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Transport of Radioactive Material Code of Practice

Good Practice Guide to Drop Testing of Type B Transport Packages

Produced by the Transport Container Standardisation Committee

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This Code of Practice has been prepared by the UK Transport Container Standardisation Committee (TCSC). The Committee comprised:

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Special Note

The information embodied in this document has been compiled and agreed by the TCSC. Neither the TCSC members nor their parent organisations shall be liable for any detrimental consequences resulting from following the recommendations in the document.

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Preface

Drop testing of a package designed for the safe transport of radioactive material is a key activity in the application for Competent Authority approval. It is often a time consuming and expensive exercise, and therefore important that not only is it carried out correctly, but that it is performed effectively. It should be noted that this guide provides guidance on the drop tests for Type B packages.

This good practice guide concentrates on good practice in planning, executing and analysing drop tests while the companion volume TCSC 1087 discusses good practice in using finite element calculation techniques to demonstrate compliance with impact performance requirements.

The Advisory Material contains useful advisory and guidance material to satisfying the requirements of the Transport Regulations. This good practice guide aims to supplement the Advisory Material and covers specific areas in more detail. Although the context of this guide is the application for approval from the UK Competent Authority, it is also relevant in the application for licences from other Competent Authorities.

This document represents good practice and takes the form of recommendations. It should be noted that the word “shall” denotes a requirement; the word “should” denotes a recommendation; and the word “may” denotes permission, neither a requirement nor a recommendation. Imperative statements also denote requirements.

1 Introduction

A normal condition free drop test as defined in Paragraph [722] of the Transport Regulations (Ref. 1) and two accident condition drop tests, as defined in Paragraph [727] of the Transport Regulations, are among the tests required to demonstrate compliance of a transport package with the performance standards of the Transport Regulations.

For the normal condition test, the package is required to suffer no more than 10^{-6} A_2 per hour loss of radioactive contents. For the accident condition tests, packages heavier than 500 kg, and with an overall density greater than 1000 kg/m³ based on the external dimensions, are required to:

(i) retain sufficient shielding to ensure that the radiation level at 1 m from the surface of the package would not exceed 10 mSv/h with the maximum radioactive contents which the package is designed to contain and

(ii) restrict the accumulated loss of radioactive contents in a period of one week to not more than 10 A_2 for krypton-85 and not more than A_2 for all other radionuclides

Regarding the method to demonstrate compliance of a transport package with the performance standards, Paragraph [701] of the Transport Regulations states:

> *"Demonstration of compliance with the performance standards required in Section VI shall be accomplished by any of the methods listed below or by a combination thereof.*
>
> *(a) Performance of tests with specimens representing LSA-III material, or special form radioactive material, or low dispersible radioactive material or with prototypes or samples of the packaging, where the contents of the specimen or the packaging for the tests shall simulate as closely as practicable the expected range of radioactive contents and the specimen or packaging to be tested shall be prepared as presented for transport.*
>
> *(b) Reference to previous satisfactory demonstrations of a sufficiently similar nature.*
>
> *(c) Performance of tests with models of appropriate scale incorporating those features which are significant with respect to the item under investigation when engineering experience has shown results of such tests to be suitable for design purposes. When a scale model is used, the need for adjusting certain test parameters, such as penetrator diameter or compressive load, shall be taken into account.*
>
> *(d) Calculation, or reasoned argument, when the calculation procedures and parameters are generally agreed to be reliable or conservative".*

Advice on this paragraph in Paragraph [701.1] of the Advisory Material (Ref. 2) states:

> "*The intent is to allow the applicant to use accepted engineering practice to evaluate a package or radioactive material. This could include the testing of full scale packages, scale models, mock-ups of specific parts of a package, calculations and reasoned arguments"*.

That is, drop tests, calculations and reasoned arguments could be used on their own or in combination to demonstrate that a transport package meets the relevant impact requirements of the Transport Regulations.

This good practice guide concentrates on good practice in planning, executing and analysing drop tests while the companion volume TCSC 1087 (Ref. 3) discusses good practice in using finite element calculation techniques to demonstrate compliance with impact performance requirements.

The Advisory Material (Ref. 2) contains useful advisory and guidance material to satisfying the requirements of the Transport Regulations. This good practice guide aims to supplement the Advisory Material and covers specific areas in more detail. Although the context of this guide is the application for approval from the UK Competent Authority, it is also relevant in the application for licences from other Competent Authorities.

2 Planning

Planning is the key to a successful test programme.

The objectives of the tests must be defined at the outset in the planning of a test programme. Given that tests are often used in combination with analyses to demonstrate compliance of a package with the performance requirements of the Transport Regulations, the objectives of the tests in relation to the analyses and to the rest of the package development programme must be defined.

The purpose of drop tests may be simply to demonstrate that the package satisfies the performance requirements. However, the drop tests may also be designed to determine package design safety margins, or to provide information for benchmarking finite element analyses of the package.

The timing of the tests and their interfaces with the rest of the programme also needs to be defined. The tighter the overall timescale, the more important this is.

