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An Analytical study of Environmental Effects on Ordnance, Munitions and Explosives

by

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Abstract

This report considers environmental test strategies for OME. It expands on the reasons why OME is environmentally tested, the process and documentation used in environmental testing, the background culture behind the testing and the overall effects on OME produced.

The report shows the test strategies and the methodology used by a major test organisation and is also supplemented with the opinion of an experienced and respected professional in the field of OME.

Two example test rigs of differing materials are implemented and assessed in simulation.

Experimentation of differing control layouts and positions was planned to find the most suitable and efficient way to gain a representative control. Commercial pressures on the equipment made this impracticable.

It was concluded that environmental testing can cause failure modes to arise at a much quicker rate that in real life due to accelerated test levels, the worst case measured levels being used and focused sequential testing.

Weaknesses found in testing were the loss of test data accuracy due to the tolerances of various pieces of equipment and test spectrums. Additionally, vibration rigs and fixtures must impart the forces from the vibrator onto the test asset with minimal loss.

Recommendations such as realistic representation of test asset to vehicle interface would increase accuracy of data. The application of modal analysis on rigs and test assets prior to vibration testing would save time in work up and allow foresight with particular attention paid to the problem frequencies and areas.

List of Acronyms and Abbreviations

The Environment that we work in is acronym heavy. This is due to the area of work (Defence and Technical). The author has used his judgement to make it as easy as possible.

Acronyms and Abbreviations	Description
AOP-15	Allied Ordnance Publication 15
APFSDS	Armour Piercing Fin Stabilised Discarding Sabot
BS	British Standards
CAD	Computer Aided Design
CADMID	Concept, Assessment, Demonstration, Manufacture, In-Service, Disposal
COTS	Commercial Off The Shelf
CR	Customer Representative
CT	Computed Tomography
DEF-STAN	Defence Standard (UK)
DOSG	Defence Ordnance Safety Group (UK)
g	Acceleration due to gravity
GW	Guided Weapon
HARA	Hazardous Activity Risk Assessment
HSE	Health and Safety Executive
ISS	In Service Surveillance
JSP	Joint Service Publication (UK)
LCEP	Life Cycle Environmental Profile
LE	Life Extension
Mil Stan	Military Standard (US)
MoD	Ministry of Defence (UK)
MSDS	Materials Safety Data Sheet
MTDS	Manufacture to target or Disposal Sequence
NATO	North Atlantic Treaty Organisation
NC	Nitrocellulose
NDT	Non Destructive Testing
NEQ	Net Explosive Quantity
NO_2	Nitrogen Dioxide
OME	Ordnance Munitions and Explosives
Op	Operation
PMP	Project Management Plan
PPE	Personal Protective Equipment
PRT	Platinum Resistance Thermometer
PSD	Power Spectral Density
rms	Root Mean Square
S^3	Safety, or Suitability for Service
SME	Subject Matter Expert
SOW	Statement of Work
STANAG	Standardisation Agreement (NATO)
TI	Trial Instruction
TNT	Trinitrotoluene
UKAS	United Kingdom Accreditation Service
UNDEX	Underwater Explosion
U.S.	United States
WOME	Weapons Ordnance Munitions and Explosives

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2 Introduction

2.1 Report Purpose

The detrimental effects of environmental factors on Ordnance, Munitions and Explosives (OME) could lead to a catastrophic failure of a munition and loss of life. This is one of the fundamental relationships between OME in the real world and the need for environmental trial testing.

2.1.1 Aim

To identify areas of weakness in the test methodology used by a major corporation for the environmental testing of OME.

2.1.2 Objectives

Using a mock, trial to illustrate the structured and controlled approach to trials process for OME testing, to replicate their in-service life.

The design and experimentation of a vibration test rig with analysis of simulation results. This is with the main intention of keeping the testing as close to real life as possible.

Examine the most representative control points for vibration testing using experimentation, research and practical knowledge.

Make recommendations to better approximate reality.

2.2 Ordnance, Munitions and Explosives

2.2.1 Ordnance

Ordnance can be described as a delivery platform for a munition, it includes [1] “weapons including directed energy, small arms, delivery platforms including barrels, launchers fire systems”

2.2.2 Munitions

Munitions can be described as a complete device, an example of which could be a 5.56mm Ball Round as it contains an explosive article in the casing to propel it. Munitions are such

things as a [1] “missile, shell mine, demolition store, pyrotechnics, mines, bullets, explosive charges, mortars, air launched weapons, free fall weapons.”

2.2.3 Explosives

Explosives are a mixture of substances that produce a hot gas by a physical reaction. The resulting hot gas, formed at such immense pressures, produces devastation upon its surroundings. Explosives can be divided into two categories:

- High Explosives
- Low Explosives

High explosives have a brisance, which is a shattering effect. Whereas low explosives produce high volumes of gas which generally produce a pushing effect.

Explosives as a whole are [1] “Propellants, energetic material, igniter, primer, initiatory and pyrotechnics irrespective of whether they evolve gasses (e.g. illuminants, smoke, delay, flare and incendiary compositions).”

2.2.4 Background

OME have been around for many years and have increasingly got more complex in design. The new designs have to meet higher specifications in; intelligence, insensitivity, safety, the effectiveness of the OME and in life-span. The way OME is integrated has also had to change with the times and new platforms available to it; modern examples include:

- Land – AJAX Class Reconnaissance Tank
- Sea – Queen Elizabeth Class Aircraft Carrier
- Air – A400M Atlas Transport Aircraft

The vibration characteristics of a Hercules C130J changed from that of its previous model; these changes in characteristics are mentioned in a vibration data study by T Irvine [2] “There are two vibration frequencies of concern. The C130J propeller shaft speed is 17 Hz. The blade passing frequency is 102 Hz, which is equal to the number of blades times the shaft speed.”

Due to the use of new multi-bladed propellers along with other upgrades to the engine and wings the C130J vibration characteristics have changed.

Another change in the way OME is integrated is shown in the reintroduction of internal weapons bays on fifth-generation fighter jets, like the F-35 displayed in Figure 1. The F-22 Raptor and F-35 Lightning’s internal weapons bays have changed the environment for the munitions carried within them. [3] “The F-35 is expected to carry far more weapon types in its bay, which has a challenging thermal and acoustic environment… A thornier issue, perhaps, will be the environmental impact of the bay on weapons employing more sophisticated electronics, sensors and motors” Munitions housed in such internal weapons

bays may have to meet higher standards to enable the integration of the munition to aircraft.

[4]

Figure 1 F-35 Lightning displaying its internal weapons bay

Environmental Test Engineering facilitates the progress of new design and increases the productiveness of old. Through data analysis, the OME can be improved and the integration of the OME can be updated to get the best overall output.

2.3 Background: MoD Culture and Life Cycles

2.3.1 Life Cycle

A life cycle is the environments, areas, conditions and use, which will be seen over the assets life. It is from the very start to the very end, including; manufacture, storage, transport, military/operational usage and finally disposal. The life cycle of OME initiates from when it is manufactured, but from then on understanding and predicting the life cycle of an OME asset is challenging, although there is much documentation and guidance on how to create a representative theoretical model.

OME assets are utilised over most areas of the globe, so the life cycle should show this. The Allied Ordnance Publication 15 (AOP-15) provides a questionnaire to help identify the environmental life cycle of a munition, a sample of which is shown in Appendix A. [5] “The safety and suitability of a munition for service use may be influenced by the natural or induced environments that the munition experiences in service use. This questionnaire has

been designed to identify the planned service environments of a new munition prior to its development. It may also be applied to existing munitions being considered for use in alternative applications, or by other NATO countries. The resulting information will be used by safety evaluation organisations to devise trials of appropriate rigour for use when making their assessments."

Once the representative life cycle is identified a test plan can be written. This will include both sequential and non-sequential testing which replicates the identified environments that the assets will experience throughout their life. [6] "To provide confidence that defence equipment is capable of surviving and operating in the environmental conditions it will encounter during its Service life cycle, it is necessary to evaluate the materiel against those conditions. Such evaluations need to consider all the natural and induced environmental conditions the materiel may experience during its Service life cycle. An environmental test programme should as far as practicable, replicate the Service environment and expose the materiel to the environmental conditions it would experience from the point of manufacture to the end of its life. This should include the environmental conditions that exist during depot and field storage, transportation, handling and operation."

Table 1 (below) illustrates that there are many scenarios to consider when producing a test sequence for the assets. The test plan must reflect all expected exposures in terms of the environment. Appendix B depicts the assessment process for the safety and suitability. [7] "It illustrates a logical process for evaluating a munition life cycle to determine the environments that adversely affect the munition to which the munition may be exposed. The assessment includes identification and examination of failure causes, modes and effects, and associated risks resulting from internal failures, external effects from friendly, or enemy munitions and battlefield conditions, environmental effects, human errors, and accidents during the entire life cycle. The assessment is based on analytical, empirical, experimental, and historical data."

[8]

Stage	Task	Sub-Task
1	Review materiel requirements and compile provisional test sequence	Evaluate materiel life cycle
		Evaluate environmental requirements
		Compile provisional lists of critical environments
2	Establish critical environments, based upon knowledge of materiel and refine test sequence	Consideration of the operational state of the materiel
		Identification of potential materiel failure modes
		Review sensitivity of materiel to sequential environmental conditions
		Consideration of sequential and non-sequential testing
3	Prepare a technically credible, cost effective sequential test programme	Identify need for combined testing, and refine test programme
		Review programme for technical credibility and cost effectiveness

Table 1 The Process to Develop an Environmental Test Sequence

The sequential and non-sequential environmental testing sequence must be realistic and correlate to the actual life cycle identified. Appendix C shows sequential testing in an order

the OME asset might realistically see throughout its life. [9] “When an environmental test programme is specified, for a particular materiel, the sequence in which the tests are carried out may be important. This is because damage, initiated by one environmental test, may not become apparent, or significant, until another is applied. Specifically, materiel may survive an environmental test programme, if carried out in one particular order, but fail if carried out in another. For that reason, the order in which the environmental tests are undertaken, should ideally reflect the order in which they appear in the materiel Life Cycle Environmental Profile (LCEP) or, for munitions the Manufacture to Target or Disposal Sequence (MTDS)”

Two largely used concepts for this are Manufacture to Target, or Disposal Sequence (MTDS) and Concept, Assessment, Demonstration, Manufacture, In-Service, Disposal (CADMID).

Commercial Off The Shelf (COTS) products will largely use MTDS, with the shelf life set out from the purchase. The manufacturer must guarantee a shelf life. However, the MoD may want to extend the shelf life. If money was no object, the munitions purchased would be used during training and exercises, or disposed of by demilitarisation before the end of its shelf life. Due to budgetary constraints, the shelf life may need to be extended. Evidence for the shelf life extension is usually obtained through environmental testing. Think of it as selling foodstuffs with a year’s expiry date, testing and analysing the data from the foodstuffs, then making a case that it is safe to eat for another year.

CADMID tends to be brand new concepts, but again will have the same initial shelf life constraints. The life extension process will be similar as to that of COTS OME, purchased through MTDS. An aid to help develop the process to extend shelf life can be seen in Table 1.

The life cycle of material is very hard to recreate given the test asset’s potential variability of exposure to different environments. [10] “In practice, it is usually not possible to exactly reproduce every aspect of a materiel life cycle, as environmental exposure can vary, especially during operational conditions.” Therefore, a representative life cycle, whilst as close as possible to its real life, is always a compromise. An example of this is the historic UK deployment to Afghanistan. Munitions saw dry conditions, very hot temperatures and low humidity. Compare this to a more recent (2017) UK NATO operations in North-Eastern Europe with it’s cold, wet and more humid environment. The life cycle has to represent all of this in the best way it can.

2.3.2 Constraints

The largest constraint on Development, Qualifying, Life Extension and Life Cycle testing is budget. [11] The 2017 UK Defence spending is estimated at £44.7 Billion and is being expended on a host of large projects, equipment procurement, service recruitment and research and development, each vying to hold onto their funding. The process of qualifying a missile, or testing it for Safety and Suitability for Service (S^3) requires much investment within the industry, as there are only a handful of suitable Test Houses available. The duration of the sequential test programme can take many years to complete, especially a full suite of testing, to meet the many requirements that may be specified.

2.4 Why Qualify Energetic Materials

The qualification of energetic materials from the point of view of the MoD is straightforward. The MoD has a legal obligation under the Health and Safety at work act 1974 which states [12] "It shall be the duty of every employer to ensure, so far as reasonably practical, the health, safety and welfare at work of all his employees."

The qualification of energetic materials also saves both time and money. It can identify, or highlight particular areas, or failure modes that may cause problems later on when in its life cycle and can make, or break launching a munition into service. This is recognised by the MoD's Ordnance Board Proceeding [13] "The safety or suitability for service of a munition may be terminated by an unacceptable degree of degradation of components or materials when subjected to normal service environment or after exposure to certain extreme conditions."

Qualifying energetic material at the start can prevent, or reduce the need for further testing when it is used in a different application. Most importantly qualification testing sets a standard, a baseline and minimum level of testing for the whole inventory of the MoD's energetics.

The UK MoD uses:

<u>In Service Surveillance (ISS)</u>

To monitor the condition and check for degradation and ageing of the OME that is currently in use. It will also include safe functioning of the munition after prolonged exposure to the in service environment.

<u>Life Extension (LE)</u>

To test and enable the extension of a munitions service life. A LE will utilise various information from previous testing and inspections including:

- The initial life assessment
- ISS results
- Trial and service inspections (including reported defects)

<u>Safety and Suitability for Service (S^3)</u>

To test new OME against current standards, providing baseline evidence.

It is also used to test older OME and provide evidence for LE. The ISS will dictate whether a full S^3 suite of testing takes place, or a more tailored sequential trial. If ISS shows faults, or possible energetic component failure, then the S^3 testing will be tailored to investigate the potential sub-system failures and not just the whole asset. Put simply, with identified moisture ingress in a 120mm round; instead of testing the whole round, the seals of the round would be checked.

Environmental testing consistently plays a crucial role in all of these. Other factors that affect whether to extend the life of OME include; cost, safety and likelihood of use in the field/theatre.

Cost

Life extension testing is costly, but not as costly as a replacement. For example, if a missile system is to be replaced, the new system will either be designed, or purchased as COTS. It will have to go through rigorous testing before its purchase, to test that it is suitable. Once purchased it will only have a certain shelf life of say 10 years, before then it will need a LE to extend its life. Additionally, the old system (which may be deployed, or stored around the country/world) will have to be disposed of which again increases the cost fourfold. Therefore, if the old missile system is still capable (in performance) it is more cost effective to carry out an LE on it and extend its life for a duration of X years.

Safety

The safety of all users of the OME is carefully thought through. For example, making sure a 105mm artillery round functions the way it should even though it is close to the end of its life is important as degradation of the 105mm rounds explosive fill could lead to problems in storage, transport, or firing.

Likelihood of use

If the UK's Armed forces are involved in a conflict against lightly armed terrorists the likelihood that they will need many 120mm Armour Piercing Fin Stabilised Discarding Sabot (APFSDS) anti-tank rounds is minimal. So, to extend all the MoD's inventory of the round would not seem cost effective. Whereas in a conflict against an adversary with main battle tanks it would.

In summary, qualifying energetic materials is carried out for the following reasons:

Safety	To make sure that the energetic materials is safe to use
Performance	To understand and gauge performance against a standard
Stability and Compatibility	To ascertain that the energetic material is stable when used with other materials
Suitability	Suitability for use in predicted, or determined environments
Availability of Materials	Relieve the need of single source supply
To save Time and Money	To prevent the purchasing of something that may not work in theatre

2.5 What is an Environmental Trial?

The Oxford English Dictionary defines a trial as [14] “A test of the performance, qualities, or suitability of someone, or something.” An environmental trial is a test, or a series of sequential, or non-sequential tests conducted in a controlled and synthetic environment that appropriately meets the specification of the customer.

Environmental testing of OME can only be conducted at specific licenced Ranges around the UK. On these test sites, regulatory requirements from a variety of sources in the military, industry and government direct the processes. Some examples of these are:

- Health and Safety Executive (HSE)
- Joint Service Publication’s (JSP)
- Defence Ordnance Safety Group (DOSG)
- British Standards (BS)
- International Standards
- United Kingdom Accreditation Service (UKAS)

An environmental trial is based on the customer need. What does the customer want out of the testing? Do they want a baseline test; i.e. a test produced to define a standard for the asset, or product? A simple example of a baseline test is 5 off 1 metre drops of a box of hand grenades; will they all function correctly when used after being dropped 5 times at 1 metre? The baseline was previously set and each new product must now meet this baseline.

The customer might seek to gain information on their product in a synthetic environment consistent with different global environments, terrains and extremes. In this case, vast amounts of instrumentation will be needed to glean as much data as possible from the test asset in the conditions set by the customer.

Environmental testing provides a suite of variables to choose from and the ability to test to the extreme, including overly challenging tests that build confidence in the product/test asset.

Environmental trials conducted on OME involve and rely on experts from an assortment of specialist disciplines; Dynamic, Climatic, Radiography, Energetics as well as general disciplines; Electromechanical, Structural, Instrumentation and a whole host of other disciplines. When these fields of expertise are combined the output yields results that are paramount to the successful completion of the trial.

The following sections build on the different segments and functions of environmental test engineering, environmental effects on OME, and the roles, documentation and processes involved in conducting environmental trials testing.

3 Research and Knowledge

3.1 Environmental Testing

Environmental testing is the replication of environmental effects by climatic and mechanical stress that the item would feasibly see throughout its life. It is the best way in the real world to replicate real life environments. In order to get the most realistic data from the test asset, the testing imparted on the test asset must be as close to real life as possible. Anything less will affect the analysis of the test asset and therefore could produce discrepancies.

Environmental testing is used worldwide in the industry to predict and analyse how products cope in an engineered "real life" (simulated) environment that is typically accelerated to prove the product before it is used in the real world. [15] "The majority of materials used in munitions degrade slowly so that critical failure modes may only be identified after a considerable period of normal use. The conduct of testing under real time conditions in order to identify failure modes consequently would be unacceptably long. To overcome this difficulty some form of testing technique is used. The use of accelerated testing enables, in a relatively short time, an assessment of the response of a munition to its expected environments."

Throughout its operational life, the test asset will go through a host of diverse challenging environments in its transport, storage, maintenance and in-operation stages. These environments will be covered in more detail further on in the report. Each stage in the test assets life will cause wear and tear, typically from inducing structural and material stresses, ageing the asset. In some cases, the testing will cause a failure of an asset, component, joint, or seal. Whilst at the outset, a failure of a test asset is disappointing and is potentially costly, there is a lot that can be learned from this failure.

Munitions, especially complex weapons like Guided Weapons (GW), cost a lot to produce. They also spend a vast majority of their in-service life packaged. As such these munitions must be protected from both mechanical and climatic environmental effects by their packaging. Environmental testing on both packaged and unpackaged test assets must take place to also prove that the packaging provides adequate protection to the munition inside.

Most test assets come in batches, for example; 8 Missiles, 100's of grenades, or 1000's of bullets. The larger more expensive test assets like missiles will have a reduced number, whereas small arms are less expensive test assets and can be brought for testing in larger numbers. Each batch is separated into two streams that will see hot, or cold temperatures as well as ambient temperatures throughout their testing as well as a host of different transport environments. Some assets are cycled to represent flight missions. An example of this is shown in Appendix C.

The use of multiple assets for testing assists in the data comparison. The history of the failed asset will be scrutinised and compared to the other test assets in its batch. The data captured throughout all of its testing up to that point will be compared to the other assets, to find both similarities and differences in the data.

The overall results can help to:

- Find the component(s) at fault for the failure and potentially the failure mode
- Provide safety data for the test asset (as test spectrums often over test the assets)
- Make an argument to remove the test item from the selection (with small arms there is more competition and multiple companies seeking to become the next provider and gain a monopoly with their product)

It is not common for test assets to fail during environmental testing. Most assets, for example, a ground to air missile, will have had many years of design and analysis behind them including modelling and smaller work up packages. The Rapier Surface-to-Air missile system (Depicted in Figure 2) began development in 1961, entered service in 1972 and is expected to remain in service until 2020. Throughout its life it would have been upgraded, [16] “The optical system ensured high accuracy, so it was developed with the intent of directly hitting its target, reducing the size of the warhead required to guarantee a kill, and eliminating the need for a proximity fuse. British Aircraft Corporation joked that the system was a "hit-ile", as opposed to a "miss-ile".” Whereas, the development of hitting a target is a performance upgrade, there are many other identifiable aspects in which the asset as a whole can be upgraded. The previous system/asset used will have most likely had problems with integration, climatic conditions, certain means of transport and many other problems identified through life surveillance. The lessons learnt from these problems and the solutions found will be used in the design to produce and develop a more enhanced, suitable and upgraded system to meet all needs.

[17]

Figure 2 Rapier Missile Firing

Failure of a test asset could be down to material stress. Stress may show as cracks, or stretching and can appear on a missile system where it has been put through a vibration spectrum that has hit the natural frequency of the structure, or component of the missile

and once at resonance will start to stress at the bending modes. Internal failures can be detected through non-destructive testing techniques such as Radiography and Computed Tomography (CT) Scanning mentioned further on in this report. In cases such as there being only one test asset, specialist, rare assets, or an asset that is worth a lot of money, the customer will try to prevent it from failing entirely. Repair of the asset may take place in order to prevent the total loss of the asset and data that could be gathered due to the test assets usability.

The desired outcome for an environmental trial is to complete the full suite of testing with all test assets still serviceable. The qualification programme can take up to 3-4 years in some cases. This long duration has both positive and negative points, some of which are listed below:

Positives:

- Amount of data collected
- Quality of the data collected
- An improved (detail) explosive safety case
- Proven against an extensive range of climatic and environmental conditions
- An all-round proven asset that the customer has confidence in and can use to sell their product
- Anticipation of problems

Negatives:

- Change in customer demands
- Cost of testing and time
- The degradation of the test assets
- Delays due to test asset failures
- Meeting contracted deadlines
- Re-negotiation of milestones
- Economic situation (Defence Review)
- Advancement in other technologies

The duration enables the customer to attain more data to analyse. The idea of attaining as much data and information as possible on the test item before it is used throughout its life will allow the manufacturers to anticipate the failure modes, faults and degradation in its products over time.

Environmental testing is also used in research and development. The test assets tend to come in fewer numbers, as they are usually brought in as a one-off prototype, mid-life assessment, or back from operational theatre. [18] “After being fielded, military systems may be assessed through developer surveillance programs that track component reliability or through full-system tests.” One reason for research and development on an OME test asset is that it may not function as desired in theatre. The use of comparison to an off the shelf version in this type of research and development aids the investigation. Another type

of research and development in environmental testing is to facilitate the enhancement of future design.

3.1.1 Climatic

Climatic testing can involve subjecting the test asset to a lot of unforgiving climatic environments. These environments are taken from different parts of the globe. There are various standardised tests that can replicate these environments such as:

- Cold temperature
- Hot temperature (including Humidity, or Dry)
- Pressure (Altitude)
- Ice tests
- Sealing tests (positive, or negative differential)
- Rain test
- Salt mist
- Sand and Dust testing
- UV and solar

Specialist conditioning and pressure chambers are used for temperature, humidity and altitude capabilities. These come in all shapes and sizes to meet the needs of the different masses of the test assets. A large climatic chamber is shown in Figure 3.

[19]

Figure 3 Climatic Test Chamber

The temperature of the conditioning chamber and test assets are measured by Platinum Resistance Thermometers (PRT's), or thermocouples which are placed internally, or

externally on the test asset to measure skin, or core temperature and above the test asset to measure the air temperature.

A PRT has a short length of pure platinum wire in the sensor. The temperature is determined by the level of resistance measured through the platinum wire.

A point to note is that all the instrumentation and chambers have an uncertainty of measurement (tolerance) up to ±2°C.

In areas, or climatic zones with conditions similar to the Arctic Circle, thermal soaking effects and ice build-up can take place. In an example environment such as this, a munition fixed to a hard point, under the wing of a fast attack jet located in an open airfield, will start to thermally soak. The soaking can take many hours. The core temperature will eventually, given time and exposure, reach the environment temperature as long as the conditions stay unchanged. This can affect the munition capability if not tested and proven.

A build-up of ice can start to form on the munition reducing its functionality and potentially damaging the munition, causing further problems and safety implications. Climatic icing tests involve manually spraying water onto the test asset at very low temperatures. The test replicates the build-up of ice on the test asset from exposure to the elements in an area like the Arctic Circle. The munition, once thawed, can be inspected, or put through further testing depending on the customer need.

[20]

Figure 4 Munition Icing Test

The temperatures that the test assets will see whilst in storage, transport and theatre before disposal is replicated by cycling. Diurnal temperature cycling is used and can include both humidity and pressure. It is based on the customer need and the environments the customer predicts and would expect the asset to see throughout its life.

Energetic materials can be inherently unstable, as they age throughout their life. Changes can occur in the materials properties that are, more often than not, a mixture of substances. It is possible and conceivable that this will affect the reliability and the overall safety of the munition.

Climatic ageing of an energetic test asset is used to calculate the shelf life during the explosives qualification. The shelf life of explosives is usually longer in cold temperatures than it is in hot. Predicting the safe life of an explosive that has sat in an environment at an average of 40°C for a year means using artificially aged explosives that have been analysed for comparison. There are many different methods available including; Chemical ageing, Conventional High temperature testing, Snapshot, etc. Using a Single temperature stability test [21] "artificial ageing is performed at only one moderate temperature (typically between 60-100°C) for only one time interval; extrapolation to lower temperatures has to be done using activation energy values obtained from experience, including the application of a safety margin. Typically, such tests determine whether the shelf life is shorter, or longer than 5, or 10 years at 25°C." The data extrapolated from such tests will be used to provide cases for the safety and lifing of the test asset.

Climatic testing also includes humidity which is used alongside heating of the test assets. [22] "The effect of humidity compliments the stress caused by temperature on a product. It has a penetrative and disruptive effect. Humidity will cause corrosion, loss of strength and stability and will effect electrical properties". The effects of humidity on OME such as corrosion and loss of material strength has the potential to weaken and create failure modes on areas that are vital to the function of ordnance and munitions such as; outer casings, joints and seals.

Throughout the world, the explosive test assets will be subjected to various climatic environments that have different levels of humidity. To replicate these specific environments, the Def Stan 00-35 has reduced them into 3 categories:

- B1 Wet Warm
- B2 Wet Hot
- B3 Humid Hot Coastal Desert

These areas are highlighted on the Location of Humid Climatic Categories found in Appendix D and show most of the humid areas to be located between the Tropic of Cancer and the Tropic of Capricorn.

3.1.2 Vibration

3.1.2.1 Vibration Background

Vibration testing involves a lot of specialist equipment. Figure 5 is a diagram to simplify the explanation of a mechanically induced vibration test. It also includes a climatic conditioning capability highlighted in green.

The vibration testing is defined and controlled by the software on the Control Computer. The Vibration Controller contains software and firmware that carries out all the calculations (Fast Fourier Transform), data acquisition and processing, using complex algorithms. There are a lot of controllers and software developed specifically for vibration testing, for example, *Siemens LMS, Data Physics and M+P* to name a few. The amount of excitation is measured from the accelerometer, typically in charge and converted to 'g', or displacement, -sometimes via a charge amplifier. At the same time, the Control Computer and Controller are continuously amending the drive output to the amplifier, which powers the vibrators output.

Again it is important to note that the accelerometers, charge amplifiers and vibration controllers will all have an uncertainty of measurement.

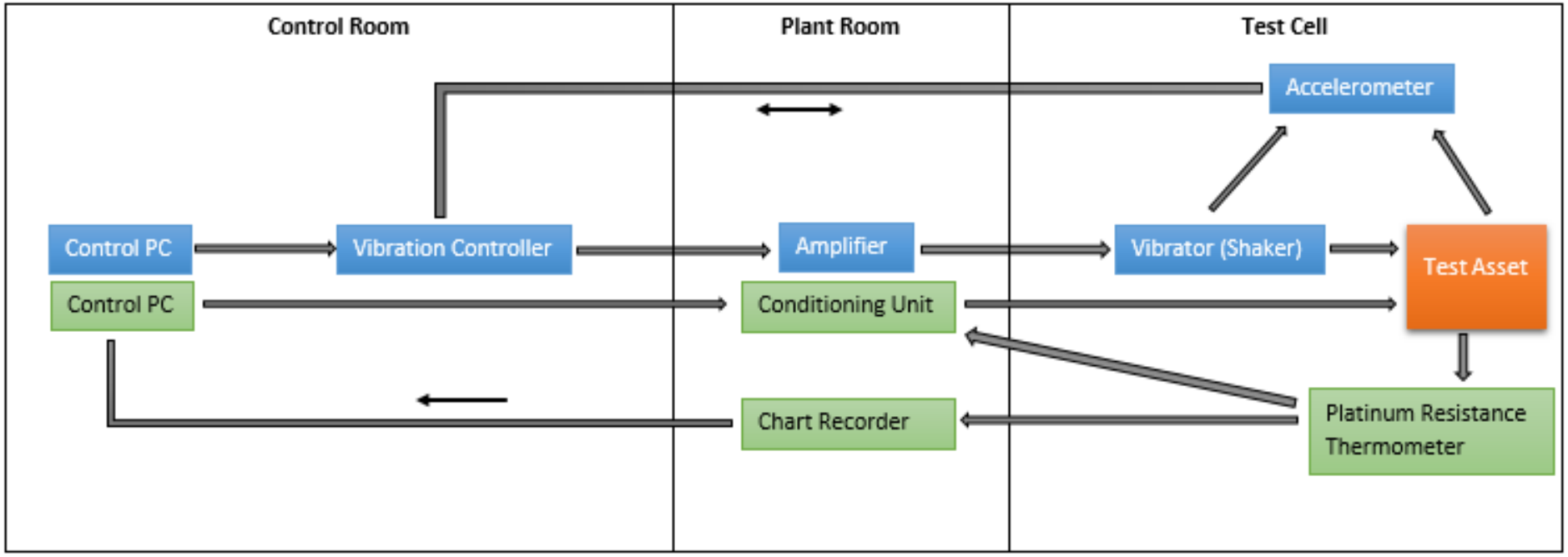


Figure 5 Vibration Diagram (with Conditioning)

The accelerometers can be utilised in different ways. The main two functions of accelerometers whilst testing are control and monitors. They don't have to differentiate in type from each other as you can have two of the same accelerometers, one can be a control and the other a monitor. It is all governed by the Control Computer and Vibration Controller. A few clicks on a mouse and a control accelerometer can be changed to a monitor accelerometer. With control accelerometers, the measured data is used to determine how much drive output from the controller is required, whereas with a monitor accelerometer the measured data is used only for the purpose of data capture, or monitoring to see how that specific area is responding.

