitate that the conditions imposed by the evaluation programmes are quantified. Currently it is rare for a weapon to be accompanied through the safety and suitability for service environmental evaluation programme, with a dedicated and suitably positioned environmental data logger. As a consequence, manually generated information from the evaluation programmes is currently frequently utilised to quantify the conditions, imposed by a sequential evaluation test programme. To facilitate the use of such data a number of assumptions have to be made, some of which are addressed in this paper. Nevertheless these issues would largely eliminated if weapons were accompanied, through the safety and suitability for service environmental evaluation programmes, with a dedicated and suitably positioned environmental data logger.

Lastly, this paper recommends, when proposing any munition life extension based upon the use of logger data, that the assumptions concerning conditions and usage for a proposed period of life extension should be clearly set out. Experience indicates that unless the conditions and usage assumptions are clearly understood, there is a tendency to adopt optimistic interpretations which may have unexpected implications on degradation. Additionally if different storage / usage options are available it may be necessary to set out the life extension options using different storage/deployment possibilities, for example setting out the life advantage of using improved storage conditions. Although some of these may not ultimately used, they can assist the end user to balance operational demands with maximising weapon life and availability. It is also worth noting that any life extension exercise should take into account the period necessary to arrange the disposal of a weapon. Typically, an allowance of two years good storage is not unreasonable to allow for disposal of weapons to be arranged.

5 REFERENCES

[1] Verification and Exploitation of Munitions Environmental Data - Data Extraction and Verification Process, D.P. Richards, KES/WSTC/0036/1, 9/10/2015.

[2] Verification and Exploitation of Munitions Environmental Data - Process for Exploitation, D.P. Richards, KES/WSTC/0036/2, 18/4/2016.

[3] Environmental Conditions – Vibration and Shock of Electro-technical equipment Dynamic field data including validation; Part 1 Process for validation of dynamic data, PD IEC Technical Report 62131-1, 2011.

[4] The Hutchinson World Weather Guide, E.A. Pearce and C.G. Smith, Helicon Publishing, ISBN 1-85986-342-6, 2000.

[5] STANAG 4370 Allied Environmental Conditions and Test Publication, AECTP 230, Climatic Conditions, May 2009.

[6] Uber die Reaktion-geschwinddigkeit EIB DER inversion VOR rhorzucker durch sauren, S.A. Arrhenius, Z. Physik. Chem., 4, 226, 1889.

[7] L.F. Whetstone Sheath, Transactions ASME, TASMA, 76, 931, 1954.

[8] Behaviour of Materials under Conditions of Thermal Stress, S.S. Manson, NACA Technical Note 2933, 1954.

[9] Palmgren A ‘Die Lebensdauer von Kugellagern’ VDI Zeitschrift, p339 to p341,1924.

[10] Langer B F, Fatigue Failure From Stress Cycles of Varying Amplitude, Journal of Applied Mechanics, Volume 4 Number 4, December 1937.

[11] Miner M A ‘Cumulative Damage in Fatigue’ Journal of Applied Mechanics, Transactions of ASME, 67 1945.

[12] Def Stan 00-970 Part 1 Section 3 Leaflet 35 Fatigue Safe Life Substantiation, Issue 2, 1999.

[13] Maximum Response and Fatigue Damage Spectra, Christian Lalanne, The Journal of Environmental Sciences, Part 1 July / August 1984 and Part 2 September / October 1984.

[14] Mechanical Vibration and Shock Volume 5, Specification and Development, Christian Lalanne, Published by Hermes Penton 2002.

[15] Def Stan 00-35 Environmental Handbook for Defence Materiel, Part 5 Part 5 Induced Mechanical Environments, Chapter 12-02 General Methodologies for Deriving Shock Test Severity and Verification Tools, Issue 5, still to be published.

[16] Understanding Model for Humidity Testing Correlation, S.D. Peck, Proc. off the Int. Reliab. Phys. Symp., P44-50, 1986.

[17] New Failure Mechanisms In Temperature And Humidity Stress, D.Y. Guan, T.F. Gukelberger, E.C. Cahoon, T.W. Joseph, J.W. Snowdon, Proceedings, 36th Year Electronic Component Conference, 1986.

[18] Review Off The Status Has Off Plastic Encapsulated Semiconductor Component Reliability, R.W. Lawson, Br. Tech telecom. J., p95-111, 1982.

[19] UK EMTAP manual, Published by Energetic Materials Testing And Assessment Policy Committee (EMTAP).

[20] Bayesian Munitions Prognosis - Application to Measurement Data, QINETIQ/15/04630, Dr. Andrew Mills, University of Sheffield, 18/12/2015.

[21] Verification and Exploitation of Munitions Environmental Data – Final Summary Report, Andrew Laing, QINETIQ/16/00052, 29/2/2016.