Budgetary constraints also need to be taken into account. Other considerations include the tests that need to be carried out, the order of the tests, the choice of size and type of test specimen.

Typical questions that should be addressed include:

- why are we doing tests
- what tests need to be carried out
- what do we hope to get out of the tests and
- what cases will be covered by analyses
- how do the tests relate to the analyses
    - will the analyses be the main demonstration of performance with tests as confirmatory or
    - will the tests be the main demonstration, with the analyses to show the worst case
- at what stage of the programme should the test model be designed and tests carried out

- what budget is available
    - what size of test model can we afford, and
    - how many

The decisions and justifications of these considerations should then be documented in a test plan. Not all the information required to make all the decisions on the tests will be available at the start of a package development programme. The test matrix may depend on the outcome of analyses, but experienced developers should have a good idea of what's required at the beginning of a project and the plan can always be updated as the package development progresses.

The test plan could be used to get stake-holder "buy-in" and could be presented to the Competent Authority for comment. Note that a test plan is distinct from a test specification which will define in detail the tests that need to be carried out, the initial conditions, the measurements and instrumentation etc which will be aimed at the test house.

3 The Test Specimen

Paragraph [701.1] of the Advisory Material (Ref. 2) as quoted above, recognises that testing could be carried out on full scale packages, scale models and mock-ups of specified parts of a package.

The ideal test specimen is one that can demonstrate the performance of a transport package with least uncertainty. This may be a test specimen that is identical to the production package in all respects, including geometry, material, manufacturing process, QA requirements and assembly process. In this case, the behaviour of the test specimen represents the behaviour of the actual package under the same conditions. There will be little uncertainty in relating the test results to the performance of the actual package besides any variation of performance arising from manufacturing tolerances and material properties.

The next best option for a test specimen is a prototype – i.e. a pre-production version of the package. If the design, manufacturing and assembly processes are modified between the prototype and the production version, all the differences will need to be catalogued and evaluated to demonstrate either that the difference has no significant effect on the package performance or that the difference is significant, but enhances performance and safety.

For large packages, using a prototype or production package could be extremely costly in terms of procurement as well as testing. Hence, for these packages, scaled models are often used. It has been demonstrated through the years, and by many organisations, that scale models are an appropriate and adequate means of demonstrating the impact performance of transport packages. Scaling rules are well established and discussed in detail in many publications, e.g. (Ref. 4). There are, however, some limitations and uncertainties relating to the use of scale models. These are:

- Not all parameters that govern the impact behaviour of a transport package are scalable, and this includes:

- strain rate sensitivity effects
- gravity effects
- fracture effects and
- buckling behaviour

- Geometry may not scale exactly, especially for:

  - welds
  - small components
  - bolt sizes and
  - plate thickness

- Fabrication methods may not scale, and this may have an effect on material properties.

- Material behaviour can vary with size. A scale model which is a perfectly scaled version of a real full size transport package, and have identical material properties as the transport package, will provide perfectly scaled impact behaviour when subjected to the same impact velocity and impact orientation, if:

  - strain rate sensitivity effects is absent
  - gravity effects is absent
  - deformation is by plastic flow and not by fracturing or buckling processes
  - size effect is not significant in the behaviour of the materials especially the materials which are components of the impact limiters

Readers are recommended to consult the papers presented by BAM at PATRAM 2004 and 2007 on this topic (Ref. 5, 6 and 7) for further detailed discussions.

4 Designing the Test Matrix

Except for small transport packages, procuring test specimens and carrying out drop tests are costly. The number of test specimen needs to be kept to a minimum and the test matrix needs to be designed carefully to make best use of the available test specimen and drop tests.

4.1 Basis of Drop Scenario Selection

There is an infinite number of orientations in which a package could be dropped in a 9m drop, or in a 1m drop onto a punch, and many permutations regarding the sequence of the drops. However, in defining the tests for demonstrating the ability to withstand accident conditions of transport, the Transport Regulations states:

> *"the specimen shall drop onto the target so as to suffer maximum damage"* (Paragraph [727]).

And in discussing the appropriate sequence of the tests, states that:

> *"The order in which the specimen is subjected to the drops shall be such that, on completion of the mechanical test, the specimen shall have suffered such damage as will lead to maximum damage in the thermal test"* (Paragraph [727)).

The Advisory Material clarifies that:

> *"the assessment of maximum damage should be made with concern for the containment of the radioactive material within the package, the retention of shielding to keep external radiation to the acceptable level and, in the case of fissile material, maintenance of sub-criticality"* (Paragraph [727.5]).

That is, the orientation of the package in the drop tests and the sequence of the tests must be chosen such that the package receives maximum damage, not in terms of largest knockback or highest deceleration per se, but in terms of those issues, such as containment, shielding, criticality and thermal performance, likely to affect the packages ability to comply with the requirements of the Transport Regulations.