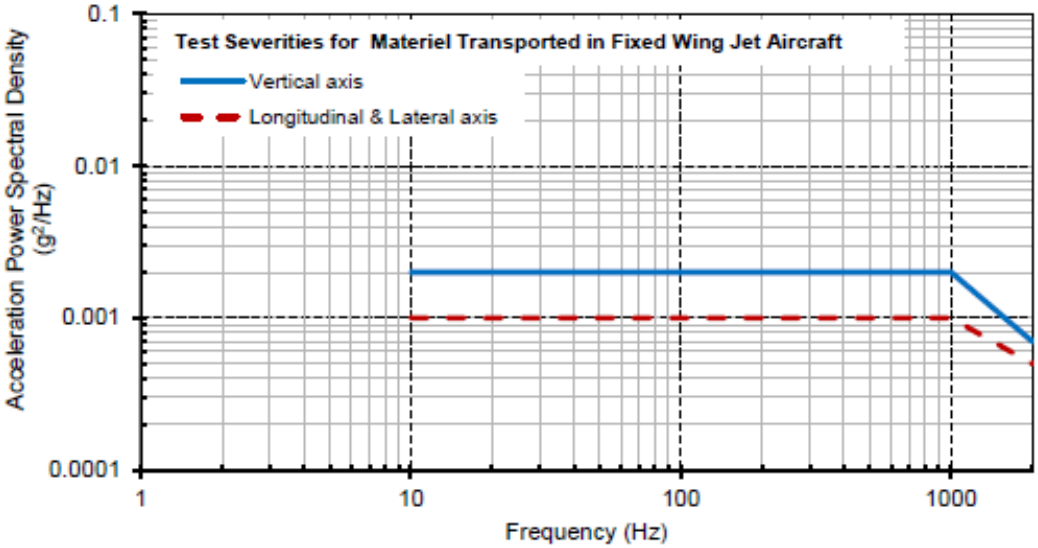
Once the customer has decided on the spectrum to test the asset, it is programmed into the Control Computer. The Software will run the vibration test to the spectrum and will adapt the drive to control the test asset so that it meets the customer spectrum, within the tolerances set.

3.1.2.2 Spectrum

Vibration testing of an OME test asset uses realistic environments replicated in laboratory conditions. The testing conducted on the test asset will have been derived from real life vibration seen in the environment that is captured through instrumented telemetry assets. The UK defence industry uses Defence Standards as well as other standards (Mil Stan, STANAG), depending on what is needed. The standards list various environmental test spectrums that have been derived from multiple sources of transport; Air, land and Sea.

The duration of the testing is calculated in response to how many miles/flight hours/time at sea the test asset will see. OME have a shorter life than most equipment in the military due to their role and this is reflected in the mileage, flight hours, (etc.) calculated. Duration under test is an accelerated version of what it would see in real life. An example of this can be seen in Figure 6 where 1 hour testing per axis equates to the equivalent of 100 hours of flight time on a fixed wing jet aircraft.

[23]



Test Severities for Materiel Transported in Fixed Wing Jet Aircraft			
Applicable to Vertical (aircraft) Axis *(or all axes if orientation of the materiel the aircraft is unknown or can vary)*		Applicable to Longitudinal & Lateral (aircraft) Axes	
Frequency (Hz)	Acceleration Power Spectral Density (g^2/Hz)	Frequency (Hz)	Acceleration Power Spectral Density (g^2/Hz)
10	0.002	10	0.001
1000	0.002	1000	0.001
2000	0.0007	2000	0.0005
r.m.s. (g)	1.77	r.m.s. (g)	1.30
Displacement pk-pk (mm)	1.2	Displacement pk-pk (mm)	0.9
Test duration per axis:	Minimum test time per axis is one hour. 1 hour of testing per axis is equivalent to 100 hours of flight time.	Test duration per axis:	Minimum test time per axis is one hour. 1 hour of testing per axis is equivalent to 100 hours of flight time

Figure A5 Test Severities for Materiel Transported in Fixed Wing Jet Aircraft

Figure 6 Fixed Wing Jet Aircraft Vibration Spectrum

The environmental test spectrums are not always accurate with regard to the test item, due to packaging, location, or platform variations. The spectrums are generalised for any test asset and are a worst case, making them severe. The positioning and mounting of the test asset is also thought about carefully, as shown in Def Stan 00-35 Deployment on Land Vehicles: [24] “The severity of the environment seen by materiel installed in a vehicle depends on where the materiel is mounted. Evidence suggests that hull vibration, expressed as the overall ‘g’ rms (0 to 1000Hz), can be significantly more severe than in the turret, depending on vehicle type and measurement axis. With respect to the relative severity of axes, vibration in the vertical axis in the hull, or turret has often been seen to be

more severe than that in the transverse, or longitudinal axes. The mass and mounting arrangements of the material can also influence its response." Although the standards are not exact the worst case is always taken.

[25]

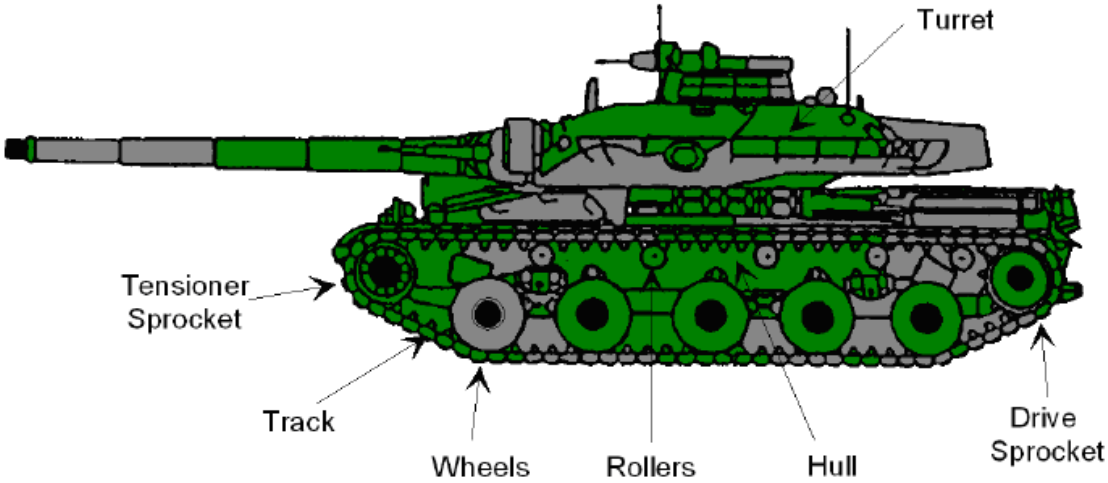


Figure 7 Equipment Mounting Zones and Track Features

Depending on the need, the customer uses supplementary information from further in life surveillance they have carried out, to add to the standard generalised spectrum. Most current versions of these standards expect the customer to enhance the spectrum with additional measured, or calculated vibration levels, producing a tailored specification for that certain test asset. Tailored test spectrums make the testing as realistic as is possible. Other added benefits from a tailored spectrum:

- More accurate test levels – Testing is more realistic
- Time and cost – Tailoring a spectrum will be expensive, but if the test durations are reduced due to the findings from the measured data, the testing will be less expensive as it will take less time
- Information – Help to design more robust components

3.1.2.3 Test Durations

Test durations can decrease from the set standards, especially when they become tailored tests. In some cases, the test durations are not able to be met due to impracticality. When this happens the test durations are decreased by utilising fatigue damage laws. The following equation is used for metallic materials and should be used with extreme care when used with OME.

[26]

$$t_2 = t_1 \left[\frac{S_1}{S_2} \right]^n$$

t_1 = the actual duration at the presumed level

t_2 = the equivalent duration at the test level

S_1 = the rms level of the measured spectrum

S_2 = the rms level of the test spectrum

n = slope of the fatigue (S/N) curve for the appropriate material). A value of 5 is preferred. (If PSD levels are used in place of rms levels then the preferred value of n is 2.5.)

Equation 1 Palmgren Miner Hypothesis

An example of reducing the test duration is shown below.

The test asset must see 100 hours actual duration of vibration.

To reach this:

t_1 = 100 hrs S_1 = 1.5 g rms S_2 = 1.908 g rms n = 5

$$\mathbf{30\ hrs = 100\ hrs \times \left[\frac{1.5\ g\ rms}{1.908\ g\ rms} \right]^5}$$

It may be unsustainable, or impractical to test the asset for 30 hours and therefore a reduced equivalent test duration may be sought by increasing the level of the test spectrum. An example shown below:

t_1 = 100 hrs S_1 = 1.5 g rms S_2 = x n = 5

$$\mathbf{10} = \mathbf{100} \times \left[\frac{\mathbf{1.5}}{\boldsymbol{x}}\right]^{\mathbf{5}}$$

$$\frac{\mathbf{10}}{\mathbf{100}} = \left(\frac{\mathbf{1.5}}{\boldsymbol{x}}\right)^{\mathbf{5}}$$

$$\sqrt[5]{\frac{\mathbf{10}}{\mathbf{100}}} = \frac{\mathbf{1.5}}{\boldsymbol{x}}$$

$$\sqrt[5]{\frac{\mathbf{10}}{\mathbf{100}}} \times \boldsymbol{x} = \mathbf{1.5}$$

$$\boldsymbol{x} = \frac{\mathbf{1.5}}{\left(\sqrt[5]{\frac{\mathbf{10}}{\mathbf{100}}}\right)}$$

$$\boldsymbol{x} = \mathbf{2.377339} \ldots$$

t_1 = 100 hrs S_1 = 1.5 g rms S_2 = 2.377 g rms n = 5

$$\mathbf{10}\ \boldsymbol{hrs} = \mathbf{100}\ \boldsymbol{hrs}\ \boldsymbol{X} \left[\frac{\mathbf{1.5}\ \boldsymbol{g\ rms}}{\mathbf{2.377}\ \boldsymbol{g\ rms}}\right]^{\mathbf{5}}$$

This means that the test level is increased, but the duration that the test asset is tested for is decreased.

3.1.2.4 Control

There are many problems that can obstruct the Vibration Controller from getting the desired output.

- Very dynamic test asset
- Make-up of the asset
- Structure
- Fixings
- Interfaces
- Material
- Natural resonance (test asset, test asset components, test rig)
- Electrical interference of the signal
- Wrongly selected, or faulty instrumentation

These can all effect the overall control of the test, meaning that the test asset does not meet the test required and has either been over, or under tested.

[27] "In a random vibration test control is maintained by measuring Power Spectral Densities (PSDs) and comparing them to the reference PSD profile. There are two important aspects to the control system:

- To shape the drive spectrum such that the excitation of the control transducer matches the pre-defined level and shape.
- To verify that the test structure is not in danger and to shut down the test if it is. This is done through the checking of abort and alarm conditions."

The tests usually have a tolerance of ±3dB, as set in most standards. This is set as an abort, with ±1.5dB as an alarm. Go higher, or lower than ±3dB and you could have an unhappy customer that wants their money back as the asset was inappropriately tested. On the other hand, whilst over testing means that the test asset receives vibration environments above what it already requires proving the strength of design, it potentially could result in a broken test asset. Although, the customer would not know if their assets would have survived the required test anyway. Retesting is both costly and time consuming.

[28]

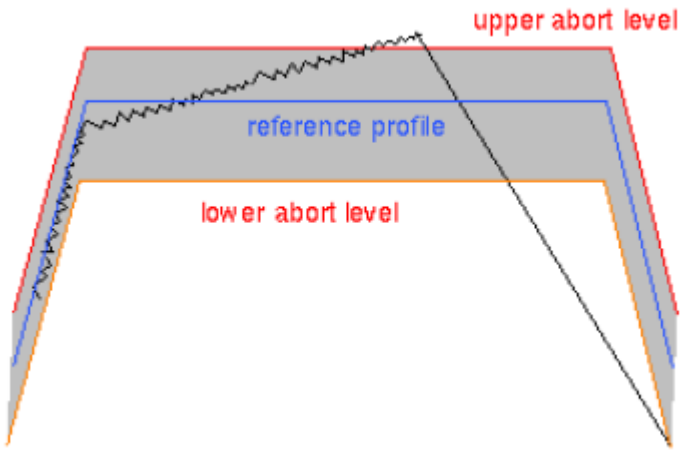


Figure 8 Abort Diagram

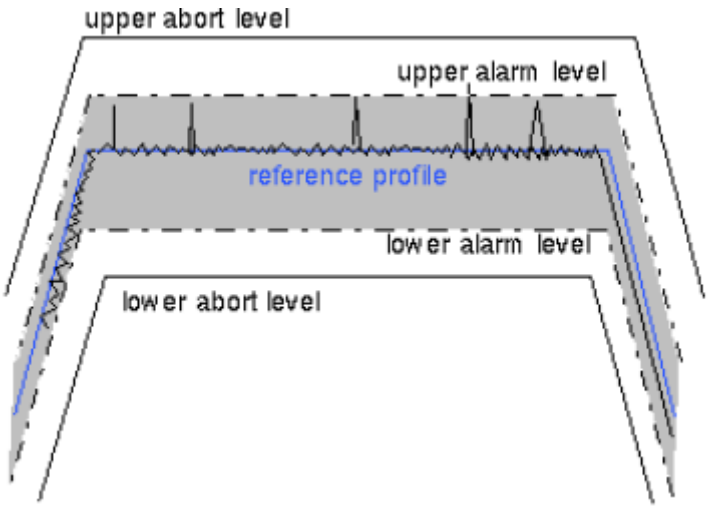


Figure 9 Alarm Diagram

Resonance is one of the major issues when vibration testing. A lot of defence transport vibration testing is within the 10-2000Hz bandwidth, which for the test assets, most of its component parts will have a resonant frequency in that bandwidth. As the test asset is vibrated, those component parts are excited by the vibration at their specific frequencies and will resonate freely. This effects the control as the control accelerometers will pick up the energy produced by the resonating component, feed it back to the Vibration Controller and Control Computer which will reduce the required drive energy at that frequency.

Vibration testing requires a lot of skill and knowledge by the engineer that oversees the testing. The placing of control positions has to be carefully thought out to balance between getting the best output and data, meeting the spectrum across the full interface of the test asset and getting the best overall control. Control strategies differ to create the best strategy for the test asset and to get the information the customer wants.

The control accelerometers are placed in a rigid part of the test asset that will not resonate as freely as other parts. Control positions can also be placed on the rig, or armature of the vibrator, as rigs are designed in theory to have resonances at higher frequencies than that of the higher end of the bandwidth.

Data may show that a certain part of the test asset on previous testing was seeing an amplified amount of vibration compared to the rest of the test asset. The control accelerometer moved closer to this area could, depending on the structure of the test asset, reduce this effect.

Control of the test asset can be single, or multi point control. A single control accelerometer can be used to control a test asset. For a larger, more complex test asset, with a more focussed input, a multi-point control strategy is used to prove the input is the same across the interface. Multiple accelerometers are positioned in strategic points over the test asset. By doing so it controls more closely the areas of the test asset that are important to see the correct level of vibration.

3.1.2.5 Input and Output testing

There are two main ways in which the asset can be tested. These are based upon the customer need and understanding of their product. Input testing is the simplest and cheapest of the two. A known and defined spectrum is inputted on the test asset. The control is monitored to make sure the test asset has been tested accurately to the spectrum and the asset usually responds as it wants to the input energy. The results are given to the customer and because it is an input test, no specific data is taken from the test asset. Input testing tends to be for less expensive assets which just need to meet the baseline set in the defence standards, or which the customer has not got any measured data for. Dependent upon the customer requirement, data is sometimes measured for base lining later testing.

Output testing is more complex. The customer is seeking data it can analyse to foresee how the asset will cope in real life. The test spectrums are tailored to replicate the actual conditions the test asset will experience. The testing will have a predetermined control strategy designed by the customer to achieve the best information they can get from the testing. It will also try to control the asset through its bending mode. An assortment of accelerometers will be used to monitor important points that might be thought to be weak, or problem points. Whilst testing, the rigs can cause unrealistic modes and therefore failures in the test asset. The overall objective of Output testing is to collect as much realistic data out of the asset as possible.

3.1.2.6 Conditioning

To keep the environmental conditions as close to those naturally induced in life, the temperature can vary whilst, for example, carrying out On Road vibration. This is specified in the life cycle at the start of building the “life cycle of material” mentioned in section 2.3.1 and is considered at the outset, as shown in pictorial form in flowchart boxes D and E in the Safety and Suitability Assessment Process (Appendix B).

Conditioning whilst testing permits the test asset to expand and contract allowing a more realistic test scenario (usually tailored by the customer). As shown in Figure 5 and highlighted in green there is a requirement to keep the test asset conditioned whilst under vibration testing. The Climatic team may precondition the asset in a specialised conditioning chamber before it is moved to the vibration test cell and the conditioning is carried on by the mobile conditioning units. The difference in the way the test asset will control and react will be apparent right from the start. The reaction to temperature varies between individual test assets. In warmer environments, the vibration will differ slightly from ambient environments as the test asset will expand. Colder environments are a lot harsher on the test assets becoming rather stiff and rigid. A negative impact of this is that the test asset can become harder to control.

3.1.2.7 Vibrator

A common electromagnetic vibrator (shaker) is an LDS 964 (depicted in Figure 10). The surrounding red frame is secured to the test facility floor and supports the vibrator body in either the horizontal, or vertical axis. The vibrator body is isolated from the frame by 16 rubber air rings. These stop any residual vibration being transferred to the frame. The picture provides a view of the vibrator armature at the centre of the vibrator body. The armature displacement provides the vibration that is programmed through the spectrum.

This 964 vibrator is capable of testing assets up to 907Kg, delivering random and sine forces up 89kN.

[29]

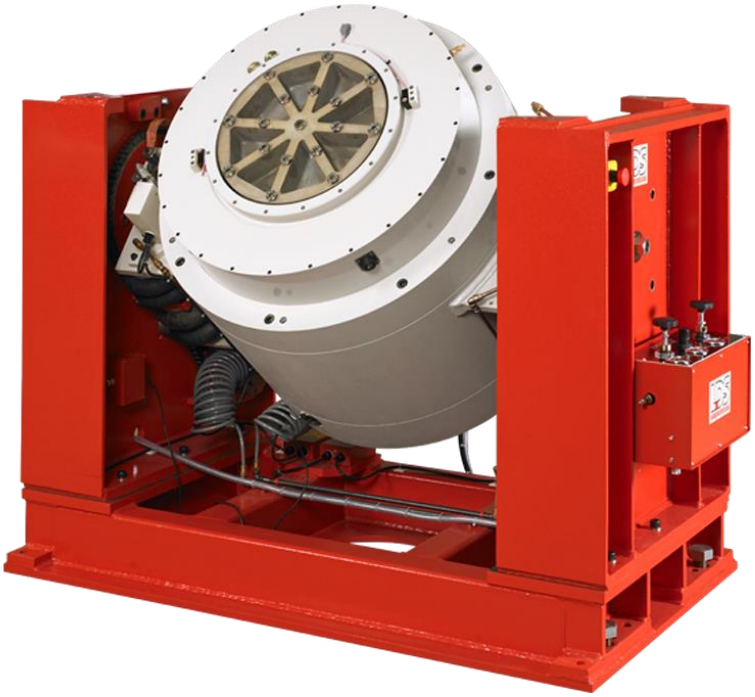


Figure 10 LDS 964 Vibrator System (Shaker)

[30]

Figure 11 Large Scale Assembled Munition under Vibration Testing

3.1.3 Shock and Impact

Shock & Impact (if instrumented) testing uses similar instrumentation to that of vibration testing. Whereas shock replicates such events as underwater explosions, Impact testing replicates the test asset being dropped, or bumped whilst packaged (Logistical Drop) and unpackaged (Tactical Drop).

Impact testing is carried out by tests such as drops, bumps, topples and other styles. Impact testing is important, as in real life, dropping assets can be quite common and has the potential to cause both faults and failure modes. [31] “Drop tests have been commonly used for product fragility assessment, prototype testing, package and cushion evaluation, and compliance with military standards. There are many different types of drop testing ranging from freely dropped boxes to guided rail drop test hardware.”

The life cycle determines the exact timing of the test in the sequential test sequence. A test in the latter half of the sequential test sequence may replicate the transport of small arms munitions (any munitions under 30mm) to the Forward Operating Base. The test will utilise the severities in Table 2 which details the specific impact velocity and fall height of the test item.

[32]

Equipment Handling Type	Applicable Categories	Impact Velocity (ms^{-1})	Fall Height (m)
Man handling (up to 40kg) – note 1	Storage and transport to forward depot and/or to front line, wheeled & tracked vehicle and ship equipment	5	1.25
Man handling (>40kg & <100kg) – note 1	Storage and transport to forward depot and/or to front line, wheeled & tracked vehicle and ship equipment	3.8	0.75
Man handling (>100kg) – note 1	Storage and transport to forward depot and/or to front line, wheeled & tracked vehicle and ship equipment	3.4	0.6
Man handling	Infantry and man-carried equipment	6.25	2.0
Man handling (safe to use if no visible damage)	Infantry and man-carried equipment	7.7	3.0 max
Forklift Truck	Storage and transport to forward depot	3.8	0.75
ISO Container handling	Storage and transport to forward depot and/or to front line	2.0	0.2
Helicopter Underslung load set down (on land)	Storage and transport to forward depot and/or to front line	2.4	0.3
Movement using VERTREP	Helicopter transport to ship	Refer to **Table 4**	
Horizontal Impact to equipment	Storage and transport to front line	2.5	0.32
Parachute Drop (with shock absorber) – note 2	Storage and transport to front line	12.5	8.0

NOTE 1 The test is not intended to encompass all credible accident conditions or severe mishandling conditions. Where the drop heights quoted are exceeded by those specified elsewhere in the table or for other phases of Service use then the higher values should be substituted

NOTE 2 This test may not be suitable to simulate certain effects which can occur during parachute drops in high wind conditions

NOTE 3 The angle of impact should be that likely to cause maximum damage to the materiel.

Table 2 Vertical Impact Severities for Typical Service Applications

Shock testing is the replication of a shock that the test asset might receive throughout its lifetime. [33] “Mechanical shock is introduced in the missile, when launched and airborne, by ignition firing, booster operation, rough burning, booster cut-off, separation of stages, sudden manoeuvres, etc. Pre-firing shock environment, which is sometimes more critical than launch and airborne mechanical shock, is introduced to the missile structure and its associated ground support equipment by a multitude of transportation media and/or careless handling”

The United States (U.S.) Army Test and Evaluation Command Common Engineering Test Procedures are concentrating on an airborne missile system. Although test assets such as missiles will receive shocks through their launch, the latter half of the passage is more in keeping with general OME. As stated in the article, the pre-firing shock environment is critical. This includes tests such as naval shocks, or Underwater Explosion (UNDEX) shocks, which replicate the shockwaves seen from an underwater explosion when the test assets are either loaded, or in storage.

Shock testing can be conducted by various different methods. One common method is the use of a Free Fall Shock Machine shown in Figure 12.

[34]

Figure 12 Free Fall Shock Machine

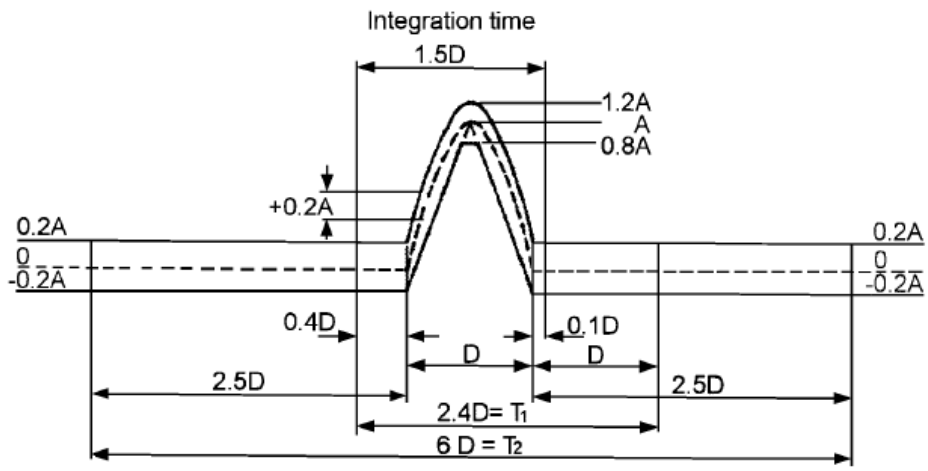
With a classical half sine test, the amplitude and duration of the pulse are achieved through two settings of the free fall shock machine:

- The height the load table (which the test asset sits on) is dropped from
- The physical programmers set

The programmers are rubberised test plates differing in density. Each density gives a different characteristic in the form of; rate of compression (providing the pulse duration) and hardness (creating the shock).

The final dependency is the weight of the test asset. A depiction of an annotated half sine shock pulse is shown in Figure 13.

[35]



KEY

- - - = normal pulse

—— = limits of tolerance

D = duration of nominal pulse

A = peak amplitude of nominal pulse

T_1 = minimum time during which the pulse shall be monitored for shocks produced using a conventional shock testing machine

T_2 = minimum time during which the pulse shall be monitored for shocks produced using a vibration generator

Figure 13 Labelled Half Sine Diagram

Whilst the main focus of testing is to replicate specific mechanical shock environments seen, Shock and Impact testing can produce results which can identify faults within the design. The testing can also build on weaknesses, stresses and fatigue from the previous testing conducted on test asset, further creating more focused failure modes. Both Shock and Impact testing can identify weaknesses in the test asset, such as areas like fixings, interfaces and the general structural rigidity that will get a lot of scrutiny from both testing.

3.2 Surveillance Techniques

Throughout the period of testing and throughout the OME's life, explosive munitions are regularly removed from storage and analysed. The analysis is used to build up data on the assets, of how well it is ageing, wear and tear, fatigue and other effects from the environment they are in (discussed in Section 5.2). According to the Swedish Defence Research Agency, FOI, [36] "It is standard practice to remove munition samples and

explosives from long term storage at regular intervals and analyse the influence of ageing…Usually these tests are destructive for the samples selected. Such a test scheme gives a statistical estimate of the ageing of the munitions in that particular batch and under the specific storage conditions of that storage".

Surveillance of a munition throughout its lifetime utilises both destructive and non-destructive techniques. Non-destructive techniques like a visual inspection of the test asset, where an examination of the entire test asset takes place to check for potential faults and ageing such as degradation, corrosion, damage, or any other discrepancies. The visual inspection will take place after every:

- Set period of time in storage (Month/years depending on the condition of storage)
- Long distance journey travelled (Road, Rail, Sea & Air)
- Occurrence (Accident, Drop, Nearby Explosion)

Other Non-destructive techniques include:

- Radiography
- CT Scanning
- Full breakdown and inspection of the asset (to component level)
- Borescope

Samples may also be taken of asset to further analyse its degradation and ageing. To obtain the samples, destructive techniques are used such as sectioning of the munition using Mills, Lathes and Bandsaws to carefully divide the munitions explosive content into manageable portions. Each portion with go through further testing, or chemical analysis.

3.3 Environmental Effects on OME

Understanding the environmental effects on OME is pivotal to development and production of new and advanced OME. It is also important to consistently improve the OME currently being used, the way it is used and the way it is handled.

Another important reason to study the environmental effects on OME is to understand why the OME failed, specifically looking into:

- The nature in which it failed
- Its history, before it failed:
    - Environments seen
    - Defects
    - Build standard
- Events that led up to failure

These points would help build an understanding of how the OME failed and potentially identify the reason the OME failed. Also, the lessons learnt from current testing and analysis can improve the safety of a munition causing it, for example, to be less sensitive to shock.

Failures as a whole are not likely caused by one single fault (although it can happen), but multiple faults occurring over a set timescale. The definition of a failure in testing and service life is defined by the customer.

Standard customer definitions of failure:

- Failure to function
- Failure to maintain the munitions safety (S^3; Safety and Suitability for Service)
- Detonation (unforeseen)

Similarly, the customer might define failure modes for testing. [37] "A failure mode is a description of the way in which an item of materiel, or a component of that materiel fails. It is therefore defined by the manner in which the materiel is judged to have failed and so a condition that would result in the failure of one component does not necessarily result in failure of another similar component used in a different application."

[38]

	Potential Failure Mechanism / Mode	Mechanical Shock	Vibration	Thermal Shock	Temperature Cycling	Temperature Extremes	Salt Mist	Sand and Dust	Solar Radiation	Moisture Ingress	Rapid Change of Pressure
Mechanical	Brittle Fracture	✓		✓		✓					
	Fatigue	✓	✓	✓	✓	✓					
	Plastic Collapse	✓									
	Leakage	✓	✓								
	Erosion		✓					✓			
	Creep		✓								
	Wear & Fretting		✓								
	Stress Concentrations	✓	✓	✓							
	Broken or Deformed Seals	✓	✓			✓					✓
	Component Cracking	✓	✓	✓	✓	✓					
	Induction of Fissures into Energetic Material	✓	✓			✓					
	Migration of Energetic into Cracks, Screw Threads etc		✓		✓	✓					
	Distortion	✓		✓		✓					
	Broken or Damaged Mechanical Parts	✓		✓							
	Loosening of Fasteners	✓	✓	✓							
	Optical Misalignment	✓	✓			✓					
	Cracking & Rupture	✓		✓		✓					
	Impacting	✓	✓								
	Cavity Collapse	✓	✓	✓		✓					

Table 3 Potential Failure Mechanisms and Modes

The aim of testing is to prove the OME test asset against a host of tests specified by the customer against a set, or tailored standard. Failure to function, and/or failure to maintain safety, will see the munition fail the suite of testing, thus losing confidence in the abilities and consideration of redesign, or limited deployment might be envisaged. Whereas an unexpected detonation would be a stop moment, leading to an investigation and a halt in movement and use of the specific asset until further information regarding safety is gleaned. A failure mode might be expected. The OME's design might not account for specific conditions, but the OME is tested still to investigate how it copes under them.

Some of the following aspects provide an insight into the various means an environment can affect OME.

3.3.1 Thermal Expansion

On a complex guided explosive munition, the fatigue of assembly and explosive bonding through temperature ageing and vibration has the potential to cause failure and/or detonation of the munition. The explosive is contained by a munition body, or shell. This might be made of Aluminium, Steel, or another metal.

Explosives can be very sensitive to temperature. The coefficients of expansion for explosives range from $50x10^{-6}$ m/°C (metres per degree centigrade) to $200x10^{-6}$m/°C as there are many compositions. [39] Whereas, the coefficients of expansion of Aluminium and Steel are roughly $23x10^{-6}$ m/°C and $12x10^{-6}$ m/°C.

This means in theory that for every 1°C change of temperature there are $23x10^{-6}$ m/°C of movement in Aluminium and potentially up to $200x10^{-6}$m/°C of movement in an explosive composition. This vast difference can create problems in the interfacing between the explosive fill and munition body.

Standard UK magazine temperatures range from 20-30°C, at the munitions maximum operating temperature (in the region of +65°C), there is an increase of over 30°C. Therefore, with the coefficient of expansion of $200x10^{-6}$m/°C the explosive increased by 0.2mm per degree, meaning at its maximum temperature it might increase by up to 6mm.

One thing worthy of noting is that $200x10^{-6}$m/°C would be a very soft material and that this result would be an extreme.

Temperature extremes and vibration that are seen throughout the munitions life and testing, can cause upmost stress and fatigue on the whole munition as well as the explosive fill itself. This is concluded in a report based on Thermal Expansion Studies on Trinitrotoluene (TNT) [40] "The high values for expansion coefficients, the variation in expansion with crystallographic axis and the non-uniform expansion along a particular axis impart anisotropic physical properties to TNT crystals. Lattice distortion, depending upon the thermal history of a crystal, causes abnormal behaviour resulting in the alteration of physical characteristics." The alteration of characteristics, due to crystallisation of the TNT and lattice distortion, has the potential to make the compound more sensitive.

There are a variety of solutions to solve the problem of thermal expansion. A 105mm shell as depicted in Figure 14 is not filled to the top (100%) with explosive. It is instead filled and

then sealed with a small void above the filling to allow for the thermal expansion. The expansion is calculated and an allowance is made in the munition.

[41]

Figure 14 105mm Munition Internal Diagram

When designing a munition one would want to use materials with a similar, or close coefficient of expansion. This would reduce the fatigue on both assembly and explosive bonding. Another solution would be to modify the munition design by adding another material between the two surfaces to mitigate the coefficient of expansion. This material with a middle coefficient of expansion would allow by design the expansion and contraction of the two materials, although this is always a compromise.

3.3.2 Adiabatic Compression

During environmental testing, mainly vibration and shock, the munition might start to heat internally. Adiabatic heating is common with gasses, but has been proven to occur in solids as well. [42] “Solids subjected to high pressures, shocks, and/or deformation, experience an increase in internal energy density and temperature due to adiabatic compression, shock heating, and plastic work heating, respectively.”

Inside a munition, the explosive fill will usually have lots of minute voids and air bubbles. The ideal explosive fill would have no voids, or bubbles in it at all. When under test from shock, or vibration the low frequencies put upon the munition excites the softer materials inside that have similar consistencies to rubber (explosive materials tend to be semi-solids). The excitement of the material produces energy. The energy imparted on the material

pumps the pockets of air, in a compression and expansion action. Over a period of time, the area can heat up substantially. The outcomes of this heating could be:

- Increased sensitivity
- Cracking of the explosive fill
- Brittleness of the explosive fill

It may later effect, or cause uncertainty over the safety, or performance of the munition and lay the foundations for eventual failure.

If the munition is exposed to a large shock, the wave propagation from the shock could cause the rapid collapse of the air bubbles, or voids causing enough heat to initiate the explosive. [43] “If you put a large amount of shock energy into an explosive, there can be enough heating from adiabatic compression in the shock front to propagate a detonation immediately.”

An everyday example of adiabatic compression is when the output of a bicycle pump is covered. The air heats up as it is compressed by the pump and has nowhere to escape. The faster the pump action the quicker the compression and the hotter the air and surrounding pump body gets.

3.3.3 Service Life

Like food stuffs, munitions have a shelf life, known as a Service Life. The service life consists of two parts; Safe Life and Functional Life.

[44] “The safe life… covers the period of time during which the explosive can safely be stored without representing any hazard to its environment.”

“The functional life is the period of time during which the explosive can be used safely and during which the functional requirements remain fulfilled.”

[45]

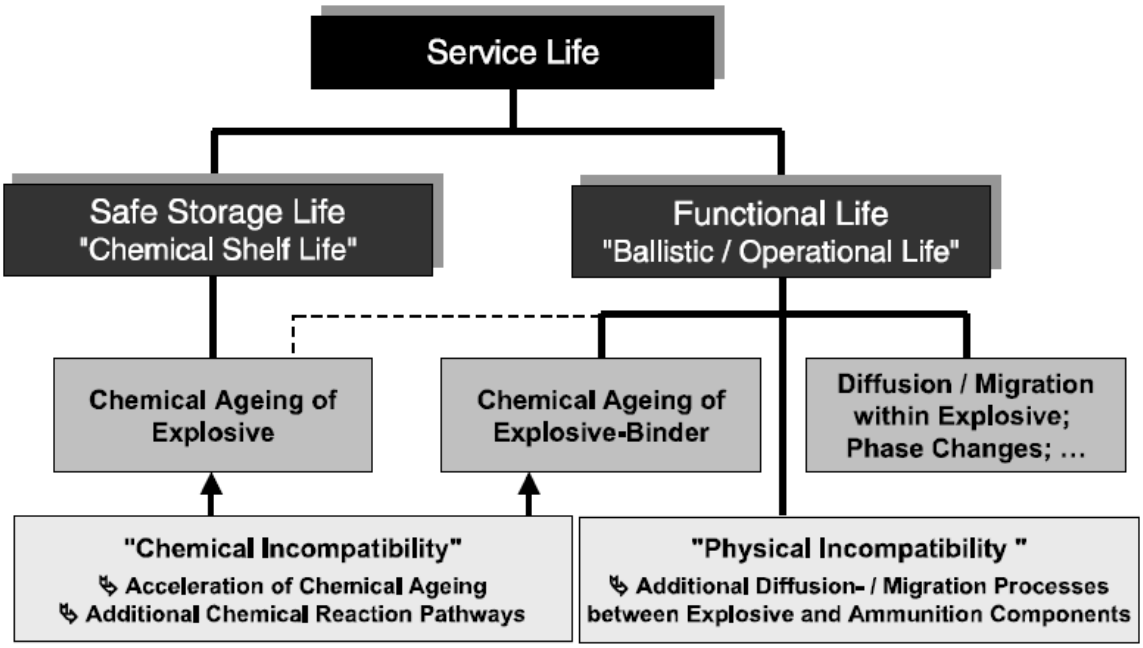


Figure 15 Service Life Flow Chart

Incompatibility between explosive chemical compositions in the munition can vastly increase the munitions ageing and breakdown. An example of chemical incompatibility is galvanic corrosion of two dissimilar metals. It increases the corrosion, with one metal deteriorating a lot quicker than it would without contact with the second metal.

Another example of chemical incompatibility is Nitrocellulose (NC), which is used in a variety of explosive propellants. [46] “The main causes of NC degradation are well known today, and can be mainly attributed to the unstable nitrate ester group. The breakage of the nitrate ester bond and the liberation of very reactive Nitrogen Dioxide (NO_2) (the result of its radical properties with one unshared electron) is the first step in the degradation process. The nitrogen dioxide formed is capable of catalysing further exothermic reactions involving fresh NC. A series of exothermic reactions can cause self-ignition of NC propellants during storage, which can cause devastating accidents. It is therefore of great concern to predict whether or not ammunition containing NC propellants will ignite.”

In summary, NC has the tendency for autocatalytic decomposition, as it is incompatible with nitrous acid. Due to the weakness of the C-N bonds in the nitrate esters, NC generates its own nitrous acid from NO_2 and moisture. The nitrous acid facilitates and amplifies the decomposition process, creating instability in the explosive propellant.

Similarly, the incompatibility of the explosive fill to other component materials in the munition can add to age acceleration. This is known as physical incompatibility.

To reduce the chemical incompatibility, the explosives are designed to be chemically neutral, or have stabilisers. Only compatible materials are used otherwise materials will start to react with the explosive (chemical reaction).

Overall this unstable chemical reaction:

- Reduces the life of the munition
- Effects the safety (by making the asset unpredictable)

Temperature is another known factor to the ageing of explosives. Again just like with food, the higher temperatures tend to accelerate ageing and decomposition, whereas colder temperatures slow down the process. Using diurnal cycling, which is a normal temperature ageing technique, the products ageing performance can be analysed and an analysis of how the materials decompose can take place.

Both chemical and physical incompatibilities added with large temperature changes can increase the acceleration of the explosive composition. Over time the bonds in the explosive composition breakdown and the munition starts to decompose. The decomposition depending on explosive has either a stabilising effect, or a destabilising effect. The destabilisation can affect the sensitivity to shock, vibration and temperature, making the handling and transportation of the munition more hazardous.

3.3.4 Degradation of Materials through Artificial Environments

Artificially introducing different conditions such as high heat and high relative humidity can degrade the materials of the test asset. These internal materials are designed not to see wet/damp conditions, but moisture can seep in through unknown faults in the design and start to degrade the different explosive compositions in the munition and short electronics, as well as accelerate the degradation of the munition shell/body (rust and corrosion).

3.3.5 Other Effects

Thermal Expansion, Adiabatic Heating and Service Life are just a small number of environmental effects on OME. Environment, be it mechanical, or climatic, affects OME in many ways that are also common with automotive, petrochemical and various other industries.

General wear and tear on the OME throughout its life creates many problems and potential safety concerns. Some environments are a lot harsher than others and so accelerate these effects. The safety considerations and general performance of the OME will rely on how the OME is affected by the environment. An example of this is shown in Figure 16, identifying the main vibration frequencies at which mechanical and fatigue damage will take place as well as other effects.

[47]

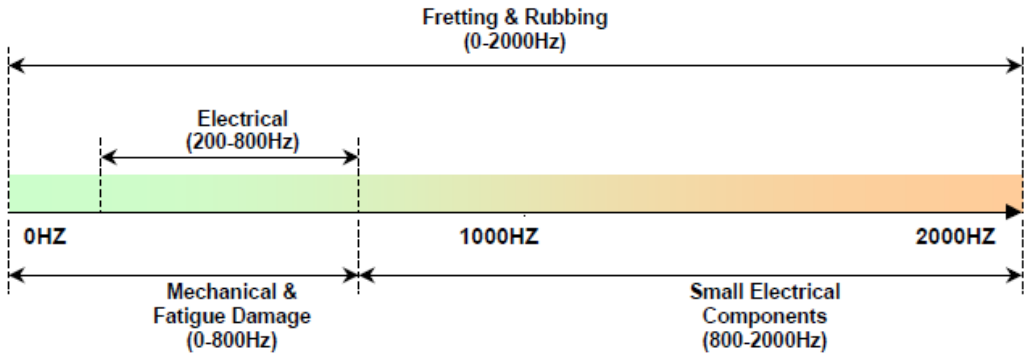


Figure 16 Mechanical Failure Modes Frequency Spectrum

Effect	Cause
Fretting/Friction	Fretting between two materials caused by vibration and/or constant shock. The friction between moving parts such as the igniter and main fill can cause heating, brittleness, flaking, cracking and general failure.
Powdering	Another result from fretting and friction, but could also be cause by climatic effects.
Flaking	Flaking can be caused from thermal shock as well as that mentioned in fretting and friction. These causes can exasperate a potential underlying problem with the explosive fill which might come from a problematic manufacturing process.
Fatigue, Stress (Material/Concentrated) and Brittleness	Constant wear and tear from climatic variations, vibration and shock.
Spot Heating	Caused through constant vibration and can be an effect of fretting and friction
Ageing (Temperature/Chemical/Physical)	Caused by the climatic and mechanical environment and composition of the munition.
Chemical Change	Caused by ageing, heating and imbalance of composition it is made up of.
Physical change in explosive	Heating and cooling of explosive compositions can lead to physical effects such as a solid material once heated turning into a liquid, or semi liquid state.

All of the effects listed have the possibility to fail the munition, or explosive. It must be said that most failures are a chain of effects that have led to an overall failure, be it functional, safety, or unforeseen detonation.

Figure 17 Chain of Effects Example

Whilst it is unlikely that one effect could cause failure, there is always a possibility.

4 Trial Setup

4.1 Purpose

This section is an example of a full test specification using test house methodology and documented approaches to demonstrate the author's ability to manage and design such a trial.

The Environmental Trial will be for a suite of theoretical environmental tests on OME test asset(s). These test assets will work their way through Vibration, Shock, Impact and Climatic sections of testing. The trial will use the same safety cases, risk assessments, specifications, schedules and other trials documentation and processes as a real trial, testing OME, would.

The OME test asset for the purpose of this trial will be a generic explosive munition. It is a Hazard Type 1, with a Net Explosive Quantity (NEQ) of 5Kg. There will be 10 test assets in total; these will be split into two equal amounts for separate test streams, Hot and Cold streams.

4.2 Trial Documentation and Processes

In order to carry out environmental testing of an OME test item there are many processes that need to be carried out, for commercial, security, safety and financial reasons.

Planning, Processing and forms including safety and security:

Statement of work	A brief statement from the customer specifying list of work to be performed.
Trial Specification	A full specification from the customer with detail on testing and references to a standard of testing to be performed.
Project Management Plan	A plan of how the Project will be managed.
Hazard Activity Risk Assessment (HARA)	A risk assessment containing all the hazards foreseen on the trial whilst testing.
Trial Safety certificate	A sign off procedure for managers and safety managers to approve; the HARA, that the testing will be suitable for the test asset and the testing process is safe.
Safety brief	A brief to all staff working, or involved in the testing.
Movement plan	A plan for the transport of the explosive test asset.
Trial Instruction	A detailed instruction of how to test the asset including setup, references to standards, durations of testing, testing temperatures, etc…
Trial file Review	A review of the safety brief, trail instruction and movement plan, ensuring that they are fit for issuing to the test team.
Trial Schedule	A detailed day to day schedule of the testing to be performed on the test asset.
Security Aspects Letter	Details how to treat the test asset, information, pictures and data.

4.2.1 Statement of Work

The Statement of Work (SOW), or Trials Specification is a customer document, written by the manufacturer, the end user, or the owner (in-service). As the vast majority of OME testing is for the defence sector, the end user and owner tends to be the MoD.

The SOW, or Trials Specification details the key customer requirements of the environmental testing. It must be clear and concise; giving all information needed to safely and effectively carry out all the testing.

Listed below are a range of topics that make up the main body of a SOW, or Trials Specification:

- Details of what is wanted from the testing
- Security details
- Safety information

- The schedule of testing (similar to the sequential test programme diagram shown in Appendix C)
- Defined environmental test specifications (with relevant standard tests referenced, or supplementary testing added to create a bespoke test)
- Rigs and test platforms
- Setup instructions and processes
- Structure of test report

The timely delivery of the SOW, or Trials Specification is of upmost importance. For a successful suite of testing, depending on the duration of trial, the SOW, or Trials Specification should be delivered ahead of the activity by a minimum period of two months.

4.2.2 Trial Instruction

The trial instruction is used to instruct the trial staff on exactly how to conduct the testing. It includes the test spectrums' references to either the exact standard spectrum, or customer derived spectrum. It uses the information gleaned from the SOW, to build the order of testing. This could include climatic, vibration, impact, radiography, as well as inspection and the dispatch of OME test assets.

Finally, the trial instruction is a set control measure that governs the testing. It makes certain the testing doesn't deviate from the customer specification. This governance is needed for the following reasons:

Safety	To ensure the OME test asset is not over tested, or tested incorrectly which could have safety implications
Security	To ensure all OME test assets are accounted for and the staff have the right clearance to work on the trial
Cost	To ensure that all testing conducted has been confirmed with the customer, as environmental testing is both costly to run and to afford. To carry out uncontracted testing would eat into the time of other environmental trials

Trial Instruction Sheet – Series 1 Issue 1

NOTES:
Trial specific Hazardous Activity Risk Assessment (HARA). Ensure you have received the safety brief for this trial before commencing work. There is a 30 min safety wait after testing of explosive items.

Ref 1 – Customer SOW
Ref 2 – Trial Specification

OP No	STORES	INSTRUCTIONS
1001	**From E.S.H** Cold test assets 1-5 Hot test assets 1-5	**RECEIPT INSPECTION** Customer Representative (CR) or his nominated and suitably certified representative is to inspect the stores in accordance w Customer's instructions. The CR is to certify the stores as fit anc for further testing. Pass Hot test assets 1-5 to Op 1003 Pass Cold test assets 1-5 to Op 1005
1002	**NO TEST ITEMS**	**PRECURSOR VIBRATION AND SHOCK** Conduct sufficient pre-cursor testing to meet the requirements tests detailed below in accordance Ref 1, Ref 2 and Def Stan 00 Part 3, Chap 2-01 and 2-03, Test M1 and Test M3. At ambient, - and +71°C in all 3 major orthogonal axes. A mass/size represent shall be used. **Test** Wheel Transport Restrained Cargo Shock Test (On Road Vehicles) Once complete progress to Op 1003
1003	**From Op 1001** Hot test assets 1-5	**HOT CONDITIONING** Condition test items to +71°C ±3°C for a minimum of 16 hrs anc maximum of 32 hrs as detailed in Ref 1. Pass all Test Items to Op 1004
1004	**From Op 1003** Hot test assets 1-5	**HOT VIBRATION AND SHOCK** Conduct Vibration and Shock testing in accordance with the tab below to meet the requirements of Ref 1, Ref 2 and Def Stan 00 Part 3, Chap 2-01 and 2-03, Test M1 and Test M3.

Complete testing in all 3 orthogonal axis.

Test
Wheel Transport
Restrained Cargo Shock Test (On Road Vehicles)

Pass all Test Items to Op 1007

1005 **From Op 1001**

Cold test assets 1-5

COLD CONDITIONING

Condition test items to -46°C ±3°C for a minimum of 16hrs and a maximum of 32hrs as detailed in Ref 1.

Pass all Test Items to Op 1006

1006 **From Op 1005**

Cold test assets 1-5

COLD VIBRATION AND SHOCK

Conduct Vibration and Shock testing in accordance with the table below to meet the requirements of Ref 1, Ref 2 and Def Stan 00-35, Part 3, Chap 2-01 and 2-03, Test M1 and Test M3.

Complete testing in all 3 orthogonal axes.

Test
Wheel Transport
Restrained Cargo Shock Test (On Road Vehicles)

Pass all Test Items to Op 1007

1007 **From Op 1004**

Hot test assets 1-5

From Op 1006

Cold test assets 1-5

VISUAL INSPECTION

CR supported by site staff to conduct a visual inspection of all test items referring to Inspection Document in Ref 2 and sentence as safe to continue testing.

Pass Hot test assets 1-5 to Op 1009

Pass Cold test assets 1-5 to Op 1011

1008 **NO TEST ITEMS**

PRECURSOR LOGISTIC DROP 1.5M

Conduct sufficient pre-cursor testing to meet the requirements of tests detailed in Ref 1, Ref 2 and Def Stan 00-35, Part 3, Chap 2-05, Test M5. A mass/size representative shall be used.

Once complete progress to Op 1009

1009 **From Op 1007**

HOT CONDITIONING

Condition test items to +71°C ±3°C for a minimum of 16 hrs and a

	Hot test assets 1-5	maximum of 32 hrs as detailed in Ref 1. Pass all Test Items to Op 1010
1010	**From Op 1009** Hot test assets 1-5	**<u>HOT LOGISTIC DROP 1.5M</u>** Conduct Drop test in order to meet the requirements of Ref 1, Ref 2 and Def Stan 00-35, Part 3, Chap 2-05, Test M5. There is a 30 minute out time. Pass all Test Items to Op 1013
1011	**From Op 1007** Cold test assets 1-5	**<u>COLD CONDITIONING</u>** Condition test items to -46°C ±3°C for a minimum of 16hrs and a maximum of 32hrs as detailed in Ref 1. Pass all Test Items to Op 1012
1012	**From Op 1011** Cold test assets 1-5	**<u>COLD LOGISTIC DROP 1.5M</u>** Conduct Drop test in order to meet the requirements of Ref 1, Ref 2 and Def Stan 00-35, Part 3, Chap 2-05, Test M5. There is a 30 mins out time. Pass all Test Items to Op 1013
1013	**From Op 1010** Hot test assets 1-5 **From Op 1012** Cold test assets 1-5	**<u>VISUAL INSPECTION</u>** CR supported by site staff to conduct a visual inspection of all test items referring to Inspection Document in Ref 2 and sentence as safe to continue testing. Pass Hot test assets 1-5 to Op 1015 Pass Cold test assets 1-5 to Op 1017
1014	**NO TEST ITEMS**	**<u>PRECURSOR AIRCRAFT VIBRATION C17/C130J</u>** Conduct sufficient pre-cursor testing to meet the requirements of Ref 1, Ref 2 and Def Stan 00-35, Part 3, Chap 2-01, Test M1. At ambient, -46°C and +71°C in all 3 major orthogonal axes. A mass/size representative shall be used. Once complete progress to Op 1015
1015	**From Op 1013** Hot test assets 1-5	**<u>HOT CONDITIONING</u>** Condition test items to +71°C ±3°C for a minimum of 16 hrs and a maximum of 32 hrs as detailed in Ref 1. Pass all Test Items to Op 1016

1016	**From Op 1015** Hot test assets 1-5	**<u>HOT AIRCRAFT VIBRATION C17/C130J</u>** Conduct Vibration testing in accordance with the requirements of Ref 1, Ref 2 and Def Stan 00-35, Part 3, Chap 2-01, Test M1. Complete testing in all 3 orthogonal axes. Pass all Test Items to Op 1019
1017	**From Op 1013** Cold test assets 1-5	**<u>COLD CONDITIONING</u>** Condition test items to -46°C ±3°C for a minimum of 16hrs and a maximum of 32hrs as detailed in Ref 1. Pass all Test Items to Op 1018
1018	**From Op 1017** Cold test assets 1-5	**<u>COLD AIRCRAFT VIBRATION C17/C130J</u>** Conduct Vibration testing in accordance with the requirements of Ref 1, Ref 2 and Def Stan 00-35, Part 3, Chap 2-01and 2-03, Test M1. Complete testing in all 3 orthogonal axis. Pass all Test Items to Op 1019
1019	**From Op 1016** Hot test assets 1-5 **From Op 1018** Cold test assets 1-5	**<u>VISUAL INSPECTION</u>** CR supported by site staff to conduct a visual inspection of all test items referring to Inspection Document in Ref 2 and sentence as safe to continue testing. Pass Hot test assets 1-5 to Op 1020 Pass Cold test assets 1-5 to Op 1022 **<u>FURTHER TESTING TO FOLLOW</u>** • Air Vibration A400M • B3 and B2 Diurnal Cycling • C2 Diurnal Cycling • Air Transport Vibration Rotary Wing • Vibration (Off Road) Wheeled Transport • Restrained Cargo Shock Test • Tactical Drop • Saltwater Immersion

Figure 18 Example Trial Instruction

4.3 Safety and Risk Analysis

Testing of OME is inherently risky, due to the nature of the product being tested and the reason behind the activity. Environmental testing proves the product before it is used and functioned in real life, as mentioned previously in section 3.1 it also proves the safety when the life of the OME is extended.

The main aim of the safety and risk analysis documentation and processes is to keep testing safe, including staff, visitors and the public. To do this one must first consider the risks involved, as will be shown in the next sections of this report. The information is gathered and reviewed. The safety case is made and is used to prove that the control measures are suitable at peer review.

Other information for the safety case:

The explosive regulations are consulted, using safety distances provided by the Health and Safety Executive (HSE)

The use of remote testing is used to create a barrier between the staff and OME

Controlling access to the explosives area such that all staff and visitors are registered and briefed before entering the explosive test area, they are also checked along with their vehicles for contraband.

How many people are going to be in the test cells, or inspection buildings at one time? The least amount of people should be in the buildings at one time. Man limits may be put in place.

Responding to defects found whilst testing. If the defect is considered a safety risk, then a stop moment will be put into effect with the customer and specialists consulted and a way forward agreed.

4.3.1 Safety Data

Safety data is essential. The trial cannot go ahead without the complete safety data to build the safety case around the trials testing. The customer will deliver a complete Materials Safety Data Sheet (MSDS) that gives specific detail on the composition of the explosive. It will list results and data on small scale testing of the explosive, particularly sensitivity and friction factors of explosive compounds.

The information gathered form the MSDS is used in the risk assessments and safety brief, as well as the engineering controls designed for the testing on the munition.

4.3.2 Explosive Safety Traces/Distances

The Environmental Trial consists of various different tests. This section will explore the explosive safety traces/distances for the Inspection and Vibration aspects of the trial.

Explosive safety traces are important to keep staff, contractors, customers, visitors and the general public safe. Understanding the danger area involved with explosives is vital to building a safety case for the trial and to allow the testing to succeed harmoniously with the other operations happening around the site. Controlling access to the explosive area is a must and all staff and visitors must be registered and briefed before entering the explosive test area.

Explosives licencing for a non-military/government organisation is governed by the HSE. The HSE have many guidelines that govern and control the use, storage and testing of explosive articles. [48] "The Explosives Regulations 2014 (Amendment) Regulations 2016 (ERAR2016)" is the set guideline and legislation produced by the HSE.

The [48] "2014 regulation" includes a section labelled [49] "Annotated Separation Distance Tables" this is the guidelines on producing the safety traces, or distances when an explosive test article is in a building.

The vibration test facility depicted in Figure 19 as building 1 will throughout testing only have either the hot, or the cold stream of test items. Each test item has an NEQ of 5Kg, so with 5 test assets in each stream there will be a maximum of 25Kg, Hazard Type 1 in building 1.

The building according to Figure 19 is metal built and mounded. Using the separation distance table (Table 4) provided by the HSE, the safety trace, or hazard distance, is 10 metres.

[50]

Table 3 Hazard Type 1 explosive in a metal-built mounded store

Column 1	Distance in metres to protected works and/or buildings of							
Quantity of explosives (kg)	**Class A** Footpath, lightly used road	**Class B** Minor road, railway	**Class C** Major road, place of public resort	**Class D** Buildings	**Class E** Vulnerable building	**Class F** On-site buildings	**Class G** On-site stores	**Class H** On-site manufacture & processing
0.1–10	7	10	21	23	40	12	9	18
10–20	9	13	26	29	42	15	9	18
20–30	10	15	30	33	44	17	9	18
30–40	11	16	33	37	46	18	9	18
40–50	12	18	35	40	48	20	9	18

Table 4 Hazard Type 1, Metal Built, Mounded, Store Separation Distance Table

The inspection facility, depicted in Figure 19 as building 3, will have both streams for inspections. This means that there will be a total of 50kg NEQ for the 10 test assets.

The building is brick built and has no mounds apart from the revetment separating it from building 2. Using the separation distance tables provided by the HSE, the safety trace, or hazard distance is 53 metres.

[50]

Table 2 Hazard Type 1 explosives in a brick-built unmounded store

Column 1	Distance in metres to protected works and/or buildings of							
Quantity of explosives (kg)	**Class A** Footpath, lightly used road	**Class B** Minor road, railway	**Class C** Major road, place of public resort	**Class D** Buildings	**Class E** Vulnerable building	**Class F** On-site buildings	**Class G** On-site stores	**Class H** On-site manufacture & processing
0.1–25	47	70	141	141	141	70	141	141
25–30	48	72	144	144	144	72	144	144
30–40	50	76	151	151	151	76	151	151
40–50	53	80	159	159	159	80	159	159
50–60	56	84	168	168	168	84	168	168

Table 5 Hazard Type 1, Brick Built, Unmounded, Store Separation Distance Table

The calculated distances will now be used throughout the trial and in support of the safety case. Beyond the security fence line are farmers' fields (rented from the MoD). When the test assets are inspected the safety distance for building 3 was calculated at 53 metres. This goes beyond the security fence line, therefore the farmers must be notified and the fields shut to them until the explosive test assets have been removed from that building.

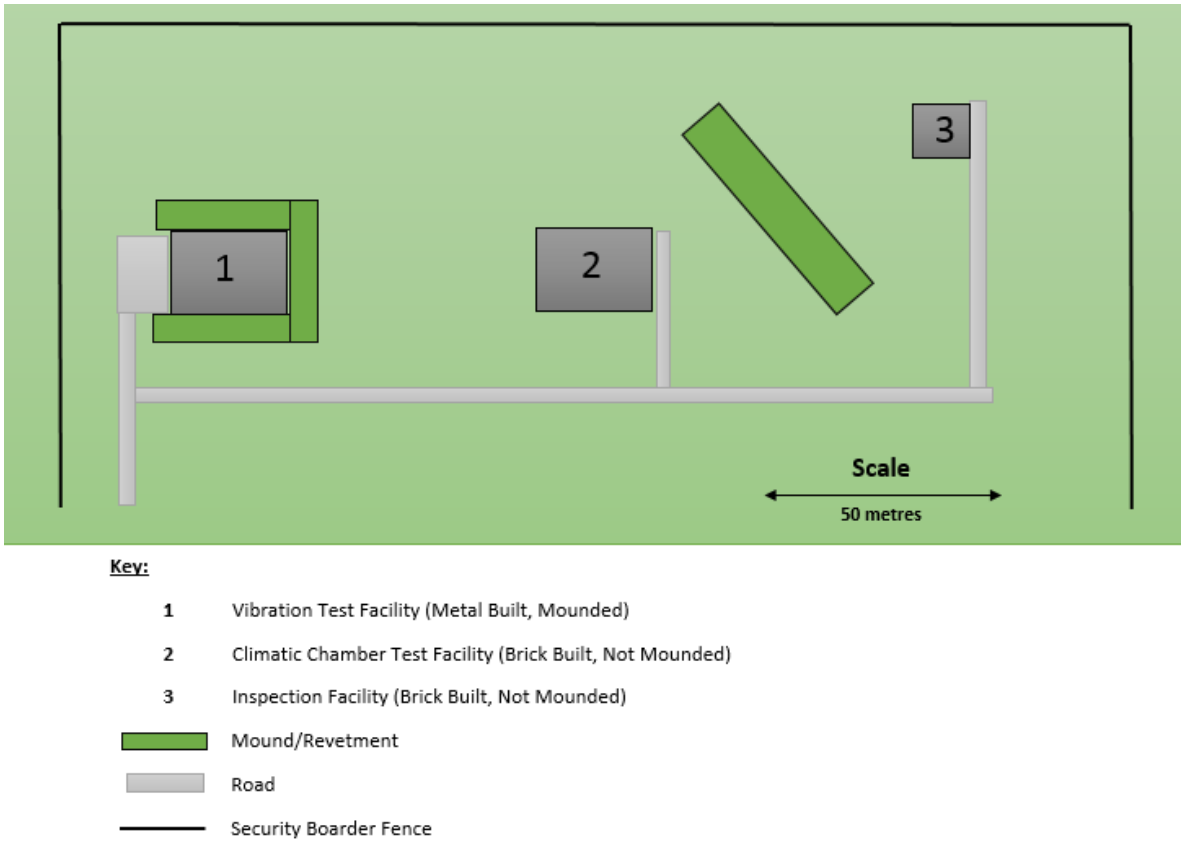


Figure 19 Site Diagram

4.3.3 Hazardous Activity Risk Assessment

The testing of OME is deemed a Hazardous Activity. Instead of producing a regular occupational safety based risk assessment, a Hazardous Activity Risk Assessment is used. This differs in the severity and the consequences of the proposed activity. The HARA (Figure 20) looks at some examples of hazards that might be seen whilst testing and how the control measures put in place, mitigate the risk.

Part 1 : Assessment Details			
Activity Title :	OME Trial 1	Assessment No:	1
Location:	TEST HOUSE	Assessment Date:	.....
Assessment Team:	.....	Lead Assessor :	.....

	C	Cr	Se	M	N	LIKELIHOOD		SEVERITY	
F	VH	VH	H	M	L	Frequent	Not surprised, will occur several times	Catastrophic	Multiple fatalities and/or 3rd party fatality or severe widespread environmental damage
P	VH	VH	H	M	L	Probable	Occurs repeatedly / an incident to be expected	Critical	Single fatality and/or multiple severe injuries and/or 3rd party severe injuries, occupational illness or environmental impact
O	H	H	M	L	T	Occasional	Infrequent, but could occur sometime	Serious	Single severe injury or occupational illness and/or multiple minor injuries or minor occupational illness and/or 3rd party minor injuries
R	M	M	L	T	T	Remote	Unlikely though conceivable	Minor	Minor injury / short term absence and/or 3rd party trivial injury
I	L	L	T	T	T	Improbable	Could happen but probably never will	Negligible	Trivial injury (First aid only) / environmental damage to plants

	RISK RATING
VERY HIGH	Work shall not proceed or facility shall not be used
HIGH	Reduce risk through additional controls. Permit to Work may be required in addition to Safe Method of Work; competency levels appropriate and documented
MEDIUM	Reduce risk through additional controls if practicable, if not, add to the Safe Method of Work the levels of competency should be appropriate competency should be appropriate
LOW	This work which may be of a routine nature will require a Safe Method of Work
TRIVIAL	Additional controls required only if the benefits justify the effort

Part 2 : Activity Specific Tasks

Task Description (1): TRANSPORTATION									
No.	**Hazard**	**Who might be harmed & how**	**Initial Risk**			**Control Measures**	**Residual Risk**		
			L	**x S**	**= R**		**L**	**x S**	**= R**
1	Road traffic accident caused by vehicle failure, leading to an impact shock on the packaged Generic Explosive Munition causing initiation. **The NEQ of each Generic Explosive Munition is 5kgs hazard type 1.**	**Immediate localised effects:** The staff carrying out the transportation (2) Resulting in multiple fatalities or severe injuries from the effects of Blast, Fragments and Thermal. **Secondary effects to personnel not in the immediate localised area:** Multiple indirect, including staff, contractors and visitors. Resulting in potential multiple fatalities or severe injuries from the effects of projectile.	R	C	M	ESTC classification number confirms the packaged Generic Explosive Munitions are safe for transportation. All vehicles shall be regularly serviced and have a thorough examination. Vehicles shall be checked daily by the driver before work commences. In accordance with the OME Transport code of practice, only electric and diesel vehicles are authorised to enter the explosive site. The speed limit is 10 mph. Road signs and markings indicate the priority of movement at junctions. Access to the explosive site shall be controlled via the permit to work process and the number of vehicles on site is kept to a minimum.	I	C	L

Task Description (2): HANDLING OF PACKAGED TEST ITEMS (CLIMATIC, VIBRATION AND INSPECTION)									
No.	**Hazard**	**Who might be harmed & how**	**Initial Risk**			**Control Measures**	**Residual Risk**		
			L	**x S**	**= R**		**L**	**x S**	**= R**
1	Failure of equipment within the building leading to a fire which will cause the packaged Generic Explosive Munitions to initiate. **The NEQ of each Generic Explosive Munition is 5kgs hazard type 1.**	**Immediate localised effects:** The staff carrying out the task (2). Resulting in multiple fatalities or severe injuries from the effects of Blast, Fragments and Thermal. **Secondary effects to personnel not in the immediate localised area:** Multiple indirect, including staff, contractors and visitors. Resulting in potential multiple fatalities or severe injuries from the effects of projectile.	O	C	H	All testing is carried out remotely. People other than those directly involved with the task are constrained from approaching buildings where inspections or testing is being carried out by physical barriers. The auto ignition temperature for a Generic Explosive Munition is ...°C as stated in the Material Safety Data Sheet. The Generic Explosive Munitions are held in their ESTC cleared packaging. The building electrical installation is to CAT C standard. Fire exits in all buildings within the test house are clearly labelled. Equipment is subjected to servicing and maintenance annually. All staff receive Fire Awareness training on an annual basis and are taught to only fight a fire it is blocking a fire exit.	I	C	L

Task Description (3): DYNAMIC TESTING OF PACKAGED TEST ITEMS (VIBRATION AND IMPACT)									
No.	**Hazard**	**Who might be harmed & how**	**Initial Risk** L	x S	= R	**Control Measures**	**Residual Risk** L	x S	= R
1	Initiation of packaged Generic Explosive Munitions as a result of being subjected to Dynamic (vibration and impact testing) testing. **The NEQ of each Generic Explosive Munition is 5kgs hazard type 1.**	**Immediate localised effects:** The staff carrying out the task (2). Resulting in multiple fatalities or severe injuries from the effects of Blast, Fragments and Thermal. **Secondary effects to personnel not in the immediate localised area:** Multiple indirect, including staff, contractors and visitors. Resulting in potential multiple fatalities or severe injuries from the effects of projectile.	O	C	H	All testing is carried out remotely. People other than those directly involved with the task are constrained from approaching buildings where inspections or testing is being carried out by physical barriers. A 30-minute safety wait is observed before staff are allowed to go past the safety barrier to enter the building. The Generic Explosive Munitions are held in their ESTC cleared packaging. The auto ignition temperature for a Generic Explosive Munition is ..."C as stated in the Material Safety Data Sheet. The highest temperature the Generic Explosive Munitions will be subject to is ..." C during temperature testing The building electrical installation is to CAT C standard. All staff receive Explosive Awareness training on an annual basis.	R	C	M

Part 3: Lead Assessor Signature		
Review Date:	Name & Position:	Signed:

Part 4: Management Confirmation Signature		
I have reviewed the above assessment and confirm it is suitable and sufficient		
Review Date:	Name & Position:	Signed:

Part 5: Periodic Review		
I confirm that the above assessment remains valid, controls remain effective and there has been no increase in risk		
1st Review Date:	Name & Position:	Signed:
2nd Review Date:	Name & Position:	Signed:
If significant changes are required as a result of the review process, then a new assessment should be issued		

Figure 20 Example Hazardous Activity Risk Assessment

4.3.4 Safety Brief

The safety brief is created using the information and data gathered whilst producing the HARA. It is broken down into a brief that is easier to read and to understand by the trials staff.

Safety Brief

Trial No.	Date:	Area:	Briefed By:	Signature:
1	December 2017	Environmental Test	……..	…….

The briefing is to be given by the relevant responsible manager, or appropriate deputy to all personnel involved in the activity. All personnel that receive this brief are to sign to confirm they have been made aware of and understand the significant hazards and controls associated with the activity and agree to follow the procedures explained to them.

Activity Aim:

The OME test asset is generic explosive munition. The customer would like a bespoke suite of testing based on set defence standards, to prove the asset against the specific environments.

Test Assets:

There are 10 generic explosive munitions. 5 for the hot stream and 5 for the cold stream.

- **Each generic explosive munition has an NEQ of 5Kg**
- **All generic explosive munitions to be tested on the trial are Hazard Type 1**

The generic explosive munition is Hazard Type 1 when packaged and unpackaged.
The generic explosive munition is classes as 1.1D.

Check for compatibility groups when arranging storage.

Apply ammunition training and if you are unsure of anything, request refresher training.

Reminder:

Hazard Type 1 – Mass Explosion (Blast Fragments)
Hazard Type 2 – Projectile (Frag Blast)
Hazard Type 3 – Thermal (Blast Fragments)
Hazard Type 4 – Local Effects (Projectiles, Frag, Thermal)

Activity Specific Hazards:

Loading of the generic explosive munition is to be carried out by trained staff that hold the relevant certificate of technical competency.

The test item is sensitive to both static and shock.

Briefing topics for Trials Team:
<u>First Aiders</u> Refer to the First Aid Notice displayed on all buildings which lists First Aiders and Trauma trained staff. <u>Emergency Number</u> In case of an emergency the control office must be notified immediately by dialling the emergency number 1111. <u>Fire and Emergency Evacuation point</u> This is located outside the main gates in the car park. <u>Fire Alarm</u> Operate the alarm if fitted, or shout “Fire, Fire, Fire” and dial the emergency number 1111. <u>Risk Assessment</u> A Hazardous Activity Risk Assessment has been written specifically for this trial. All identifiable risks and mitigations that are associated with the trial can be found within this risk assessment. <u>Personal Protective Equipment (PPE)</u> All standard workwear PPE. Steel toe cap boots must be worn at all times whilst working in the explosives area. Hard hats must be worn when slinging is taking place. When handling the test generic explosive munition, a full conductive anti-static regime must be in place. PPE includes: Conductive footwear Full flame retardant and anti-static overalls Anti-static gloves Anti-static wrist strap <u>Safety Wait</u> A safety wait of 30 minutes is to be strictly adhered to after dynamic testing has completed.

Name	Company	Role	Signature	Date

Figure 21 Example Safety Brief

4.3.5 Engineering Controls

Engineering controls are the main preventative safety measure. Personal Protective Equipment (PPE) is not considered to be an engineering control.

All risks should be mitigated by engineered controls, which are written into the general site processes and both the site's general and specific risk assessments. The site processes and risk assessments cover the points listed below as well as other more specific processes for different equipment.

- Appropriate signage
- Maximum man limits in a building, or vicinity at one time
- Explosive building distances
- Explosive building Net Explosive Quantity limits
- Interlock devices to prevent access to areas when testing is taking place
- Emergency stops
- Alarm systems
- Warning lights/beacons
- PPE
- Emergency precautions

Other controls will be put in place from the outcome of the MSDS. If the explosive is particularly sensitive to static then a full conductive, or anti-static regime would be used to prevent occurrence of static initiating the explosive.

4.3.6 Peer Review

Peer review involves a host of Explosive Specialists, Safety Managers, Subject Matter Experts (SME) and Trials Managers. The safety documentation for the trial will be presented by the Project Engineers, utilising specialists in their fields, if need be. The information given in the presentation and documentation is then scrutinised. The Peer Review Panel can ask for changes to be made before the trials safety documentation is deemed suitable.

4.3.7 Trials Safety Certificate

Once Peer Review have accepted the trials and any changes have been made the Trial Safety Certificate can be signed. The document is signed by the head of site, head of facility, project manager, ordnance safety manager, site safety manager and trials manager. The expiry date is set to the end date of the trial with additional contingency.

4.4 Programme Management

4.4.1 Resources

The resources required for this trial are as follows:

Staff

Project and Planning Staff

Trials Manager	Responsible for managing all trials at the Environmental Test Centre.
Project Engineer	Responsible for project engineering the trial from start to finish liaising with Planning staff, trials staff and supporting roles.
Scheduler	Helps schedule each separate trial created by the project engineer into one coherent schedule.
Trials Staff	
Environmental Trials Engineer (for each part of testing Vibration, Impact, climatic)	Responsible for the testing carried out in their building, supported if needed by the Technical Specialist.
Environmental Trials Technician	Supports the Engineer in testing the OME test asset.
Support	
Head of Site	Understands the overall testing and studies the safety case and processes put in place for the trial before approving the trial.
Head of Facility	Evaluates the testing to be conducted and examines the safety and processes put in place before approving for the trial.
Trials Safety Manager	Understands the testing and scrutinises the safety processes put in place for the trial.
Ordnance Safety Manager	Understands the testing and safety processes needed. Helps the Project Engineer build the safety process. Questions the finished safety case before approving.
Technical Specialist	Supports the Engineer with a greater knowledge of testing built on from years of experience.
Ammunition Technician	Responsible for both internal and external ammunition moves.
Ammunition Inspector	Responsible for the inspection of the ammunition at the start, throughout and at the end of testing.

Facilities

Suitable facilities will be needed to enable the testing to be conducted as specified in the SOW and Trial Instruction.

Inspection facility	To inspect the OME test assets when they are initially delivered for testing, throughout the environmental testing and post testing before dispatch
General purpose vibration test cell	To carry out vibration testing as stated in the Trial Instruction.
Hot and cold climatic test chambers	For Climatic testing and conditioning support for the Vibration, Shock and Impact tests.
Small drop facility	To carry out Drop tests as stated in the Trial Instruction.
Shock facility	To carry out the Shock testing as stated in the Trial Instruction.
Saltwater immersion facility	To carry out the testing stated in the Trial Instruction.
Explosive Store House (ESH) (magazine)	To hold and store the test assets Pre testing, in between testing and post testing pending dispatch
Radiography facility	To carry out pre and post testing (pending dispatch) radiograph to make sure the test assets are fit to travel.

Test and specialist equipment:

Vibrator (Shaker) unit	Drives the test asset at required levels.
Vibrator Amplifier and Power unit	Powers the Vibration system.
Slip table, or Team bearings	Hydrostatic bearing used in the shaker horizontal position to support test rigs.
Oil Pump unit	Supplies oil to the bearing systems.
Head expander, or Load bearing platform (LBP)	A large platform to support the test rigs when the shaker is in the vertical position.
Thermal barrier	A barrier to prevent thermal seepage from the test asset and test rig onto the Vibrator.
Interface plate	A plate that attaches the armature of the Vibrator on one face and to either the Driver bar, LBP, or Head expander on the other.
Driver bar	A link that attaches the Vibrator armature to either the slip table face plate, or base plate (depending on the configuration).
Base plate	A base plate that attaches to both the test rig and the slip table, team bearings, head expander, or LBP.

Test Rig/Jig	A rig specially designed for the test asset to interface with.
Pedestal	A heightened base on legs for attaching team bearings to the horizontal vibrator setup at the correct height.
Conditioning unit (Mobile/Fixed)	A unit that conditions the test assets to hot, cold, or ambient temperatures.
Conditioning chamber	A chamber that is insulated to keep the test asset in temperature.
CO^2 bowser and nozzle set	Supplementary to the conditioning unit to boost cold temperature
Scaffolding and staging	To create a working platform around the Vibrator and test setup.

<u>Instrumentation involved:</u>

Vibration controller	A front end controller that controls the test program sent to the vibrator.
Charge amplifiers	A charge amplifier powers the accelerometer and amplifies the signal back for the Vibration controller.
Accelerometers	A accelerometer senses the vibration levels and conveys them back to the controller
Accelerometer cabling	A triple shielded cable used to reduce the amount of electrical interference experienced.
Isolation block	Isolates the accelerometer from the test item, or rig.
Chart recorder	Converts the data seen from the PRT's and thermocouples to temperature data that can be saved.
Skin and air platinum resistance thermometers (PRT) and thermocouples	Senses the temperatures in the air of the chamber and skin temperatures of the test asset.

4.4.2 Schedule

The schedule is vital for the Environmental Trial of OME test assets to go ahead. It lists the scheduled environmental test (Vibration, Shock, Impact and Climatic), when they're taking place, and in what test cell. It also details staffing of each test facility/cell, but most importantly to the business, it lists the milestones agreed with the customer (more details in 4.4.3).

The Environmental Trials Schedule for the OME test assets shows 416 Days of documentation and processing, testing, inspection, and reporting, which make up the whole duration of the trial. This is one of the multiple schedules that are captured as a larger facility schedule, enabling the head of facility to look at capacity, future investments, staffing and importantly more business.

Trial No	Task Name	Duration	Start	Finish
	Schedule	416 days	Tue 28/08/18	Mon 27/04/20
	Active Trials	416 days	Tue 28/08/18	Mon 27/04/20
OME Trial 1	OME Trial 1	416 days	Tue 28/08/18	Mon 27/04/20
OME Trial 1	Contract Award	0 days	Tue 28/08/18	Tue 28/08/18
OME Trial 1	Schedule agreement	5 days	Tue 28/08/18	Mon 03/09/18
OME Trial 1	Sequential Testing	390 days	Mon 03/09/18	Wed 25/03/20
OME Trial 1	Documentation	30 days	Mon 03/09/18	Mon 15/10/18
OME Trial 1	Initial Inspection	17 days	Tue 18/09/18	Wed 10/10/18
OME Trial 1	Rigs & Fixtures	51 days	Tue 04/09/18	Tue 13/11/18
OME Trial 1	Trial readiness Review	0 days	Tue 13/11/18	Tue 13/11/18
OME Trial 1	Vibration Transport and Restrained Cargo Shock	35 days	Wed 14/11/18	Wed 09/01/19
OME Trial 1	Inspection	2 days	Thu 10/01/19	Fri 11/01/19
OME Trial 1	1.5m Logistic Drop	18 days	Thu 10/01/19	Mon 04/02/19
OME Trial 1	Inspection	2 days	Tue 05/02/19	Wed 06/02/19
OME Trial 1	Air Vibration (Fixed wing C17/C130J)	42 days	Mon 28/01/19	Tue 26/03/19
OME Trial 1	Inspection	2 days	Wed 27/03/19	Thu 28/03/19
OME Trial 1	Air Vibration (Fixed wing A400M)	88 days	Wed 06/02/19	Thu 13/06/19
OME Trial 1	Hot Wet Diurnal Cycling (56days B3 & 14days B2)	60 days	Fri 14/06/19	Sat 07/09/19
OME Trial 1	Post Test Inspection	1 day	Mon 09/09/19	Mon 09/09/19
OME Trial 1	C2 Diurnal Cycling (14 Cycles)	16 days	Tue 10/09/19	Tue 01/10/19
OME Trial 1	Post Test Inspection	1 day	Wed 02/10/19	Wed 02/10/19
OME Trial 1	Air Transport Rotary Wing Vibration	58 days	Thu 03/10/19	Mon 23/12/19
OME Trial 1	Post Test Inspection	2 days	Thu 02/01/20	Fri 03/01/20
OME Trial 1	Restrained Cargo Vibration & Shocks (Off road)	33 days	Mon 06/01/20	Wed 19/02/20
OME Trial 1	Post Test Inspection	2 days	Mon 24/02/20	Tue 25/02/20
OME Trial 1	0.75m Tactical Drop	11 days	Wed 26/02/20	Wed 11/03/20
OME Trial 1	Inspection	2 days	Thu 12/03/20	Fri 13/03/20
OME Trial 1	Salt Water Immersion Test	7 days	Mon 16/03/20	Tue 24/03/20
OME Trial 1	Post Test Inspection	1 day	Wed 25/03/20	Wed 25/03/20
OME Trial 1	Dispatch of test items	0 days	Wed 25/03/20	Wed 25/03/20
OME Trial 1	Post Trial Documentation	21 days	Thu 26/03/20	Mon 27/04/20

Figure 22 Overall Trial Schedule

Trial No	Task Name	Duration	Start	Finish
OME Trial 1	**Documentation**	**30 days**	**Mon 03/09/18**	**Mon 15/10/18**
OME Trial 1	Milestone - Trials Plan Document Delivery	0 days	Mon 03/09/18	Mon 03/09/18
OME Trial 1	Inspection Procedures	3 days	Tue 04/09/18	Thu 06/09/18
OME Trial 1	Movement plan	5 days	Tue 04/09/18	Mon 10/09/18
OME Trial 1	Certs of Tech Competency fo VSO	1 day	Tue 04/09/18	Tue 04/09/18
OME Trial 1	Full Trial Risk Assessment	10 days	Tue 11/09/18	Mon 24/09/18
OME Trial 1	Safety Brief	3 days	Tue 25/09/18	Thu 27/09/18
OME Trial 1	Peer review presentation	3 days	Fri 28/09/18	Tue 02/10/18
OME Trial 1	Range Safety Cert Full Trial	4 days	Wed 03/10/18	Mon 08/10/18
OME Trial 1	Trial Instruction Full Trial	5 days	Tue 09/10/18	Mon 15/10/18

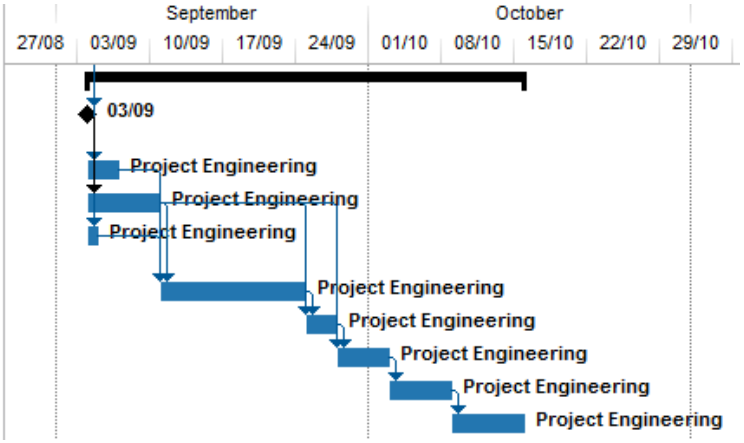


Figure 23 Schedule Documentation Section

Trial No	Task Name	Duration	Start	Finish
	Schedule	416 days	Tue 28/08/18	Mon 27/04/20
	Active Trials	416 days	Tue 28/08/18	Mon 27/04/20
OME Trial 1	OME Trial 1	416 days	Tue 28/08/18	Mon 27/04/20
OME Trial 1	Contract Award	0 days	Tue 28/08/18	Tue 28/08/18
OME Trial 1	Schedule agreement	5 days	Tue 28/08/18	Mon 03/09/18
OME Trial 1	Sequential Testing	390 days	Mon 03/09/18	Wed 25/03/20
OME Trial 1	Documentation	30 days	Mon 03/09/18	Mon 15/10/18
OME Trial 1	Initial Inspection	17 days	Tue 18/09/18	Wed 10/10/18
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OME Trial 1	Trial readiness Review	0 days	Tue 13/11/18	Tue 13/11/18
OME Trial 1	Vibration Transport and Restrained Cargo Shock	35 days	Wed 14/11/18	Wed 09/01/19
OME Trial 1	Inspection	2 days	Thu 10/01/19	Fri 11/01/19
OME Trial 1	1.5m Logistic Drop	18 days	Thu 10/01/19	Mon 04/02/19
OME Trial 1	Inspection	2 days	Tue 05/02/19	Wed 06/02/19
OME Trial 1	Air Vibration (Fixed wing C17/C130J)	42 days	Mon 28/01/19	Tue 26/03/19
OME Trial 1	Inspection	2 days	Wed 27/03/19	Thu 28/03/19
OME Trial 1	Air Vibration (Fixed wing A400M)	88 days	Wed 06/02/19	Thu 13/06/19
OME Trial 1	Hot Wet Diurnal Cycling (56days B3 & 14days B2)	60 days	Fri 14/06/19	Sat 07/09/19
OME Trial 1	Post Test Inspection	1 day	Mon 09/09/19	Mon 09/09/19
OME Trial 1	C2 Diurnal Cycling (14 Cycles)	16 days	Tue 10/09/19	Tue 01/10/19
OME Trial 1	Post Test Inspection	1 day	Wed 02/10/19	Wed 02/10/19
OME Trial 1	Air Transport Rotary Wing Vibration	58 days	Thu 03/10/19	Mon 23/12/19
OME Trial 1	Post Test Inspection	2 days	Thu 02/01/20	Fri 03/01/20
OME Trial 1	Restrained Cargo Vibration & Shocks (Off road)	33 days	Mon 06/01/20	Wed 19/02/20
OME Trial 1	Post Test Inspection	2 days	Mon 24/02/20	Tue 25/02/20
OME Trial 1	0.75m Tactical Drop	11 days	Wed 26/02/20	Wed 11/03/20
OME Trial 1	Inspection	2 days	Thu 12/03/20	Fri 13/03/20
OME Trial 1	Salt Water Immersion Test	7 days	Mon 16/03/20	Tue 24/03/20
OME Trial 1	Post Test Inspection	1 day	Wed 25/03/20	Wed 25/03/20
OME Trial 1	Dispatch of test items	0 days	Wed 25/03/20	Wed 25/03/20
OME Trial 1	Post Trial Documentation	21 days	Thu 26/03/20	Mon 27/04/20

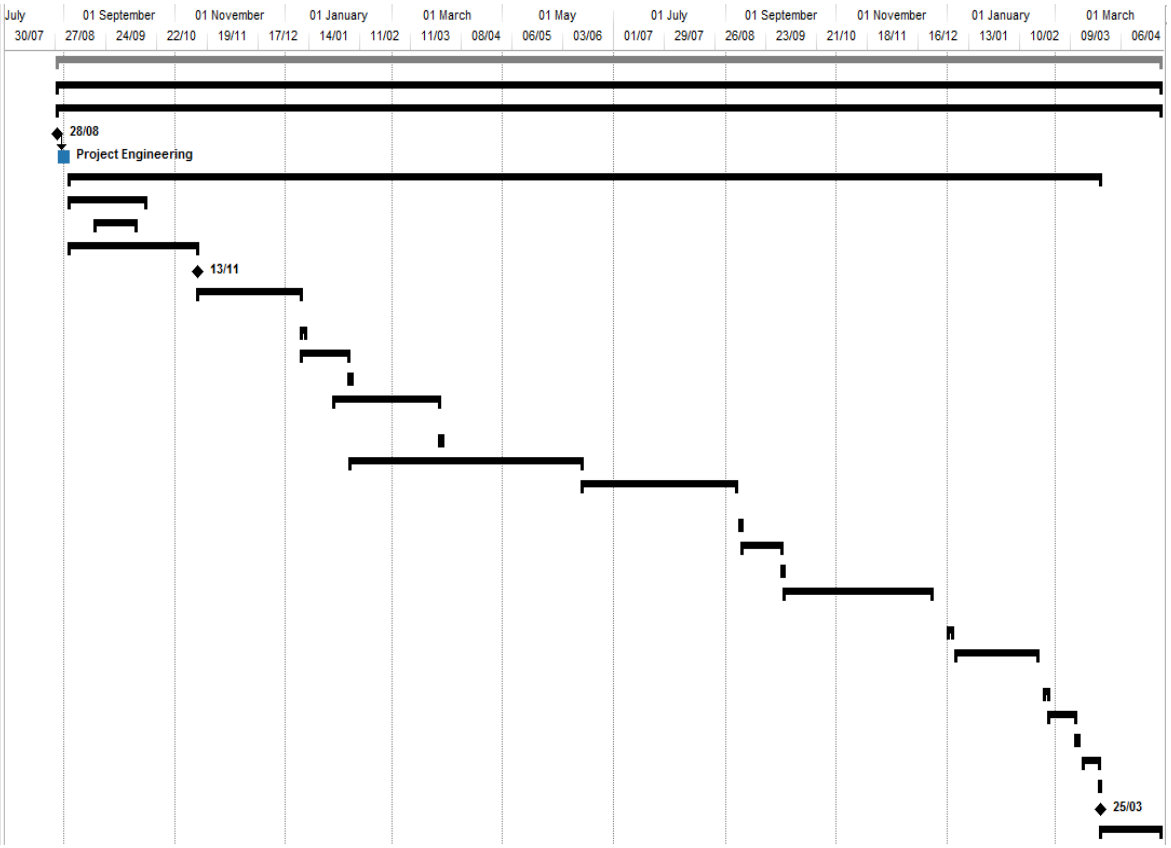


Figure 24 Overall Schedule with Gantt Chart

Trial No	Task Name	Duration	Start	Finish
OME Trial 1	**Air Vibration (Fixed wing C17/C130J)**	**42 days**	**Mon 28/01/19**	**Tue 26/03/19**
OME Trial 1	Planning	1 day	Wed 06/02/19	Wed 06/02/19
OME Trial 1	Precursor Axis 1 & 2	7 days	Mon 28/01/19	Tue 05/02/19
OME Trial 1	conditioning +71°C	72 hrs	Fri 08/02/19	Mon 11/02/19
OME Trial 1	Vibration and Shocks Axis 1 & 2	6 days	Mon 11/02/19	Mon 18/02/19
OME Trial 1	conditioning -46°C	72 hrs	Mon 18/02/19	Thu 21/02/19
OME Trial 1	Vibration and Shocks Axis 1 & 2	6 days	Tue 19/02/19	Tue 26/02/19
OME Trial 1	Axis Change	2 days	Wed 27/02/19	Thu 28/02/19
OME Trial 1	Precursor Axis 3	4 days	Fri 01/03/19	Wed 06/03/19
OME Trial 1	Conditioning +71°C	72 hrs	Wed 06/03/19	Sat 09/03/19
OME Trial 1	Vibration and Shocks Axis 3	4 days	Mon 11/03/19	Thu 14/03/19
OME Trial 1	Conditioning -46°C	72 hrs	Fri 15/03/19	Mon 18/03/19
OME Trial 1	Vibration and Shocks Axis 3	4 days	Mon 18/03/19	Thu 21/03/19
OME Trial 1	Contingency	3 days	Fri 22/03/19	Tue 26/03/19
OME Trial 1	**Inspection**	**2 days**	**Wed 27/03/19**	**Thu 28/03/19**
OME Trial 1	Visual Inspection	2 days	Wed 27/03/19	Thu 28/03/19
OME Trial 1	**Air Vibration (Fixed wing A400M)**	**88 days**	**Wed 06/02/19**	**Thu 13/06/19**
OME Trial 1	Planning	1 day	Fri 29/03/19	Fri 29/03/19
OME Trial 1	Precursor Axis 1 & 2	3 days	Wed 06/02/19	Fri 08/02/19
OME Trial 1	conditioning +71°C	72 hrs	Wed 27/03/19	Sat 30/03/19
OME Trial 1	Vibration and Shocks Axis 1	6 days	Thu 28/03/19	Thu 04/04/19
OME Trial 1	conditioning -46°C	72 hrs	Fri 05/04/19	Mon 08/04/19
OME Trial 1	Vibration and Shocks Axis 1	6 days	Mon 08/04/19	Mon 15/04/19
OME Trial 1	Axis Change	2 days	Tue 16/04/19	Wed 17/04/19
OME Trial 1	conditioning +71°C	72 hrs	Thu 18/04/19	Sun 21/04/19
OME Trial 1	Vibration and Shocks Axis 2	6 days	Tue 23/04/19	Tue 30/04/19
OME Trial 1	conditioning -46°C	72 hrs	Wed 01/05/19	Sat 04/05/19
OME Trial 1	Vibration and Shocks Axis 2	6 days	Thu 02/05/19	Fri 10/05/19
OME Trial 1	Axis Change	2 days	Mon 13/05/19	Tue 14/05/19
OME Trial 1	Precursor Axis 3	2 days	Wed 15/05/19	Thu 16/05/19
OME Trial 1	Conditioning +71°C	72 hrs	Fri 17/05/19	Mon 20/05/19
OME Trial 1	Vibration and Shocks Axis 3	6 days	Mon 20/05/19	Tue 28/05/19
OME Trial 1	Conditioning -46°C	72 hrs	Wed 29/05/19	Sat 01/06/19
OME Trial 1	Vibration and Shocks Axis 3	6 days	Thu 30/05/19	Thu 06/06/19
OME Trial 1	Contingency	3 days	Fri 07/06/19	Tue 11/06/19

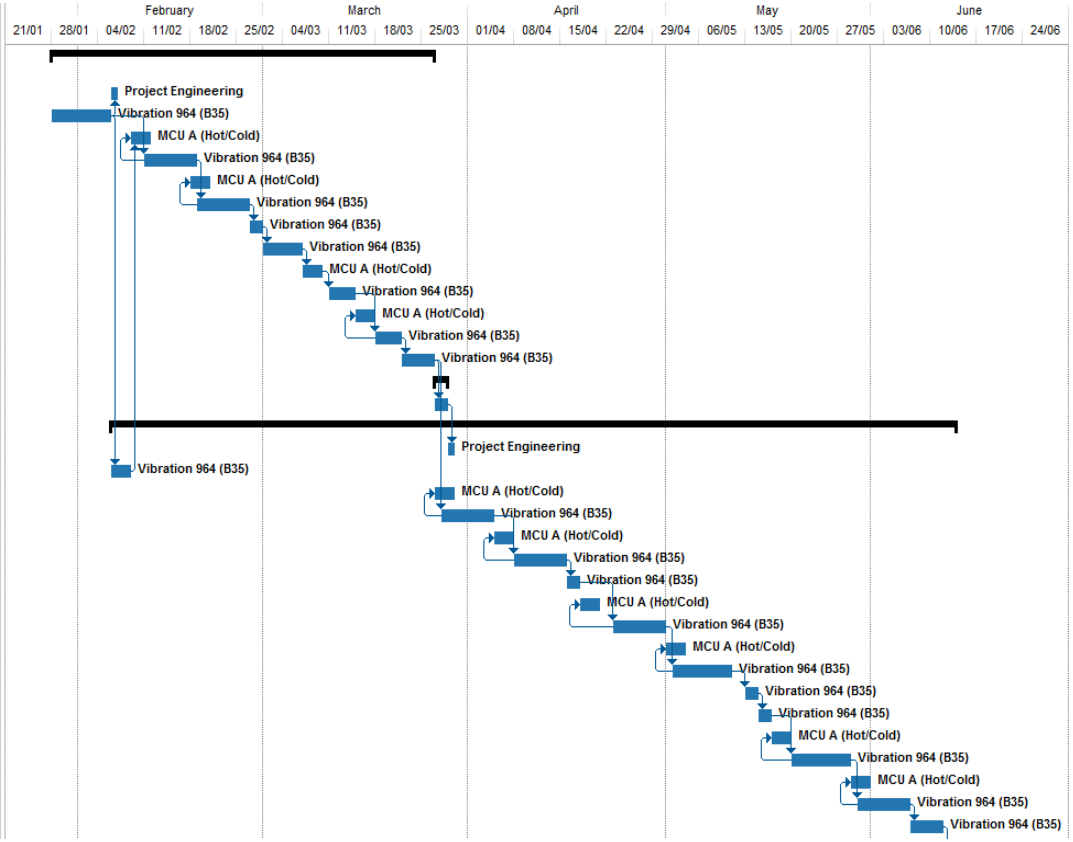


Figure 25 Schedule Vibration Section

4.4.3 Cost Plan

The overall cost of the environmental trial will depend upon many variables. A long and complex trial will utilise more staff, expertise, facilities and materials than a short and simple trial and so will be costed appropriately to express this.

Planning Staff	Projected Days	Rate (Day)	Total
Project Manager	30	£525	£15,750
Trials Manager	30	£450	£13,500
Project Engineer	40	£300	£12,000
Scheduler	5	£375	£1875
		Total	**£43,125**

Trials Staff		Projected Days	Rate (Day)	Total
Vibration	Engineer	256	£300	£76,800
	Technician	256	£250	£64,000
Climatic	Engineer	15	£300	£4500
	Technician	15	£250	£3750
Shock/Impact	Engineer	29	£300	£8700
	Technician	29	£250	£7250
Radiography	Engineer	3	£300	£900
	Technician	3	£250	£750
Ammunition	Inspector	6	£300	£1800
	Technician	10	£250	£2500
			Total	**£170,950**

Support Staff		Projected Days	Rate (Day)	Total
Host Site	Ordnance Safety Manager	1	£375	£375
Any Site	OME SME	3	£375	£1125
Host Site	Technical Specialist 1	1	£675	£675
	Technical Specialist 2	1	£525	£525
	Trials Safety Manager	0.25	£475	£118.75
	Site Safety Manager	0.25	£525	£131.25
	Head of Facility	0.25	£675	£168.75
	Head of Site	0.25	£750	£187.5
Design Team	Draftsman	5	£300	£1500
Workshops	Engineer	8	£300	£2400
	Technician	10	£250	£2500
			Total	**£9706.25**

Facility	Projected Days	Rate (Day)	Total
Explosive Store House	100	£10	£1000
Inspection Facility	2.5	£300	£750
Vibration Test Cell	256	£1250	£320,000
Climatic Chamber Hot	76	£1200	£91,200
Saltwater Immersion Facility	7	£1000	£7000
Radiography Facility	3	£2500	£7500
Impact (Drop) Test Cell	29	£1000	£29,000
		Total	**£456,450**

Projected Trial Overall Cost	**£680,231.25**

*Note:

1. Materials have not been added to the cost plan.

2. The rates shown above are a generalisation of cost for each speciality and facility. These rates will rise and fall depending on the foreseen and current business climate.

Payment of the trial is settled in separate intervals known as milestones. The milestones are agreed with the customer (usually linked to the trial schedule) and an agreed amount paid at each one. An initial, or first instalment is needed for materials and to get the trials started. By the last payment the full amount owed has been paid.

4.4.4 Security

Due to the nature of the testing and the customers involved, discretion and confidentiality is advisable.

The utilisation of the UK Government classification guidelines and how to classify information is necessary to prevent unauthorised access and exploitation. The Government Security Classifications document details how information is classified [51] “HM Government classifies information assets to: ensure they are appropriately protected; support Public Sector Business and the effective exploitation of information; and meet the requirements of relevant legislation and international / bilateral agreements and obligations. It applies to all information that government collects, stores, processes, generates, or shares to deliver services and conduct business, including information received from or exchanged with external partners.”

An overview of the security classifications shown below:

[52]

Figure 26 Security Classifications Information

5 Design and Analysis of a Vibration Rig

5.1 Purpose

This section is an experiment with two identical test rig designs that each utilise one of two favourable materials used for vibration. Modal Testing has been carried out on the test rigs and the results interpreted with views given. It demonstrates the author's particular skills at a detailed level in practical rig design.

[53] "Modal Testing: An experimentally based method for determining the dynamic characteristics of a structure."

5.2 Why design a rig?

In order to get the best and most realistic testing for the OME test asset the rigs used in vibration testing have to be fit for purpose. They are often made bespoke to the needs of the customer and are a mock interface with the test asset such as a hard point on the undercarriage of a plane, or a mounting point on a vehicle. The force imparted from the vibrator is passed through the rig and onto the test asset. It is vital that the rig does not lose this force, or it will affect the testing. [54] "An ideal fixture, then, would have infinite stiffness at all frequencies and zero mass, and it is this paradox which is the bias of fixture design" This is where rig design matters and a multitude of factors need to be met.

Each rig structure will have its own natural characteristics, with a bending deformation on each mode. Figure 27 shows typical bending deformations on modes 1-4 on sheet material, when subjected to sine dwell vibration.

[55]

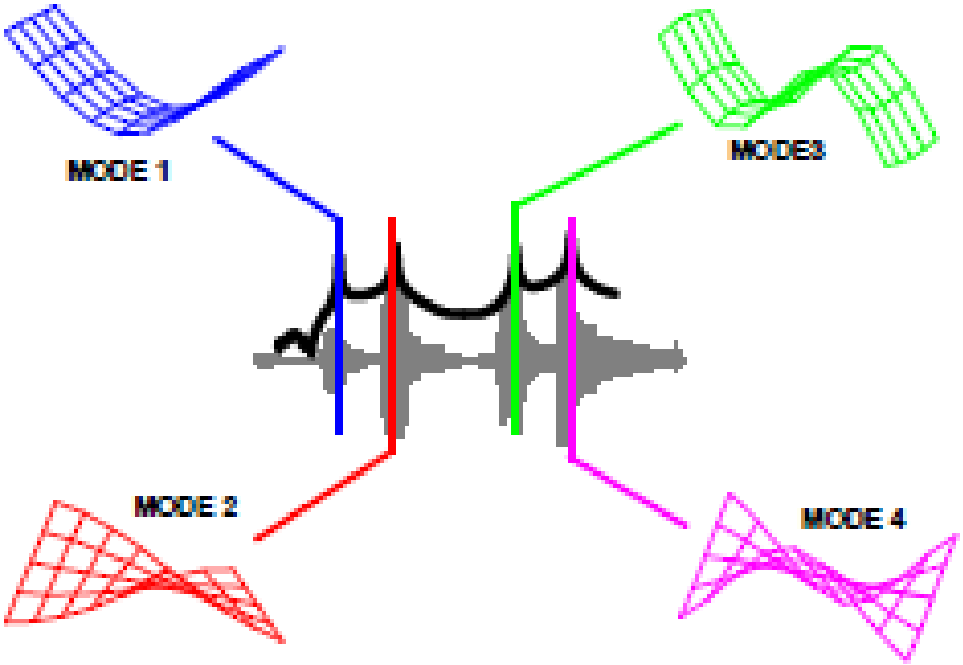


Figure 27 Bending Deformations at each Mode

The ideal vibration testing rig would meet the following points:

Lightweight	The lighter the rig the heavier the mass that can be tested. Lighter setups also require less input drive from the vibrator.
Strong	The rig will have to be strong enough to withstand a host of shock and vibration, the loading stresses and torsional effects.
Resonance different to the test asset	The resonant frequency should be as high as possible and ideally outside the test frequency range. This point is hard to meet as all rigs will resonate at different frequencies, especially more complex rigs with expansive structures.
Good damping	A rig structure with bad damping will resonate fairly easily and “ring like a bell”. Suitable materials and a strong design will prevent this.
Similar, or realistic mounting	The mounting transmits the vibration to the test item in the same manner it would see in its life.

There is always a compromise that will need to be made between the points listed above. Other factors that affect the rig design, especially on a trial are; time, cost and resources available.

Another point to note is that the fabrication choices of the rig, will affect the way it responds to testing. Common methods can be to cast the entire rig, or separate sections of the rig, but this can be costly and very specialised. More intricate rigs are machined, as one component, or multiple components. The various components of the rig are then assembled together and secured by a variety of methods, but mainly bolted, welded, or glued. Importantly though, how the rig is fabricated is all down to the specification and ultimately the design.

Design and analysis do not come cheap, neither do the favourite core materials of magnesium, aluminium, or steel. Specialist machining comes into play, as intricate and special designs are often difficult to fabricate. A carefully designed rig, analysed, modelled and fabricated to get the most out of the material and the best results from the test item takes, time money and resources.

5.3 Rig Design

The rig is designed to get the best possible results out of the test items. It often does not meet all the requirements listed in the ideal rig section and is a compromise between the listed requirements, costs and time available.

The author utilised design and simulation software to carry out the following design and modal analysis. The software was made available through the University of Wales Trinity Saint David.

The rigs are made out of 50mm thick machined Aluminium Alloy, or Magnesium, which are 620mm long, 504mm wide and 350mm tall. Each section is bolted together. The bolts thread into Keenserts which have a larger surface area and give added strength, which a steal bolt would not get threading straight into aluminium, or magnesium. The test assets interface with the rig in the same manner in which they would interface when mounted in a real life environment.

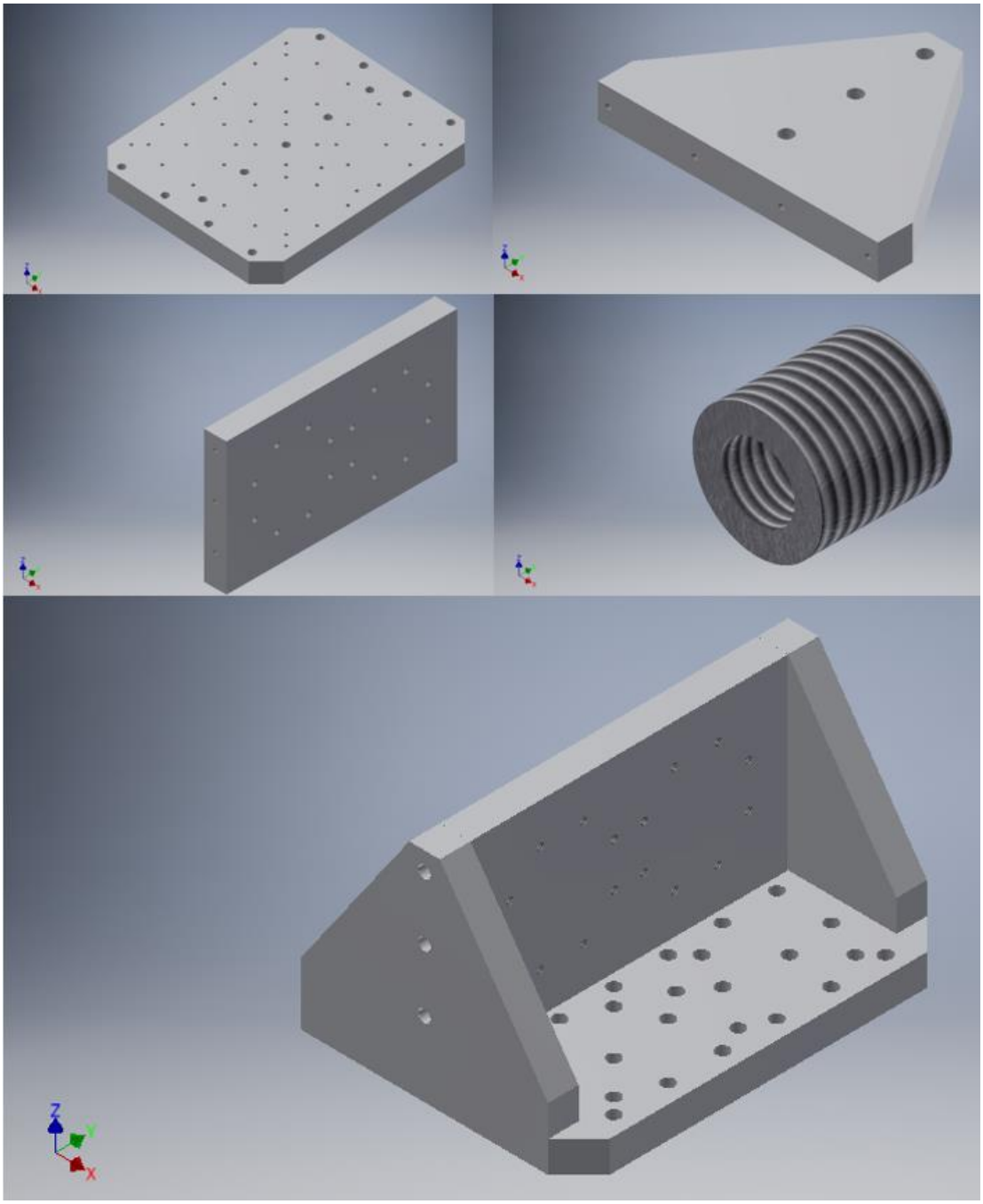


Figure 28 Rig Design and Various Components

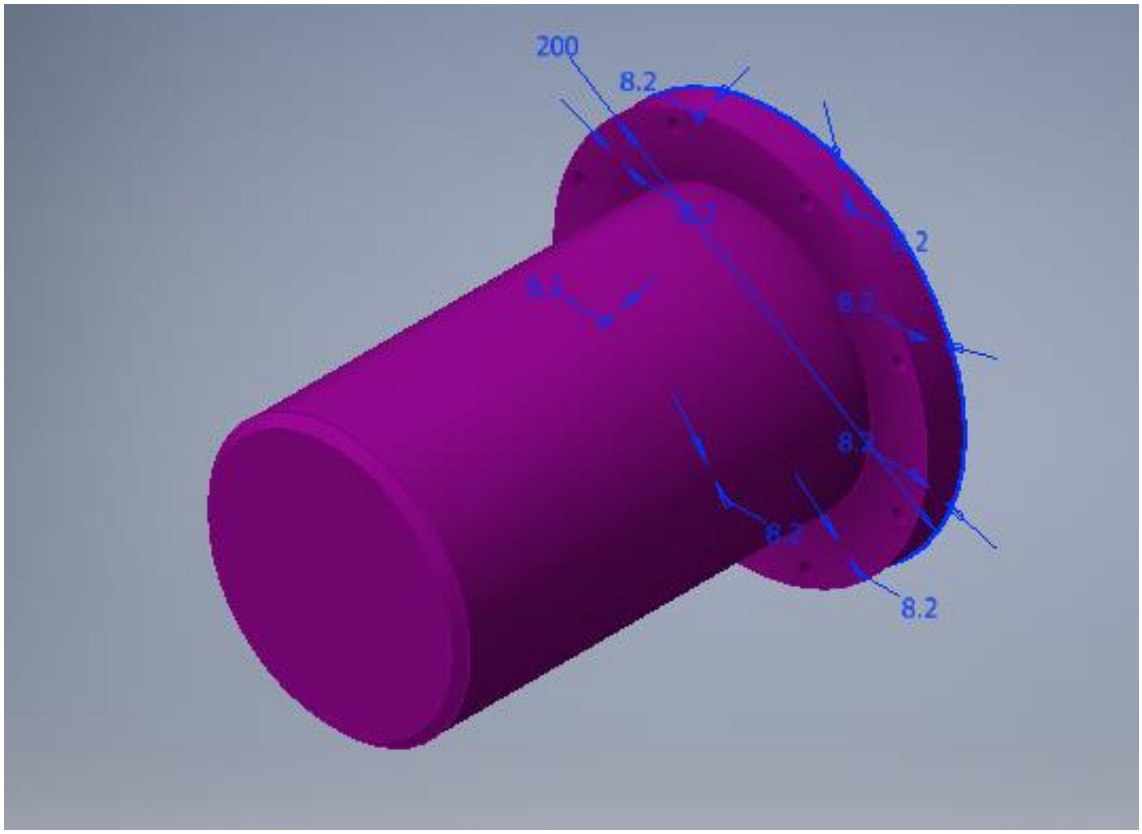


Figure 29 Test Asset

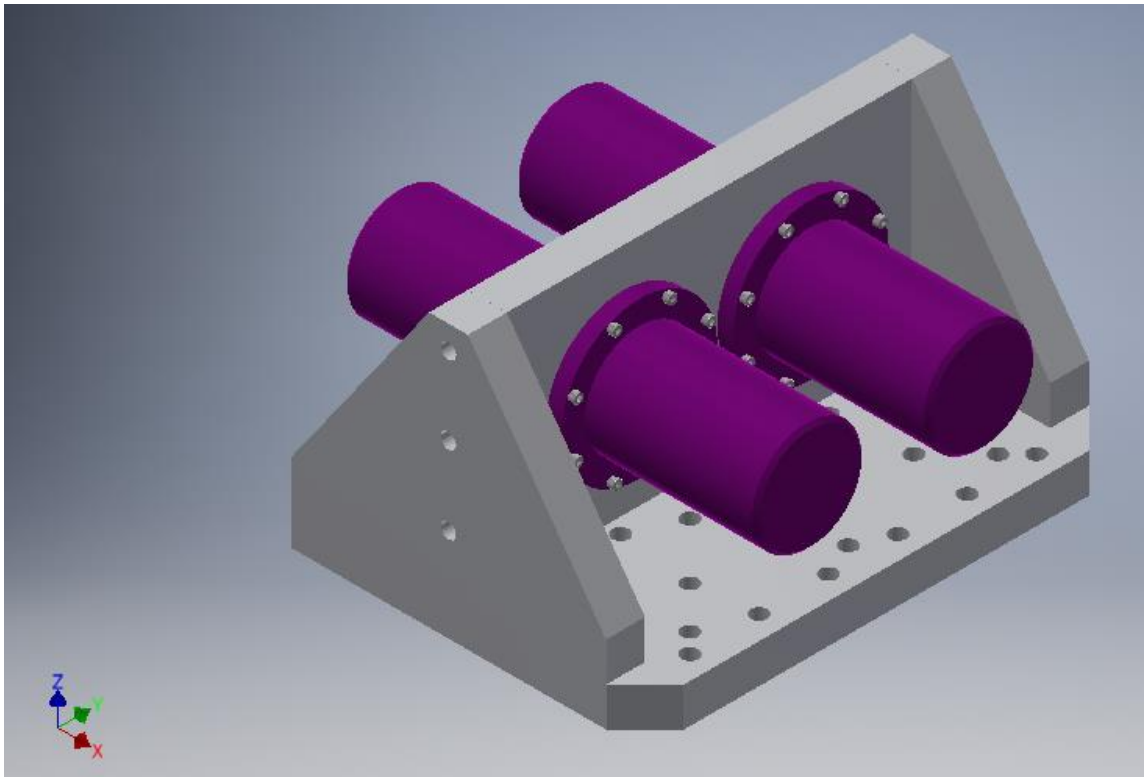


Figure 30 Aluminium Rig

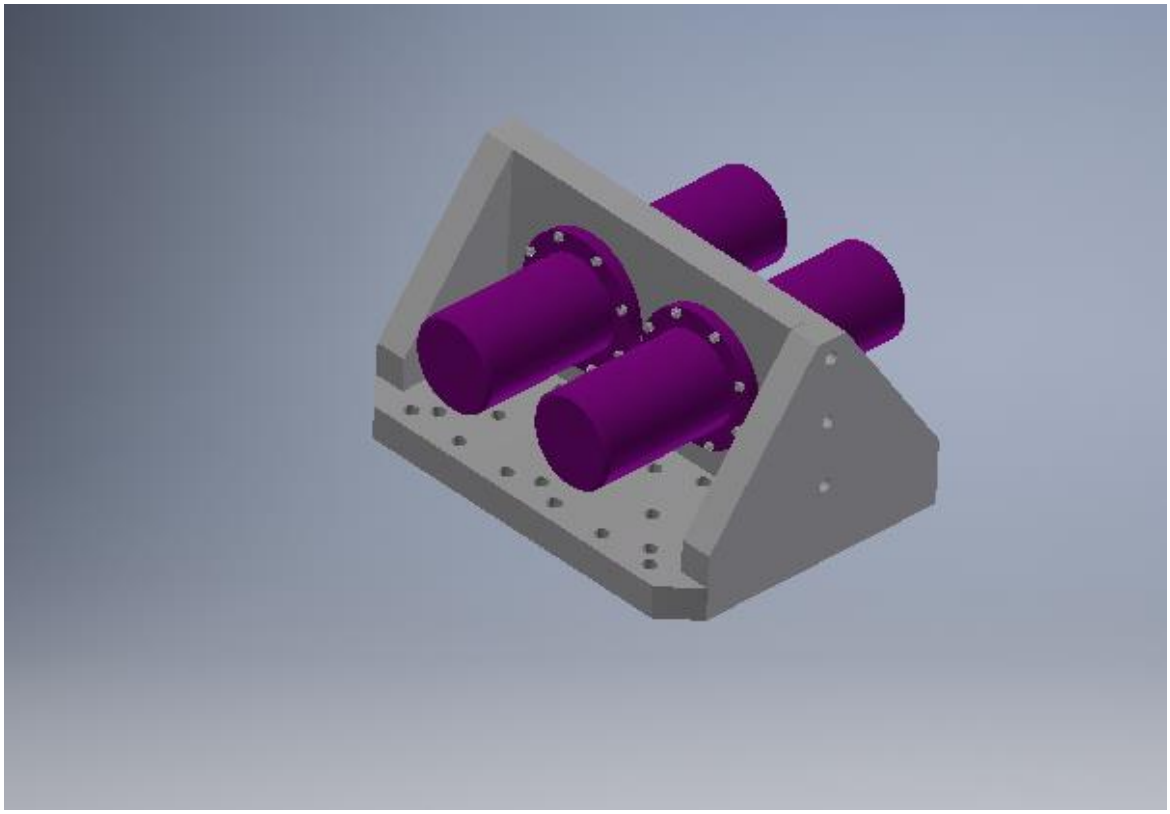


Figure 31 Magnesium Rig

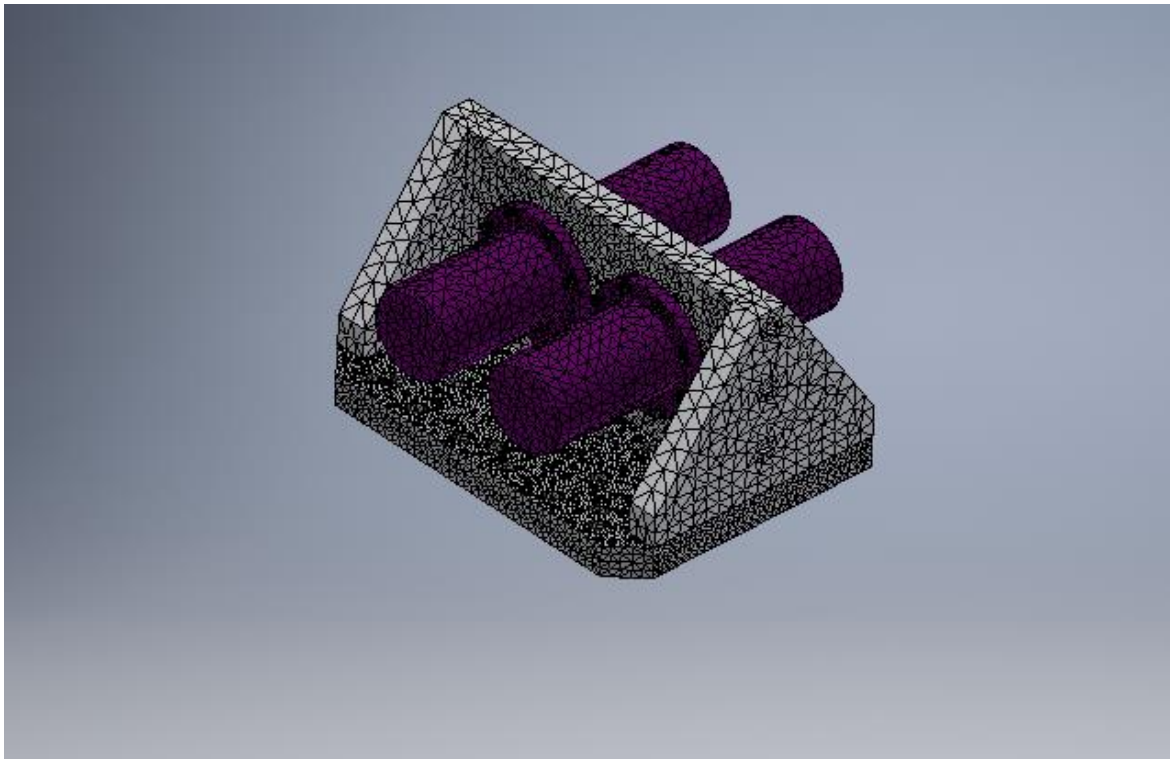


Figure 32 A MESH on both the Rig and Test Asset

5.4 Material Properties

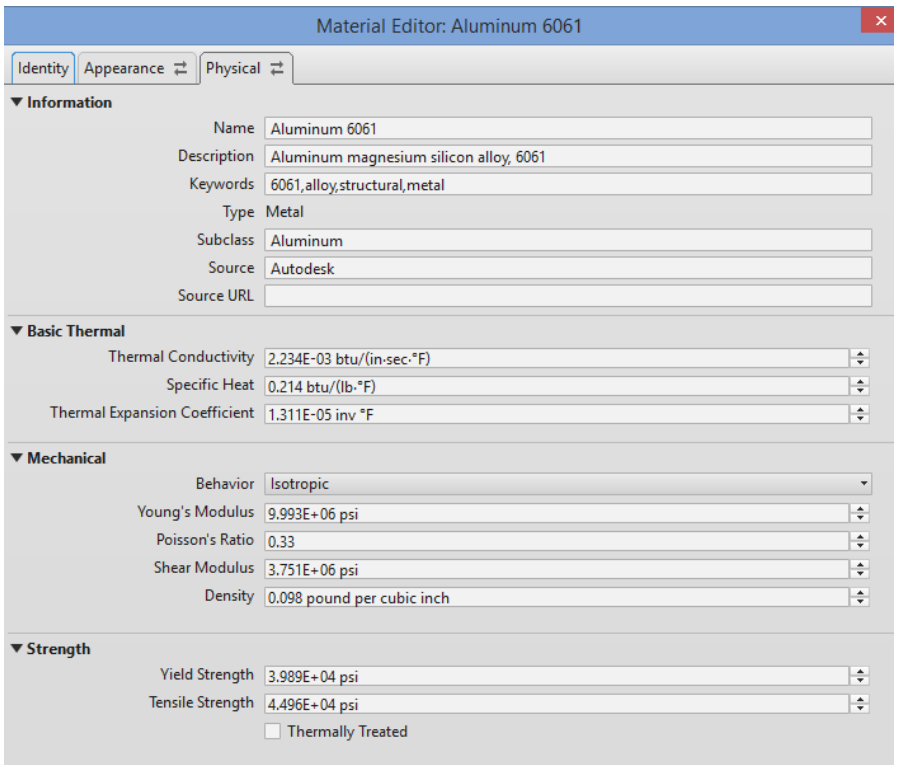


Figure 33 Material Properties Aluminium

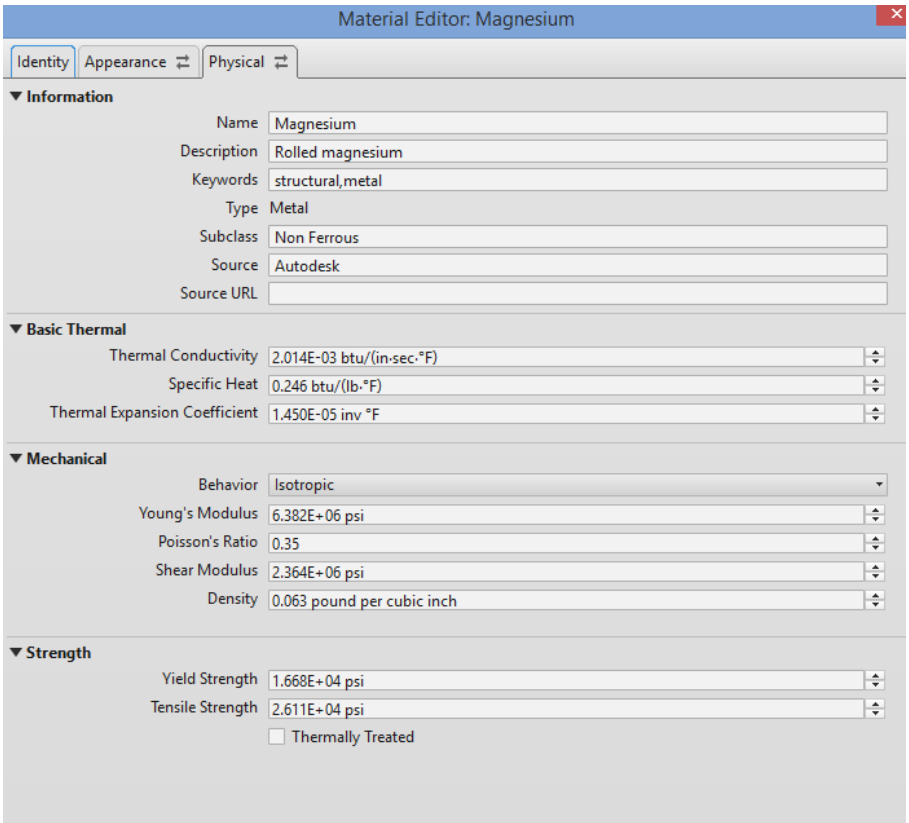


Figure 34 Material Properties Magnesium

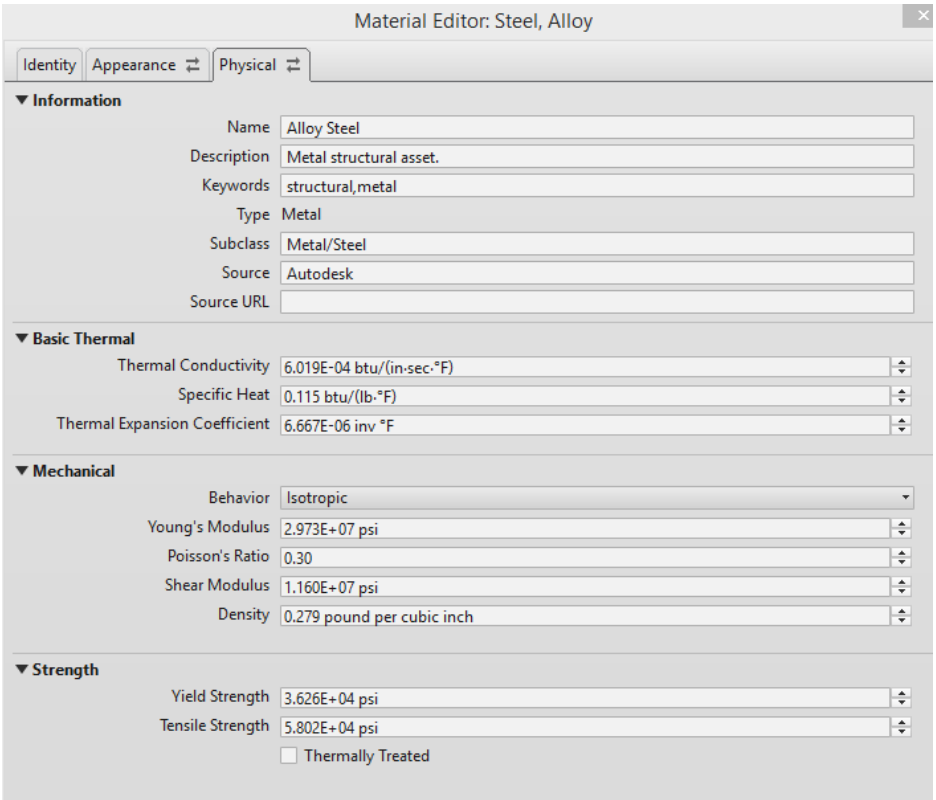


Figure 35 Material Properties Steel Alloy

5.5 Simulation Results

The bandwidth of 10-2000Hz was divided into two simulations, due to the limitations of the equipment. These were:

- 8 modes 10-1000Hz
- 8 modes 1000-2000Hz

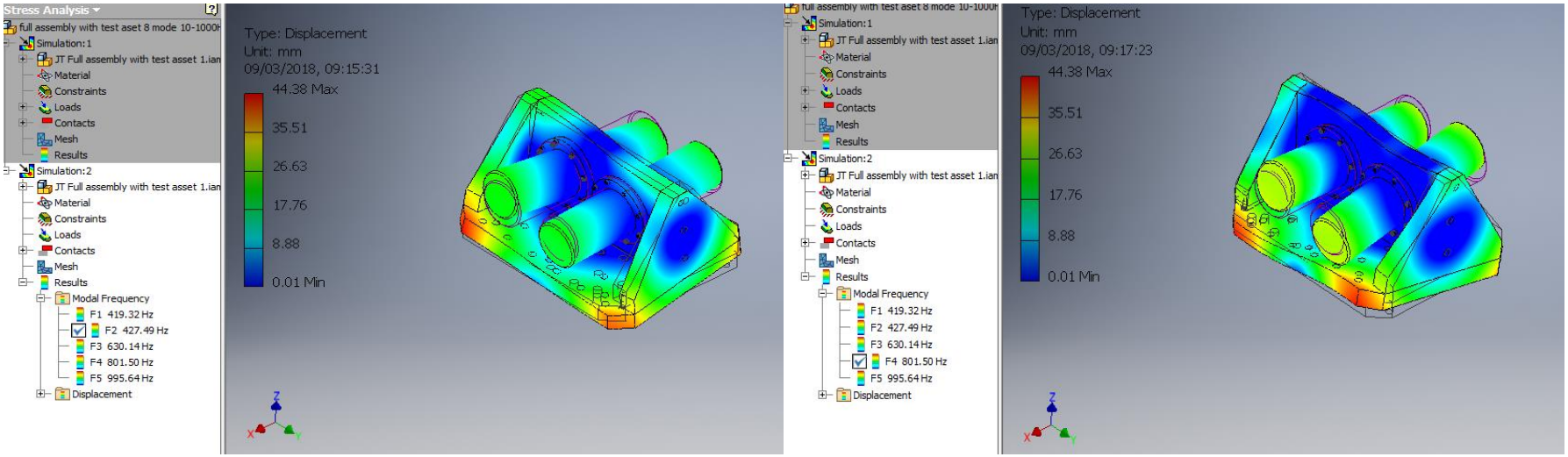


Figure 36 Aluminium Rig 5 modes 10-1000Hz

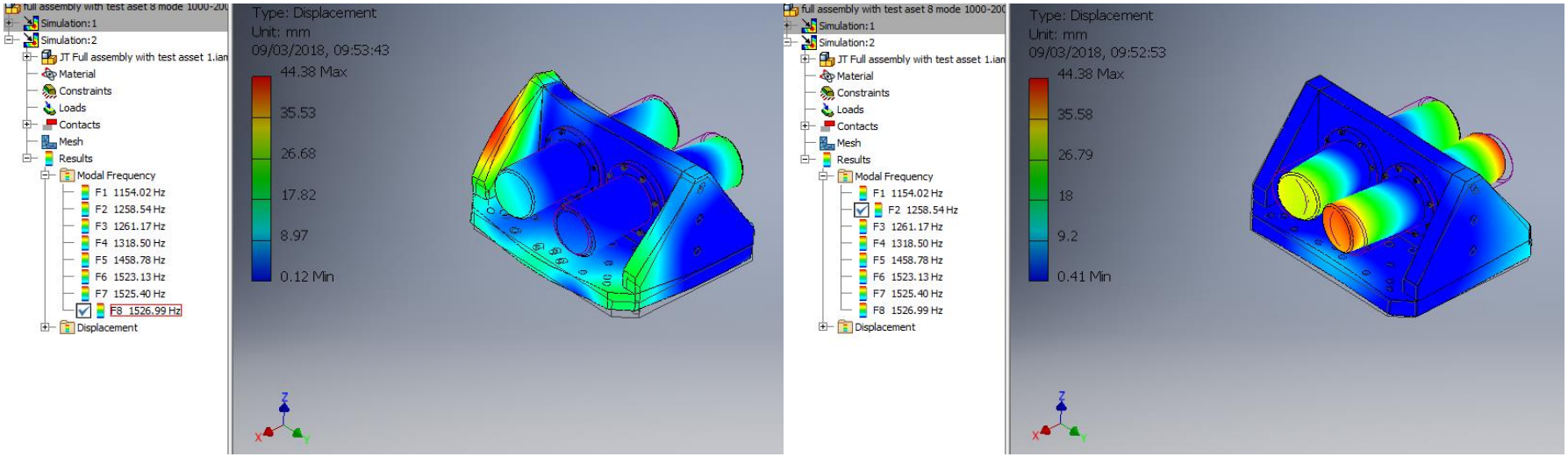


Figure 37 Aluminium Rig 8 Modes 1000-2000Hz

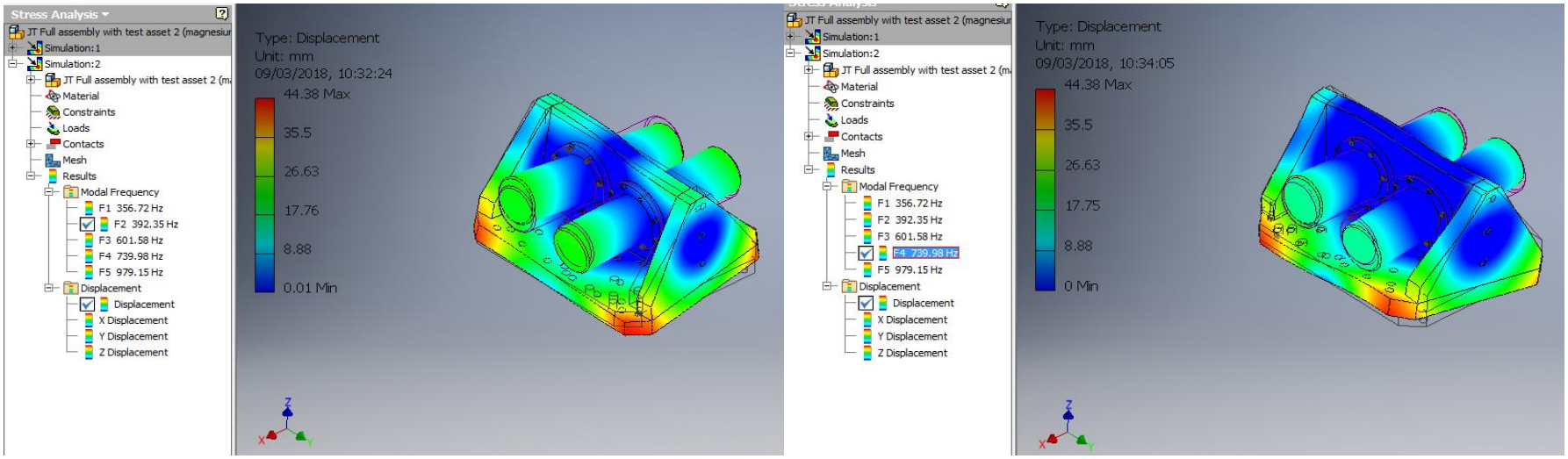


Figure 38 Magnesium Rig 5 Modes 10-1000Hz

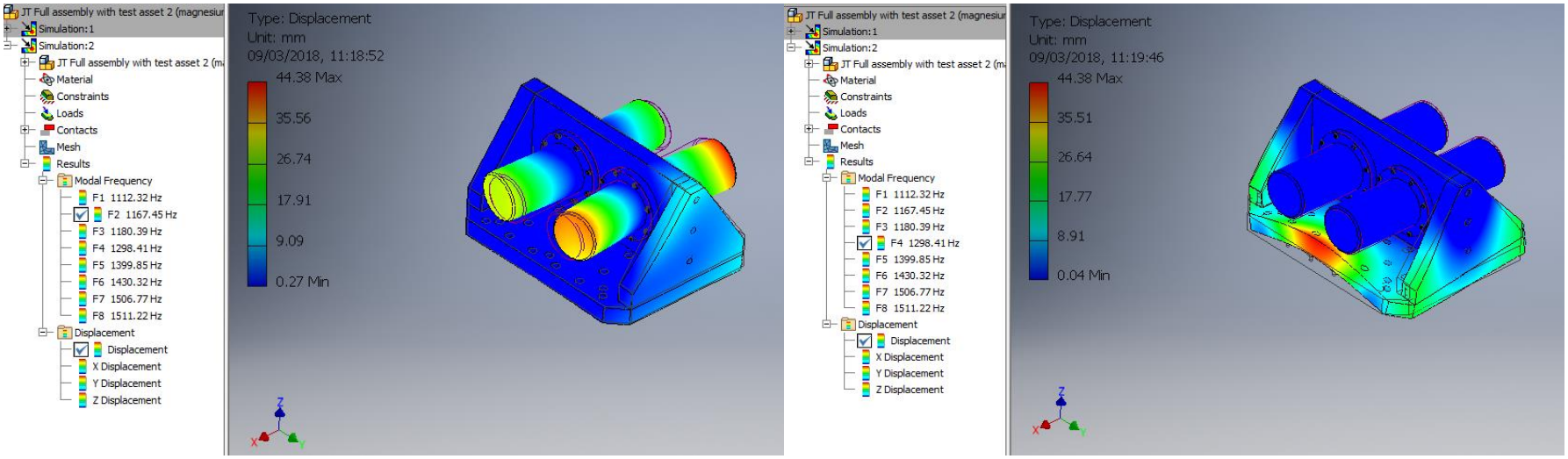


Figure 39 Magnesium Rig 8 Modes 1000-2000Hz

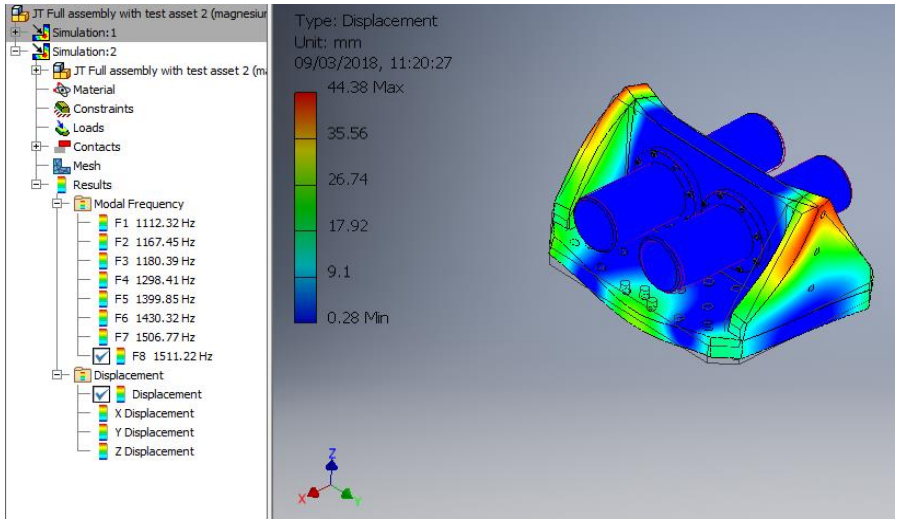


Figure 40 Magnesium Rig 8 Modes 1000-2000Hz

5.6 Analysis and Comparison

*Note: Throughout the simulation the Modal Frequencies listed differ for each material. For the simulation, 8 Modes were selected for 10-1000Hz and 8 Modes for 1000-2000Hz. The simulation calculated that there were only 5 Modes for both materials between 10-1000Hz and the set amount of 8 were found between 1000-2000Hz. The frequency of each Mode in the two materials will be different, the author has used the closest frequencies between the two materials for comparison.

In the lower frequency band of 10-500Hz shown in Figure 41, both materials react to the excitement over the body of the rig in more, or less the same areas and have similar displacement. The rig with both materials is fairly rigid specifically in the area it interfaces with the test asset, but overall distorts in shape in the corners due to its natural resonant frequency. The displacement is slightly less in that of the aluminium rig.

In the frequencies of 700-850Hz shown in Figure 42, whilst both rigs are still showing good dynamic stiffness on the main interface with the test assets, the magnesium rig is marginally better. Both rigs display contortion in the 700-850Hz frequency band, the structure of the rig is distorting due to its natural frequency. The bending modes on both rigs are shown in the corners of the bottom face plates, which show reasonably large displacement if they were not controlled down. In a test where these frequencies are of upmost importance, the magnesium rig would be the material of choice.

Both of the images in Figure 43 depict the ideal outcome for a test rig. The rigs at roughly 1200Hz show minimal displacement throughout. The rigs will uniformly transmit the force from the vibrator to the test asset.

The three pictures that are displayed in Figure 44 and Figure 45 all show problems with the rigs in the higher frequency range which is rather harsh. The two magnesium rigs depicted show reasonably large displacements that identify the bending modes of the rig. The large diplacement (shown in red) on their bending modes are the result of the way the material reacts to the excitement (simulated in the modal testing), but has the potential to disrupt the testing of the assets attached to them, consequently, this creates delays and further costs to the testing.

In Figure 44 the aluminium rig displays an odd displayment on one of its suporting sides (furthest). The author checked the simulation, but is unsure that this is accurate, as both sides are identical in; material, measurement and mass. Also the rig is symmetrical including the test assets which are all the same and interface with the rig in the same way.

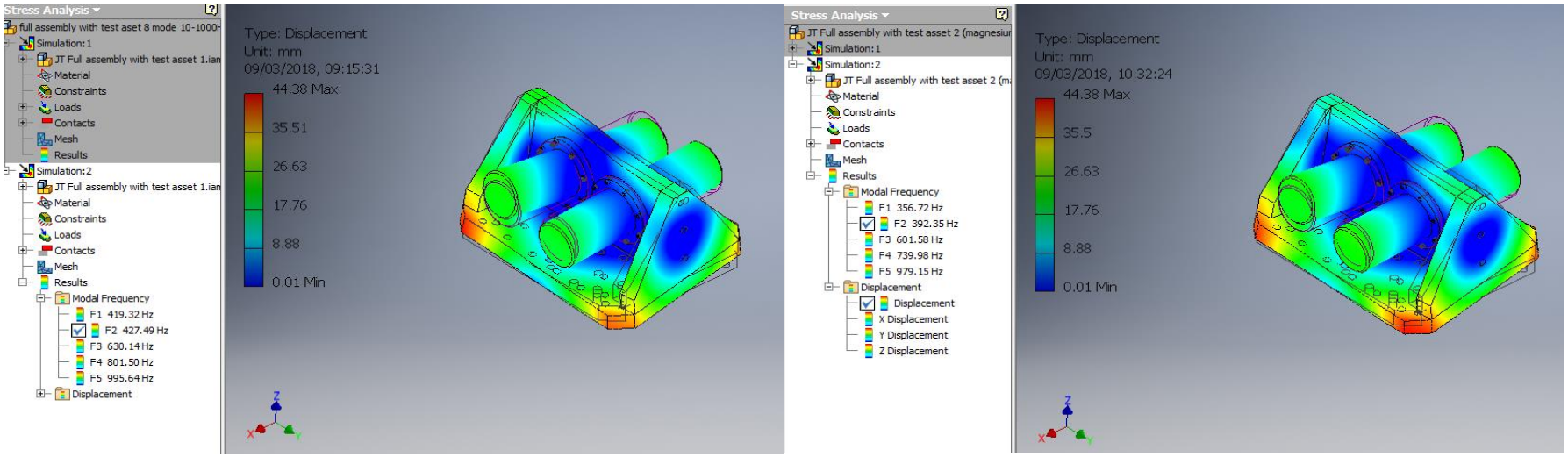


Figure 41 10-500Hz Aluminium (left) Magnesium (right)

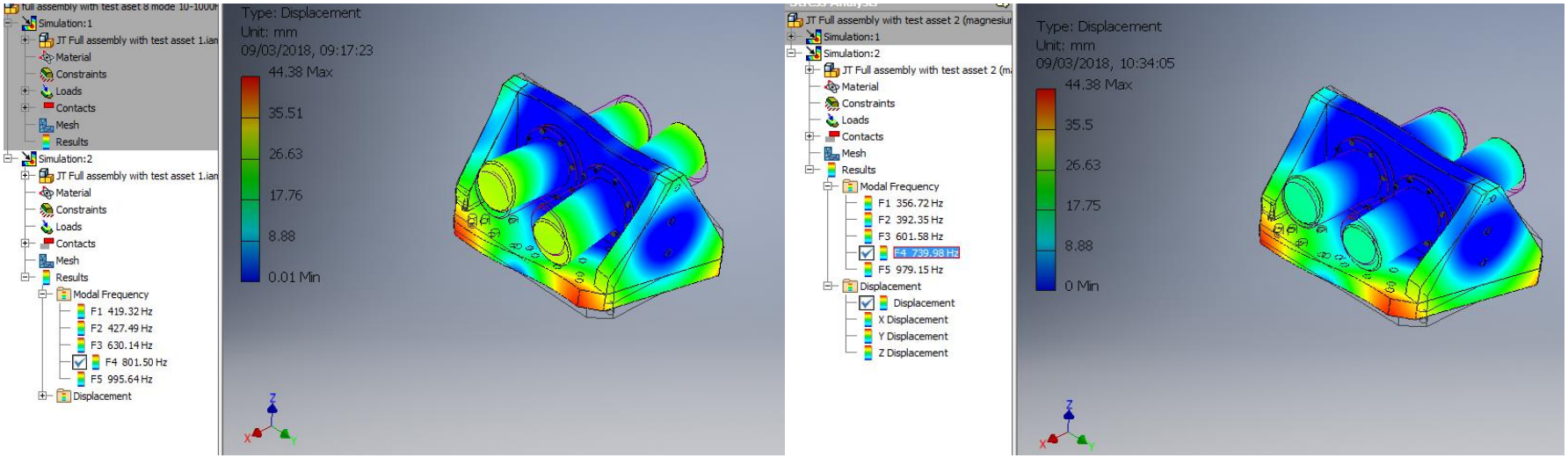


Figure 42 700-850Hz Aluminium (left) Magnesium (right)

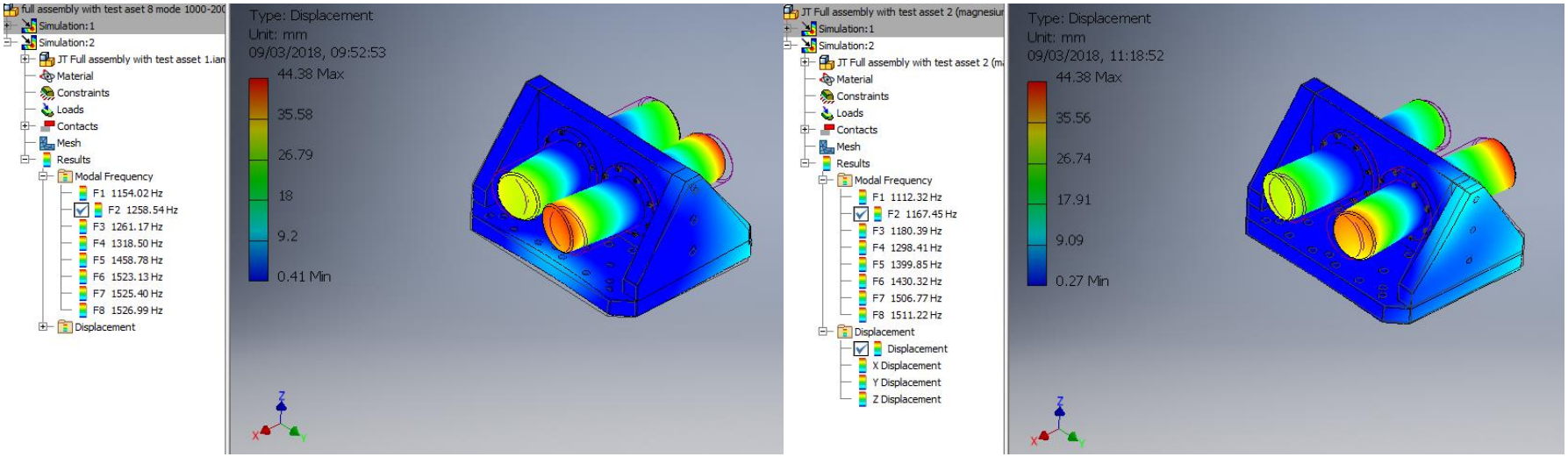


Figure 43 1100-1300Hz Aluminium (left) Magnesium (right)

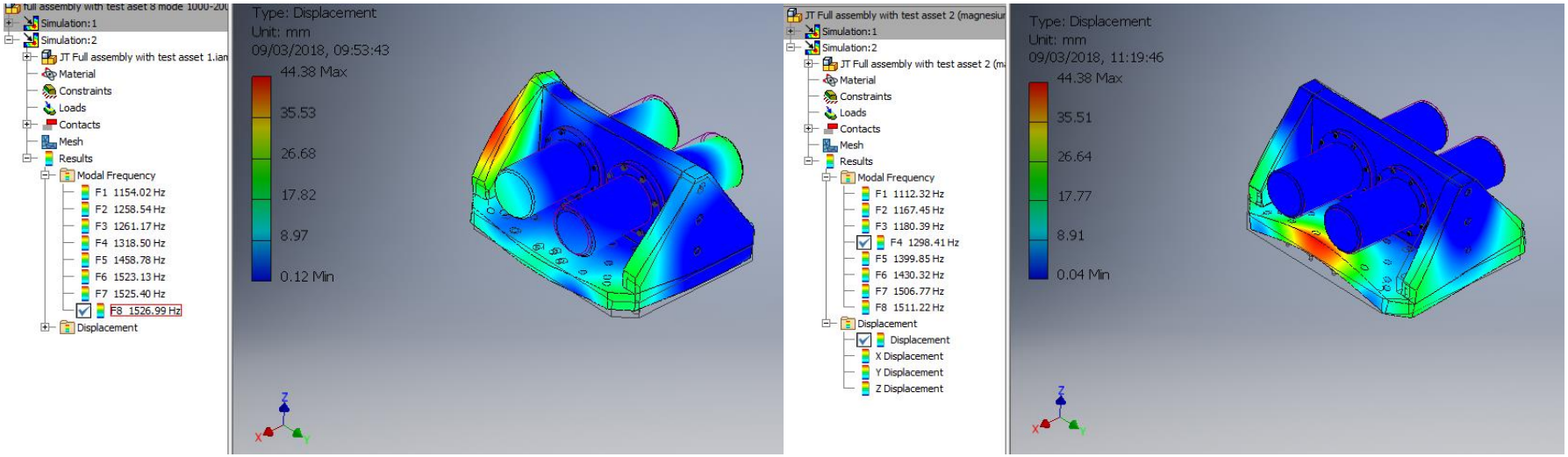


Figure 44 1300-2000Hz Aluminium (left) Magnesium (right)

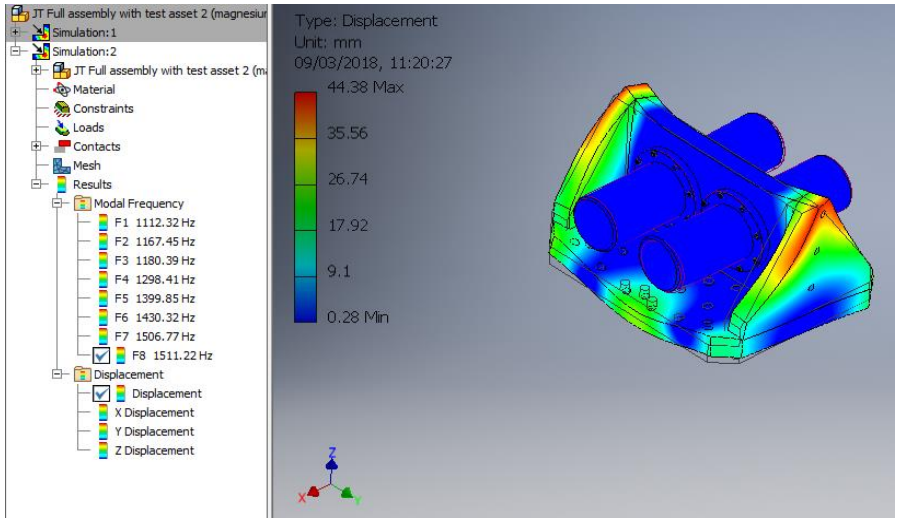


Figure 45 1511Hz Magnesium

Comparison Table		
Scale out of 10 (Worst 1 – 10 Best)		
	Aluminium	**Magnesium**
Weight	**7**	**8**
Strength	**8**	**6**
Resonance	**6**	**5**
Damping	**7**	**7**
Realistic mounting	**9**	**9**
Total	**37**	**35**

Table 6 Material Comparison Table

5.7 Summary of Results

Both the materials are popular in the industry, an example being that most vibrator armatures are manufactured from magnesium. Whilst the two materials chosen for the rig had many similarities the differences in Young Modulus and Density, as shown in the Material Properties (section 5.4), meant that the results although reasonably similar, were always going to be different. [56] "Each mode is defined by a natural (modal or resonant) frequency, modal damping, and a mode shape (i.e. the so-called "modal parameters"). If either the material properties or the boundary conditions of a structure change, its modes will change. For instance, if mass is added to a structure, it will vibrate differently."

The modal mass in this simulation was relatively small for both rigs and although the shape of the rig was of simple design, the modal shapes were comparatively hard to distinguish in regard to something as simple as a square plate (shown in Appendix E). That said, in the modes selected and depicted, the aluminium rig was the better of the two throughout the 10-2000Hz frequency band, whereas, the magnesium rig performed slightly better up to 1000Hz. The comparison table (Table 6) indicates that the aluminium rig was the better of the two.

In summary, the aluminium rig reacted less to the forces imparted on it than the magnesium rig, over the bandwidth of 10-2000Hz. This means that as an interface between a test asset and a vibrator armature there would be less interference from the rig whilst testing. Other additional benefits:

- Results from test assets are more realistic and true
- The overall control of the test asset is easier
- Problems with the test asset, rig or vibrator are easy to distinguish and are identifiable
- The test asset is receiving realistic mechanical vibration with minimal interference

Whilst the analysis concentrated on the behaviour of rigs of differing materials which were both bolted together, further experimentation and simulation could be conducted. Specifically observing the differences in results when using different interfacing and fixing methods on the rig such as: bolted, welded, or glued. Bolted rigs, in the author's experience, generally tend to have more movement between the joints.

6 Vibration Control Experimentation

6.1 Purpose

This section is an experiment with different control point locations and multiple styles of control from, single point control, to multipoint control. The end output is to gain an understanding of the process and to find the best method of controlling the test asset. The greater the control the more accurate the replication of the real life measured levels. It exhibits the author's tacit and explicit knowledge of vibration test engineering.

6.2 Background

Following on from section 3.1.2.4, the control aspect of vibration testing is vital. To be able to get the most representative test, the control needs to be as close to the test reference line as possible, as any deviation resulting in going above, or beyond the ±3dB abort would result in an over, or under test of the explosive test item. The customer would need to be contacted and approval to continue, or retest sought. Finding the best control setup can be time consuming and is dependent upon a variety of things:

Customer needs	Control is setup to account for the customer need. Do they require Input, or Output testing (as discussed in section 3.1.2.5)?
Test Specification	The Helicopter Rotary Wing spectrum has a large bandwidth from low to high frequency of 5-2000Hz whereas, the Off Road Vibration spectrum has a small bandwidth at the lower frequency level of 10-500Hz.
Makeup of the test assets	An in-depth look at the test asset is needed to ascertain the best position to locate the control accelerometer. Information on structural voids, differences in materials, changes in internal densities and the structural integrity helps support the location of a control position.
Complexity of the rig	The rig could use ratchet straps to tie down the test asset, but these will move around a lot compared to a yoke holding down a long cylindrical item. So positioning a control accelerometer so close to a moving ratchet strap would cause a lot of interference as well as possibly displacing the accelerometer.
Complexity of the setup	The amount of linkages provides loss, meaning that the drive (thrust) of the vibrator must compensate. An example of this using the vibrator in the horizontal setup with group of 5 team bearings. The vibrator armature is connected to an interface

	plate, then a thermal barrier before linking to a driver bar that attaches it to the base plate. The base plate has 5 team bearings that it is linked to with 4 bolts each. Overall there are 9 different linkages. If any of these are setup incorrectly, or are misaligned, it creates more losses and potential problems with strain on the test equipment. In an ideal world the test item is secured directly to the vibrator armature.
Vibrator (Shaker) unit that is used	Capability of the Vibrator unit is crucial. For instance, overloading a small vibrator with a heavy load will not meet the desired outcome. Similarly tests requiring large shocks may require a vibrator with a large armature displacement such as a 2” stroke.

6.3 Equipment and Instrumentation Required

- Vibrator (Shaker) Unit
- Vibrator Amplifier and Power unit
- Driver Bar
- Slip Table
- Interface plate
- Base plate
- Test Rig
- Vibration controller
- Charge amplifiers – 4 off
- Accelerometers – 4 off (single axis)
- Accelerometer cabling
- Isolation block

6.4 Spectrums to be used

The test spectrums that will be run are Helicopter Rotary Wing and Off Road Transport Vibration which can be found in the Def Stan 00-35 Part 3. The Helicopter Rotary Wing will be run for 1 hour at nR = 11Hz which if tested consecutively for an hour at nR = 17Hz and another hour at nR = 22Hz the test is representative of 40 hours flight time in any helicopter. The Off Road Transport Vibration will again be run for 1 hour which is equivalent to 5000 kilometres on road and 1000 Kilometres off road.

All testing will be conducted at ambient temperatures.

The test tolerances will be set at ±3dB for abort limits and ±1.5dB for alarm limits. Alarm limits set at ±1.5dB are there to inform the Environmental Test Engineer that the test item is deviating from the reference line (specified level).

[57]

A.2.5.3 Helicopter - Internal

A.2.5.3.1 The following three test severities shown in **Figures A15** to **A17** relate to a generic test for all transport helicopters as well as specifically to the Chinook and EH101 helicopters.

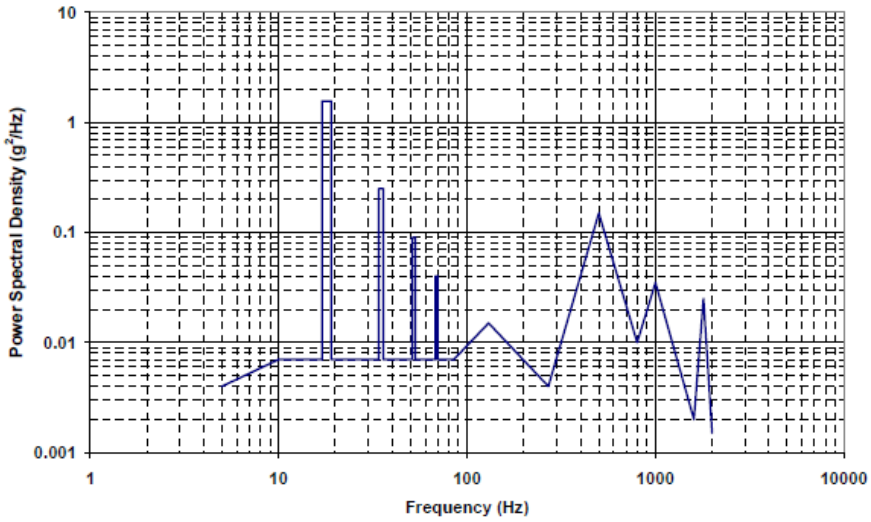
A.2.5.3.2 **Figure A15** sets out the severities applicable to all transport helicopters, **Figure A16** relates specifically to Chinook and **Figure A17** relates specifically to EH101. The generic vibration test (**Figure A15**) is conservative and should only be used where the equipment can tolerate a degree of overtest. If the test severities for both the individual aircraft are utilised then it is reasonable to assume that the two aircraft will be used to a similar extent, viz. the test duration should be split equally between the two.

A.2.5.3.3 To allow transport in any helicopter, the specification given in **Figure A15** should be used by applying nR = 11 Hz, nR = 17 Hz and nR = 22 Hz consecutively with the frequencies for the harmonics at 2, 3 and 4 nR adjusted accordingly. A test duration of 3 hours per axis (i.e. 1 hour @ nR = 11 Hz, 1 hour @ nR = 17 Hz and 1 hour @ nR = 22 Hz) should be undertaken to provide an equivalent flight time of 40 hours in any helicopter.

A.2.5.3.4 If the materiel is transported in more than one type of helicopter, then this total flight time can be split on a pro rata basis over the different types of helicopters.

Figure 46 Rotary Wing Spectrum Further Information

[58]



Frequency (Hz)	PSD (g^2/Hz)
5	0.004
10	0.007
85	0.007
130	0.015
270	0.004
500	0.15
800	0.01
1000	0.035
1600	0.002
1800	0.025
2000	0.0015
Broadband g rms = 6.384	

Blade order	g pk			g^2/Hz		
	Vert	Lat	Long	Vert	Lat	Long
nR	2.5	1.5	1.0	1.56	0.56	0.25
2nR	1.0	0.6	0.25	0.25	0.09	0.02
3nR	0.6	0.25	0.25	0.09	0.02	0.02
4nR	0.4	0.25	-	0.04	0.02	-
Overall test g rms	6.681	6.490	6.428	6.681	6.490	6.428

Test duration per axis: 1. The minimum test time per axis is one hour.

2. One hour of testing per axis is equivalent to 20 hours of flight time.

NOTE 1 Spectrum roll-on/roll-off should be a minimum rate of 12 dB/octave.

NOTE 2 nR is the helicopter's main rotor blade passing frequency, (n is the number of blades and R is the frequency of rotation of the rotor shaft).

NOTE 3 Peaks may be applied as either random narrow bands or sinusoids. For random narrow band peaks, amplitude (g^2/Hz) = (g pk)^2/2B, where B ≤ 2 Hz. The exact value of B will depend upon the environment being simulated and the frequency resolution of the vibration test control equipment used (ie: number of control lines).

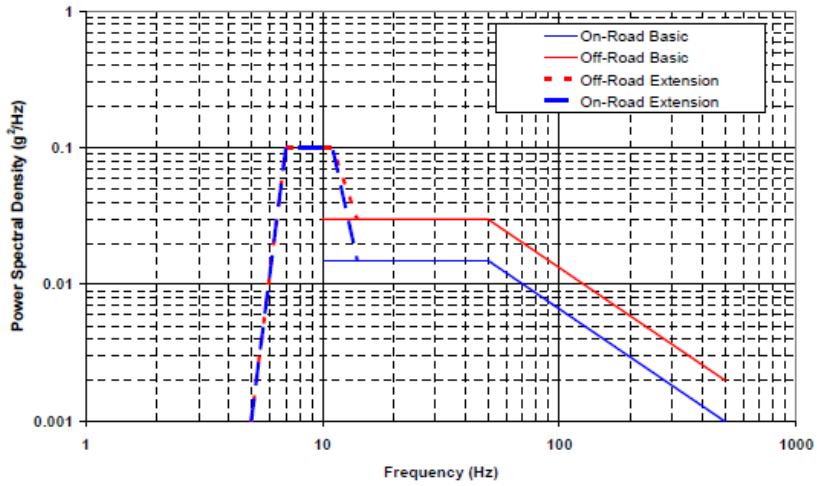
NOTE 4 For transport in any helicopter use, the above specification should be used by applying nR = 11 Hz, nR = 17 Hz and nR = 22 Hz consecutively. A test duration of 3 hours per axis (i.e. 1 hour @ nR = 11 Hz, 1 hour @ nR = 17 Hz and 1 hour @ nR = 22 Hz) should be undertaken which provides an equivalent flight time of 40 hours in any helicopter.

NOTE 5 The diagram above is an example plot only and therefore narrow band values must be taken from table.

Figure A15 Generic Vibration Test Severity for Transportation of Materiel by Helicopter

Figure 47 Helicopter Rotary Wing Vibration Spectrum

[59]



Spectrum Breakpoints for On and Off Road & Degraded Road

Basic spectrum		
Frequency (Hz)	PSD (g^2/Hz)	
	On-road	Off-road & degraded road
10	0.015	0.03
50	0.015	0.03
500	0.001	0.002
g rms	1.42	2.01

Basic spectrum plus low frequency extension		
Frequency (Hz)	PSD (g^2/Hz)	
	On-road	Off-road & degraded road
5	0.001	0.001
7	0.1	0.1
11	0.1	0.1
14	0.015	0.03
50	0.015	0.03
500	0.001	0.002
g rms	1.59	2.13

NOTE 1 The spectra for on-road and off-road & degraded road apply to the specimen's vertical, lateral and longitudinal axes.

NOTE 2 The low frequency extension to the basic spectra is applicable for:

a) Items with spring or rubber mounts

b) All military weapon systems with a mass greater than 100 kg (all up mass of the weapon and its packaging), although test tailoring is preferred in such cases

NOTE 3 This test should be carried out in conjunction with Test M3 - Classical and Sine Waveform test.

Test durations per axis: The minimum test time of one hour is equivalent to 5000 km on-road or 1000 km off-road and degraded road.

Figure A1 Vibration Test Severities for Materiel Transported by Wheeled Vehicles as Restrained Cargo

Figure 48 Off Road Vibration Spectrum

6.5 Experiment

Due to the test house facilities being utilised for commercial work, lack of an available vibration test cell and the cost and time associated with this experiment, it was neither practical nor possible to carry out the test.

In order to allow the reader to understand the control of a test, the author has sought to find data that provides a pictorial view of a vibration output. The data shown in section 6.6.3 is general testing of an object of similar size and weight to that of the OME test asset, but importantly to note, not composition.

6.6 Analysis of the Vibration Data Plots

6.6.1 Rotary Wing Vibration

At the outset, the overall control depicted in Figure 49 looks perfect and would be an ideal when vibration testing an asset. The Narrow bands that represent the separate blade frequencies do not exactly follow the reference line (green line), but are within ±1.5dB alarm lines (orange dotted lines).

The individual controls depicted in Figure 51 are a bit messy, but are still easily within the ±1.5dB alarm lines. At around 1180Hz there is a display of a resonance and anti-resonance in the individual controls. This is shown by the blue trace increasing in energy and the pink trace showing energy dropout. The resonance and anti-resonance is most likely the dynamic response of the rig and fixtures becoming excited to the energy imparted through it by the vibrator.

In Figure 50 the drive at 1180Hz reduces, stepping down to control out the resonance and anti-resonance by minimising the input at the frequency that excites the rig.

*Note: the overall control is an average of the two individual controls.

6.6.2 Off Road Vibration

In the Off Road Vibration, the overall and individual controls (Figure 52 and Figure 54) are worse than that of the Rotary wing controls. The bandwidth is much reduced compared to the 5-2000Hz bandwidth of the Rotary Wing spectrum, so control should be a lot tighter to the reference line. Again a resonance and anti-resonance can be seen on the individual control at roughly 220Hz and smaller ones from 270Hz to 500Hz. A reason for the messy control could be that the screen capture could have taken place right at the start of the test, when the vibration controller had started to measure.

Sometimes spikes can occur in the control like that depicted in Figure 55. This is usually something to do with interference from another piece of equipment, bad earthing, or instrumentation problems, but shows up in the control. The spike shown is at approximately 50Hz and would most likely come from interference from a power line.

6.6.3 Vibration Data Plots

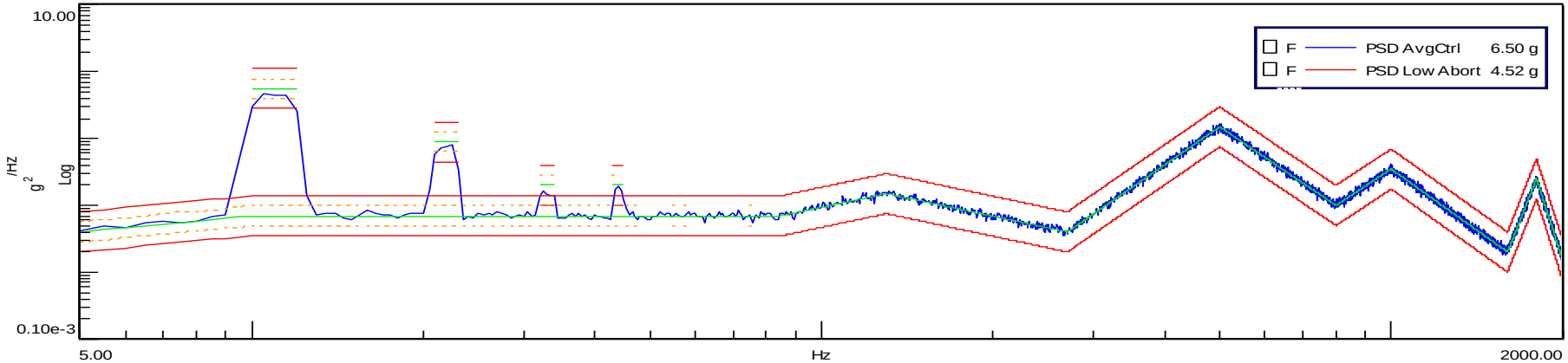


Figure 49 Rotary Wing Vibration (1st hour at 11Hz), Lateral Testing, Overall Control

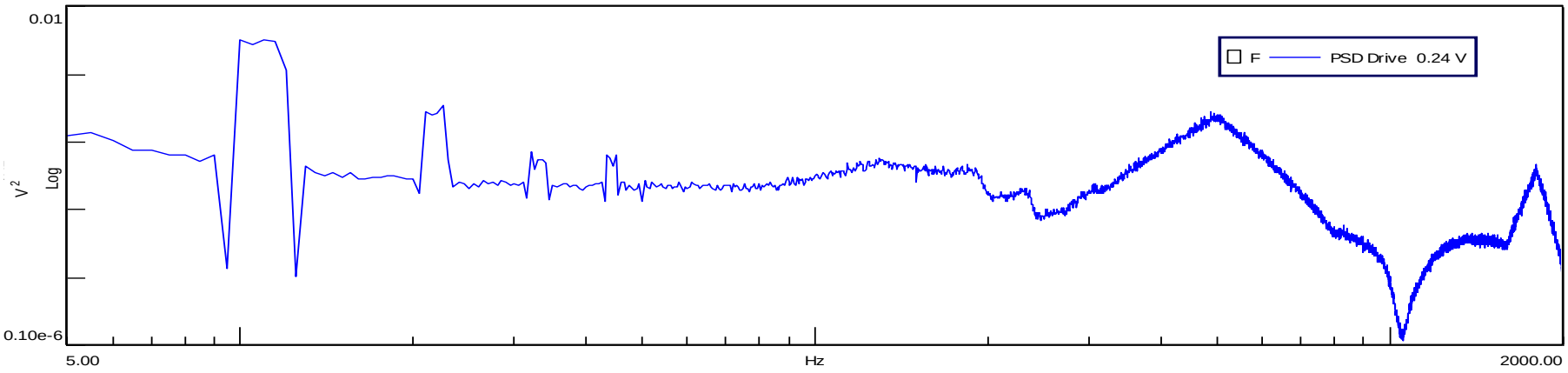


Figure 50 Rotary Wing Vibration (1st hour at 11Hz), Lateral Testing, Drive

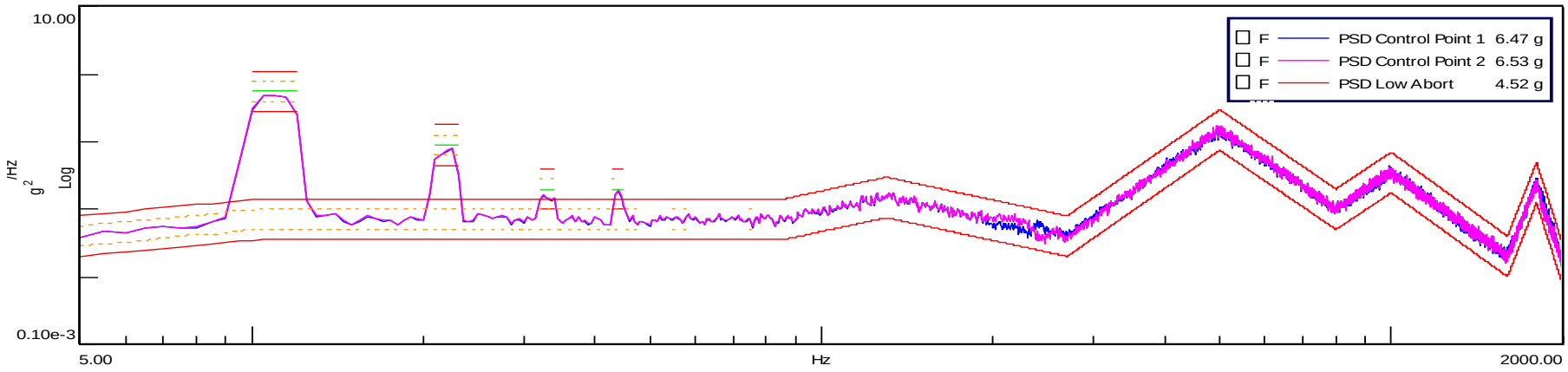


Figure 51 Rotary Wing Vibration (1st hour at 11Hz) Lateral Testing, Individual Controls

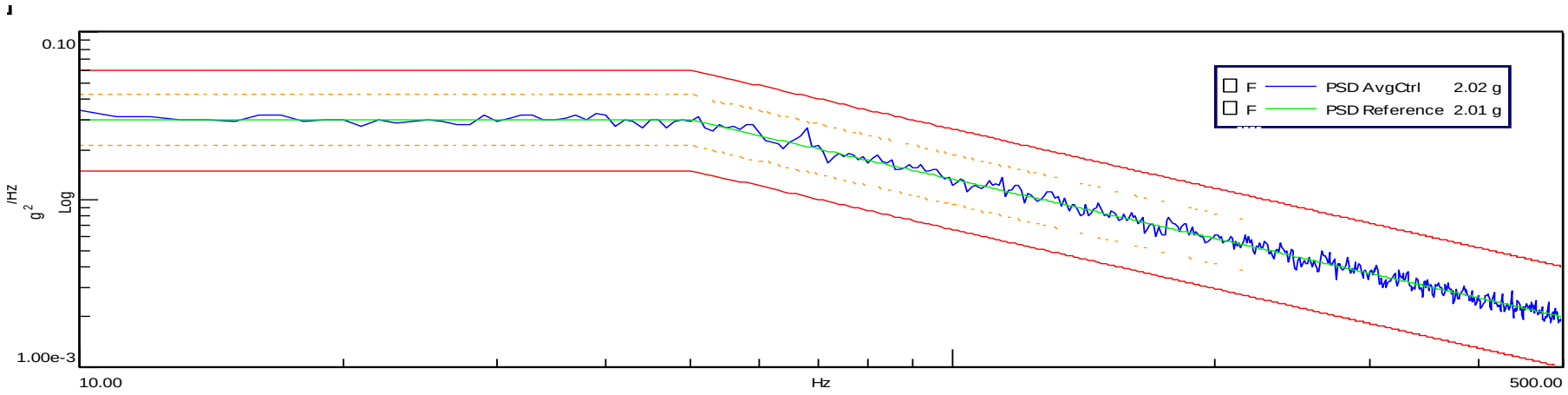


Figure 52 Off Road Vibration (1 hour) Vertical Testing, Overall Control

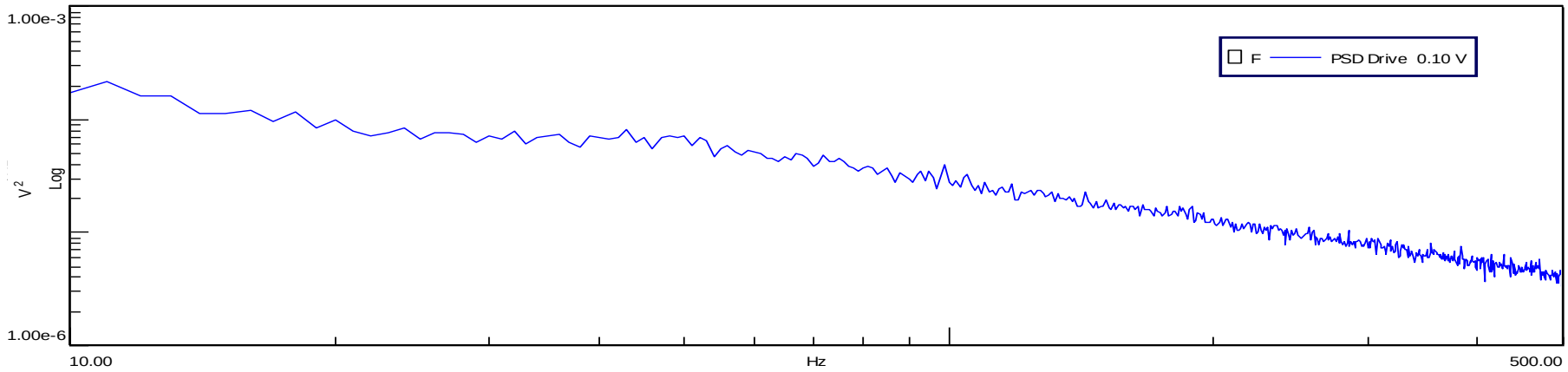


Figure 53 Off Road Vibration (1 hour) Vertical Testing, Drive

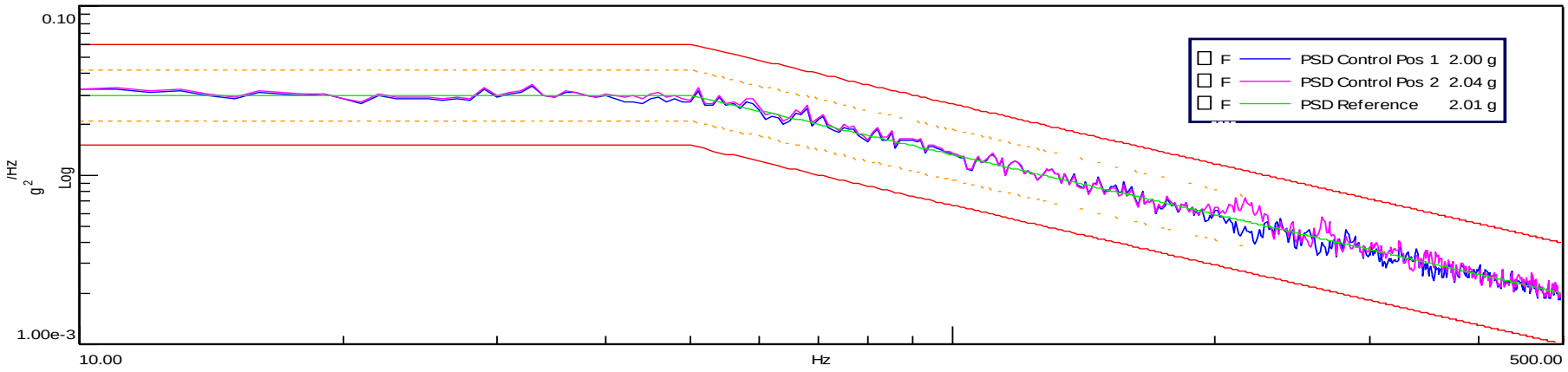


Figure 54 Off Road Vibration (1 hour) Vertical Testing, Individual Controls

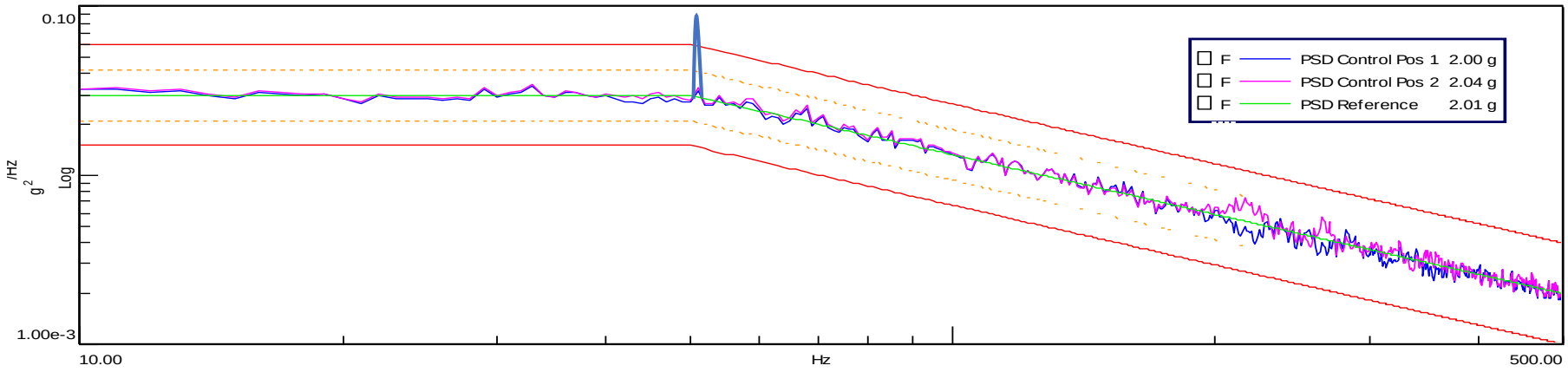


Figure 55 Off Road Vibration with 50Hz spike

7 Discussion of Results

7.1 Trial Setup

"This work demonstrates sound technical knowledge and understanding of Environmental Trials theory and methodology, coupled with technical and commercial awareness, legal and regulatory responsibilities. Its content is accurate and aligns to the operating procedures of a highly competitive Environmental Test Centre." N. Zincraft – Team Lead, Environmental Testing.

The methodology behind the trials setup process is simple and straightforward. The documentation required is used to provide instruction of what is to be tested and to enable a strong safety case to be constructed. It also affords evidence in the completion of testing, or if anything should happen to go wrong.

Its weakness is the amount of information construed in each document, of which the depth of knowledge and information projected, especially in the Specification, SOW and HARA floods the vital points. Producing the documentation is also very time-consuming.

7.2 Design and Analysis of a Vibration Rig

The use of CAD tools such as [60] AutoDesk Inventor Professional is both efficient and effective to the design process, allowing many variations of design and materials to be changed with a few clicks of a button. The addition of the Modal simulation software enhances the overall design package and creates one whole design and simulation test platform in one PC.

One of the main weaknesses is that whilst Auto Inventor is an all-encompassing design and simulation platform, its primary focus is on the design. As such the simulation is more of an add-on and is not totally accurate, or capable enough to perform detailed modal analysis on each design. This was highlighted in section 5.6 where the symmetrical rig depicted in Figure 44 showed displacement in one of its supporting sides and not the other.

8 Conclusion and Recommendations

Environmental testing can cause effects to take place such as; adiabatic compression, thermal expansion, fretting and other degradation at an accelerated rate. These effects have an impact on the OME's:

- Performance
- Service life
- Sensitivity
- Safety

Whereas failure modes in a real life asset may arise after years of use, an asset under environmental test may have a failure mode after just hours of testing. This is due to the accelerated levels to which an amount of miles, or flight hours are replicated. As shown in section 3.1.2.3 test levels can be increased to reduce the test duration. The example showed 100hrs of actual vibration reduced to 10hrs equivalent at increased levels.

Additionally, failure modes emerge earlier in environmental testing due to the tests conducted being a worst case of the real life measured levels.

The environmental testing is compressed into a concentrated amount of time in which each asset is put through focused sequential testing. In real life the predicted sequence of events for the asset may change and therefore become either less, or more severe, depending on deployment.

Whilst the environmental testing is close to real life there are some differences which unfortunately do not allow total accuracy:

- Uncertainty of measurement in instrumentation and test equipment means that there is always a tolerance and testing is performed with an overall probability of error.

- Vibration, Shock and Climatic tests all have a tolerance to which the test must adhere, this in itself may produce inaccuracies in the resulting test data.

- Due to the complexity of vibration testing, overall control can be challenging to keep within the tolerances as shown in 3.1.2.4 further exacerbating the problem of keeping the testing realistic.

- Rigs and fixtures can also affect the realism of test as shown in the analysis of section 5.6 and summary in section 5.7.

There are also other wider aspects that interfere and effect environmental testing as a whole:

- Interference from equipment near the instrumentation
- Equipment breakdowns
- Power Outages
- Test staff holiday/illness

- Natural events (i.e. storms)
- Weather (Snow)

The author has attempted to identify any significant flaws and issues of environmental testing. Below is a selection of recommendations to optimise and enhance environmental testing.

Reducing the uncertainty of measurement for equipment and instrumentation would allow a lower probability of error and greater accuracy. This would only be useful if it coincided with a reduction of the tolerances in the test specifications.

Improvement of the vibration test rigs to either:

- Realistically represent the interface, for example the hard points for a missile on a fighter jet wing. This would mean changing where the measurement of the test spectrum would be taken.
- Produce a rig that has a benign impact to the tests needed on the test asset.

Use of modal analysis on vibration rigs and with a test asset representative load:

- To make sure the rig designed is fit for purpose before being fabricated
- To give an overview of the bending moments, excitement areas, resonances etc, to the engineer to give him a head start on control positions and instrumentation setup, but also to allow him the foresight to understand where the problem frequencies and areas are on the test asset and rig.

Due to the time constraints the author was unable to study modelling and tri-axial vibration testing, but understands that with the pace that the industry is moving, these would streamline and enhance the way environmental testing is conducted in a positive manner.

9 Reflection

Throughout the process of completing the report, there has been many delays and challenges that have had to be overcome, some of which are discussed in this section.

The design and analysis of the rigs and inert experimental test items were successfully conducted on [60] Autodesk Inventor Professional 2016 with the results displayed in section 5.5. Considering I have had no formal training on the software (although I have on similar design packages) I was very pleased with the outcome and results.

Although the software was capable of conducting the analysis of the rig designs, more detailed results and setup could be attained by using more specialist software that is on the market today. The [60] Autodesk modelling Software was also not used to its full potential due to limitations of the current equipment. One outcome of this was that the simulation for each rig had to be split into 10-1000Hz and 1000-2000Hz sections.

Greater accuracy in the modelling of modal analysis could be found with a more specialist modal software such as [61] ARTeMIS Modal Pro (depicted below) as [60] AutoDesk Inventor is capable, but is generally more of a Computer Aided Design (CAD) tool.

[61]

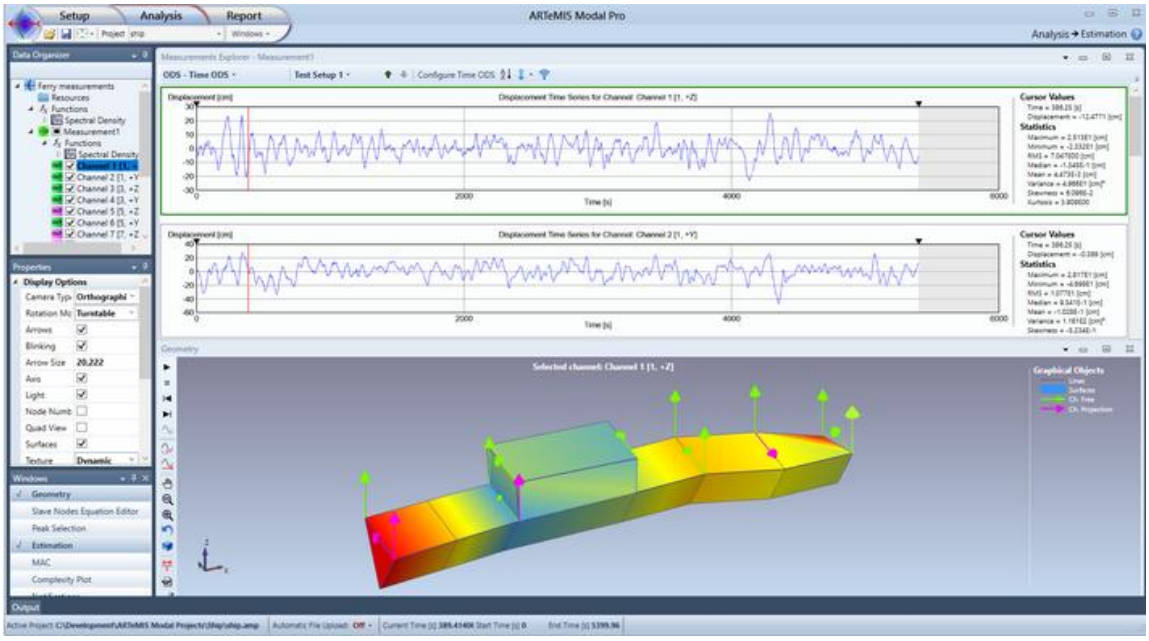


Figure 56 ARTeMIS Modal Software

A Gantt chart was provided in the original presentation, which outlined the process and specific durations for producing the report. The Gantt showed the organisation of the author and gave the ability to look ahead at what he should be doing next.

The original Gantt chart provided the best case scenario, with a lot of contingency (74 days) to carry out experimentation with the use of a vibration test facility, in the knowledge that the start date needed to be flexible. The lack of availability of the facility and equipment meant that the experiment was postponed until the commercial work was due to finish. Unfortunately, the commercial work extended.

Sometimes stages do not work out as planned, but the Gantt chart had an allowance for this in the contingency. An improvement if this was to be carried out again is to be flexible, book it in early and again have a lot of contingency.

The information and references that were gathered for use in this report provide a variety of good sources. Specifically, in the Research and Knowledge section a lot of the documentation referenced, although relevant to the subject was historic. Due to the sensitive nature of the subject, especially testing of OME and the results of testing, the information and references that exist that are not readily available in the public domain and when they are, are inherently difficult to find. They also lack detail. In some cases throughout the report information was generalised.

To improve this aspect of the report more time should be spent on finding relevant research information and academic papers to use and reference. This would in practice provide more information to be able to reference.

If the report was to be carried out again the lessons learnt and experience gained throughout the process would make a substantial positive difference to the outcome. [62] "With Concrete Experience, the learner conceptualizes (Abstract Conceptualization) findings from reflection (Reflective Observation) and modifies or applies the concepts in other similar cases (Active Experimentation)."

[62]

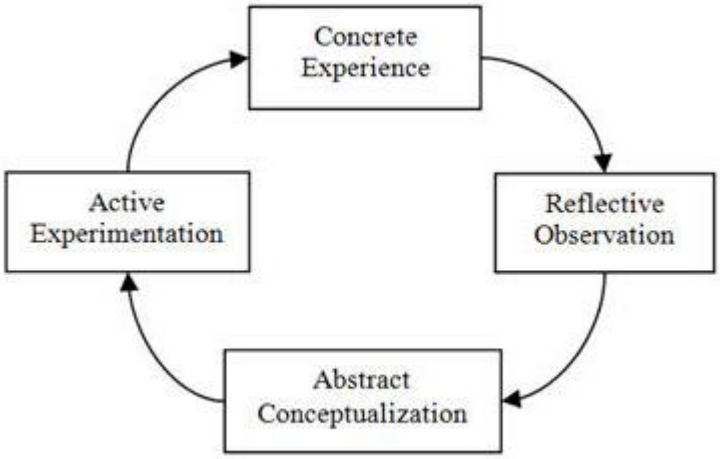


Figure 57 Kolb's Cycle of Experiential Learning 1984

In summary, the concrete experience built upon through active experimentation during the process of producing this report allows for reflection and a new approach could be used. For this report the following improvements could be made:

- Rig Design:
    - Utilise specialist modal test software
- Vibration Control:
    - Book facilities earlier
    - Add a lot of contingency
    - Increase flexibility to start at the earliest opportunity
- Research and Knowledge:
    - Spend longer on finding relevant research papers

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12 Appendices

Appendix A [63]

NATO/PFP UNCLASSIFIED

ANNEX A TO
AOP-15
(Edition 3)

Section 2 - Applicable to all Stores

No.	Question	Answer	Source Reference (e.g. Staff Requirement, Design Spec., etc. as appropriate)
(a)	(b)	(c)	(d)
2.1	**Application** Which of the Services are likely to use this munition? State from which type of weapon platform (land, sea, or air) the weapon will be operated.		
2.2	If the munition is to have detachable explosive components, are these to be stored separately? Give details. (If answer is "yes", questions 2.4-2.16 should be answered for each item.) When and where will these components be assembled to constitute the complete store?		
2.3	Is there to be a practice version which contains explosives? Is the practice version to be stored separately? (If the answer is "yes", questions 2.4-2.16 should also be answered for the practice version.)		
2.4	**Life Information** What is the minimum acceptable service life of the munition? The required operational and storage lives should be given where specified. What is the ultimate planned life for this store? (intended phase-out date)		
2.5	Can the minimum acceptable service life be achieved by replacing short-lived components? In order to achieve the minimum acceptable service life of the munition, must components having an inadequate shelf-life be replaced?		
2.6	Will the shelf-lives of all replaceable components either be approximately the same or be multiples of the shorter shelf-life?		
2.7	If there is likely to be a requirement to extend the life beyond the minimum value given in 2.4, is it acceptable to do it by using additional protection either to the package or the store itself?		
2.8	At what stage in the life of the munition will it be necessary to know whether its life can be extended?		
2.9	What will be done with munitions that exceed their service life?		
2.10	What is the proposed maintenance cycle for the munition in service?		
2.11	**Climatic and Storage Conditions** In which climatic categories (defined in STANAG 4370) or geographical areas will the munition be: a. Transported? b. Stored? c. Maintained? d. Operated?		

Table 7 AOP-15 Questionnaire to Identify the Life Cycle

Appendix B [64]

devices will behave within the system context and operational environment with an acceptable level of risk.

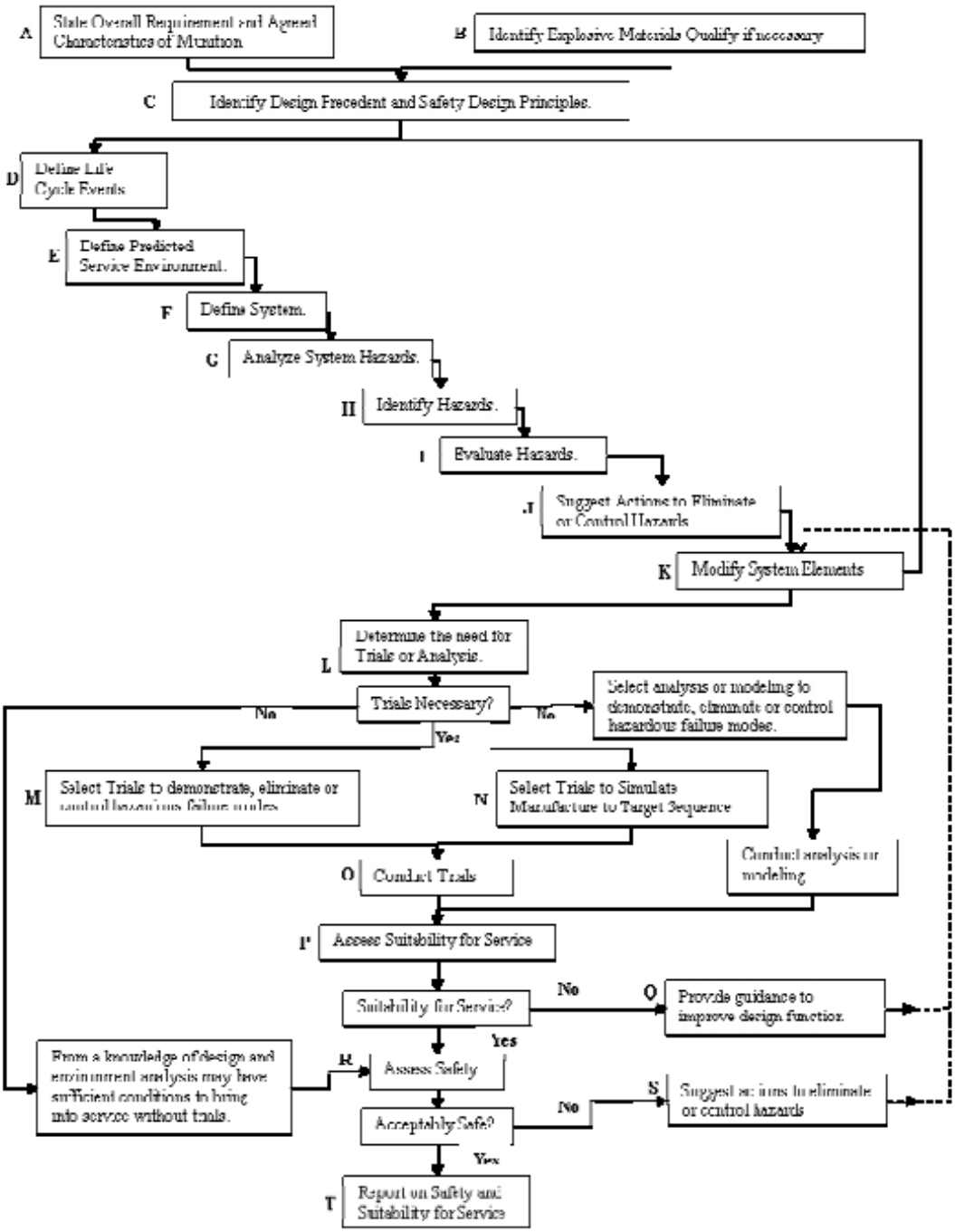

Figure 58 Safety and Suitability Assessment Process

Appendix C [65]

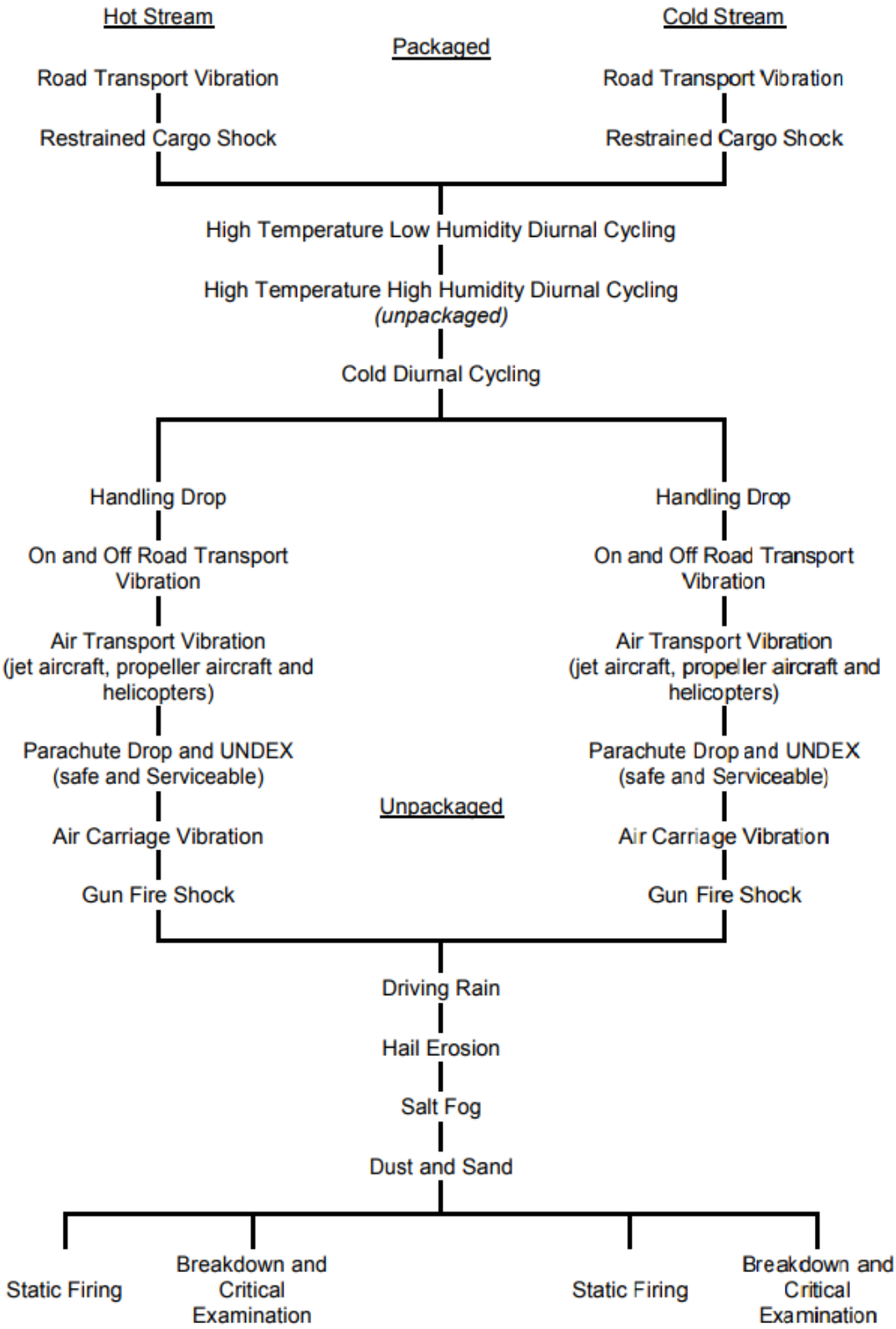

Figure 1 Example of a Sequential Test Programme (Air launched Missile)

Figure 59 Sequential Test Program

Appendix D [66]

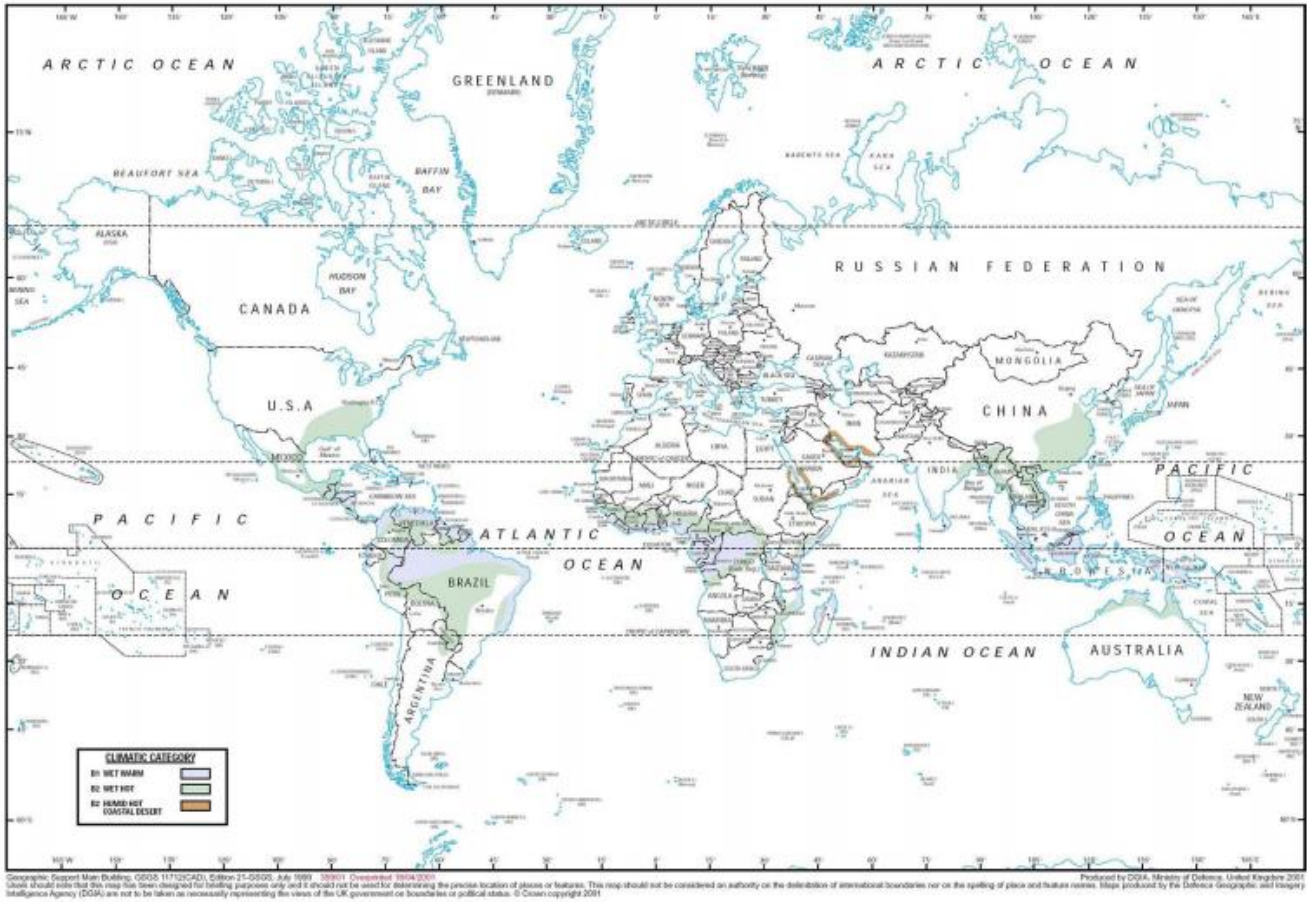

Figure 60 Location of Humid Climatic Categories

Appendix E [67]

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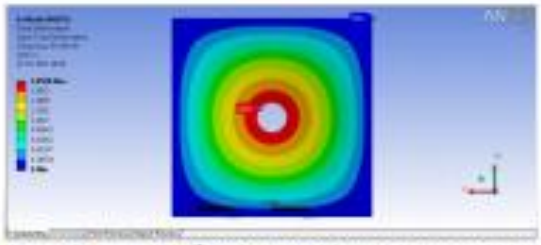

Figure 9 shows the 1st mode shape of centrally located hole , boundary condition SSSS

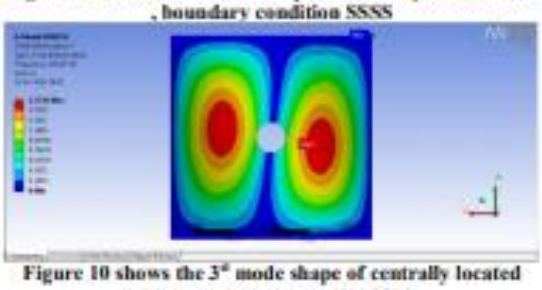

Figure 10 shows the 3rd mode shape of centrally located hole , boundary condition SSSS

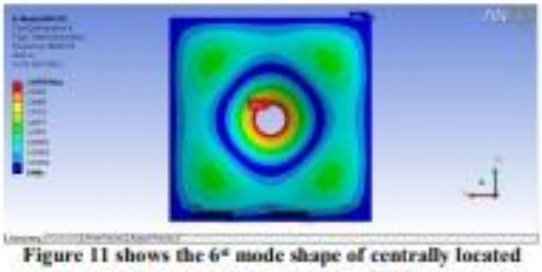

Figure 11 shows the 6th mode shape of centrally located hole , boundary condition SSSS

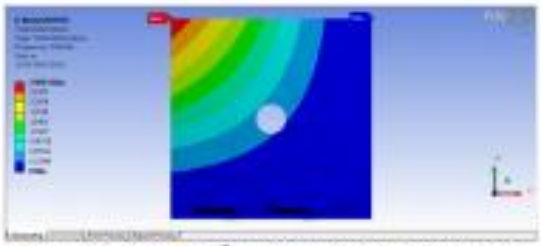

Figure 12 shows the 1st mode shape of centrally located hole , boundary condition CCFF

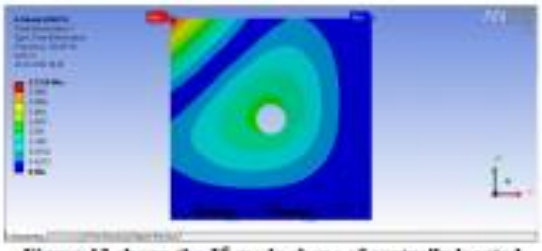

Figure 13 shows the 3rd mode shape of centrally located hole , boundary condition CCFF

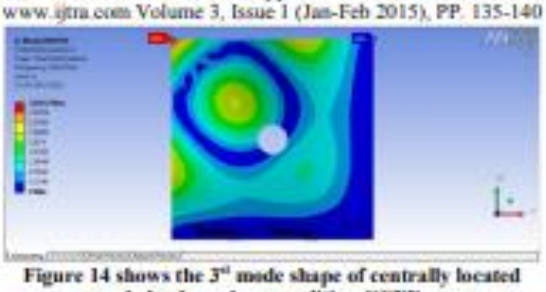

Figure 14 shows the 3rd mode shape of centrally located hole , boundary condition CCFF

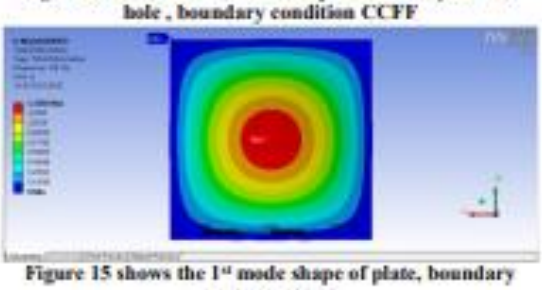

Figure 15 shows the 1st mode shape of plate, boundary condition SSSS

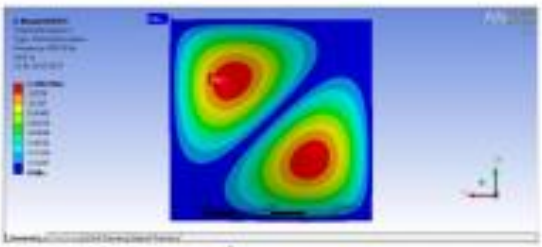

Figure 16 shows the 3rd mode shape of plate, boundary condition SSSS

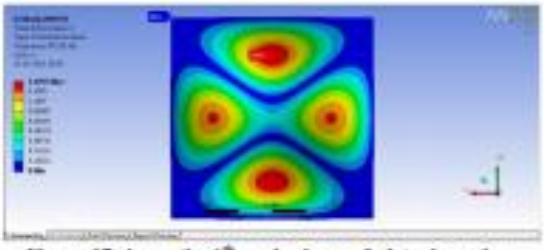

Figure 17 shows the 6th mode shape of plate, boundary condition SSSS

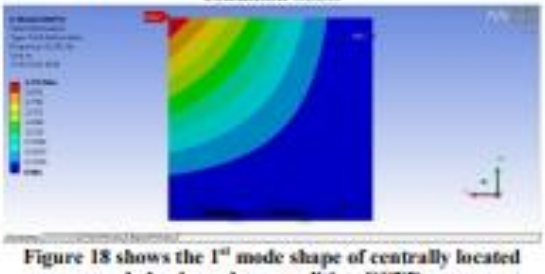

Figure 18 shows the 1st mode shape of centrally located hole , boundary condition CCFF

Figure 61 Vibration Analysis of a Stiff Plate

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