4.2 Choice of Drop Orientation – 9m Drop

There are two main classes of drop orientations, which often bound the maximum damage:

- drops with the centre of gravity over point of impact and
- oblique drops where the centre of gravity is not over point of impact

4.2.1 Centre of Gravity (CG) Over Point of Impact Drops

CG over point of impact drops include all those drop orientations in which the centre of gravity (CG) is directly above the point, edge or side of the package which makes first contact with the target. These drop orientations maximise the amount of the drop energy that needs to be absorbed by deformation of the package, and minimizes the amount of the drop energy that will be "lost" due to rigid body rotation of the package.

For cylindrical packages with bolt-on impact limiters at both ends, CG over point of impact orientations would include:

- side drop
- axis vertical drop onto the lid
- axis vertical drop onto the base
- CG over lid edge drop
- CG over base edge drop

For rectangular packages, these would be:

- flat base drop
- flat lid drop
- flat long side drop
- flat small side drop
- CG over lid corner drop
- CG over base corner drop
- CG over lid short edge drop

- CG over lid long edge drop
- CG over base short edge drop
- CG over base long edge drop

However:

- the orientations of maximum damage will depend on the design of the package
- specific features of the design may mean orientations other than CG over point of impact orientations could also produce significant bounding damage
- for cylindrical packages, the orientations listed above define the orientation of the package axis with respect to the target. But hoop orientations about the package axis must also be considered, since the geometry of most packages is not axi-symmetric

FE analyses and comparison with results from existing similar packages may be used to justify drop testing a subset of these orientations and to demonstrate that the orientations selected for testing are bounding.

4.2.2 Oblique Drops

In an oblique drop, the centre of gravity is not directly above the point of initial impact. For a cylindrical flask with impact limiters at both ends, its behaviour can be described as follows:

Assuming the base-end of a transport package impacts the target first, then during the first impact, the base impact limiter deforms, and the base end of the package decelerates. The package's CG continues its descent. The package "pivots" about its base, causing the package to rotate, and to accelerate under gravity, both adding to its initial downward velocity. At the same time, the base end starts to rebound, and increases the rotational velocity. Then the top impact limiter hits the target.

The impact velocity at second impact can be significantly higher than impact velocity at the first impact and is dependent on the package's geometry, inertial characteristic, energy absorption characteristics during first impact, rebound characteristic of first impact and the drop angle at first impact. In general, the impact velocity at second impact is higher for packages with higher aspect ratio.

For most packages, the behaviour during the first impact would be bound by one of the CG-over-point-of-impact orientations, and only the behaviour at second impact is of interest. However, long slender packages may be susceptible to large flexure deformation during the first impact and this behaviour may not be bounded by a CG–over-point-of-impact drop, and therefore must be considered.

It is seldom feasible to carry out more than one or two oblique drops due to the limitation of the number of test specimens. It is therefore desirable that the oblique drops that are carried out are with the worst case oblique drop angle, i.e. an oblique drop angle at first impact that could cause the worst damage at second impact. Because of the complexity of a package's behaviour during an oblique drop, FE analysis is currently the only satisfactory method available to determine this angle. Behaviour of the test specimen in a range of oblique drop angles can be analysed. From this, the impact velocity and stresses in the package at second impact can be determined. The oblique drop angle that causes the highest impact velocity, highest stresses and largest damage at second impact can be chosen for the drop test.

4.3 Choice of Drop Orientation – 1m Drop onto a Punch

As for 9m drop onto a flat unyielding target, the Transport Regulations specifies that in a 1m drop onto a punch, the package must be dropped to incur maximum damage, with regards to thermal, containment, shielding and criticality performance.

Package orientation, point of impact, and length of punch, to cause maximum damage will depend on the design of the package. Local features such as closures of drain holes, valves, locks, crevices, are especially susceptible to punch damage and impacting directly onto these should be considered.

For packages which have thermal insulation or shielding material enclosed within a thin cladding, package orientation to cause the punch to impact at a shallow angle could cause the cladding to tear which could cause local hot spots during the thermal accident, and release of lead shielding (where present) if punctured. For wood filled impact limiters, impact perpendicular to the cladding could cause excessive stretching and may cause puncture.

Impacts in which the CG of the package is not directly above the punch must also be considered since the damage, even with the offset of the CG from the punch and hence package rotation during impact, could still be significant.

Since the Transport Regulations specifies that the test package must be subjected to the cumulative damage of a 9m drop and a 1m drop onto a punch, the decision on the impact location and package orientation in the punch drop must take into account the worst damage that has already been incurred on the package from the 9m drop, such that after the tests, *“the specimens shall have suffered such damage as will lead to the maximum damage in the thermal test which follows”* (Paragraph [727]).

4.4 Selection of Test Sequence

As noted above, the Transport Regulations states that:

> *“The order in which the specimen is subjected to the drops shall be such that, on completion of the mechanical test, the specimen shall have suffered such damage as will lead to maximum damage in the thermal test” (Paragraph [727]).*

Although commonly, the 9m drop is carried out first and the punch drop then targets the weakened area of the specimen or areas that will aggravate the degree of damage already incurred, reversal of this order must also be considered. In some designs, the punch damage may lead to worse damage in the 9m drop and also in the thermal test. An example might be that a lid fastener or locking device could be destroyed by the punch and therefore increase the potential for catastrophic lid failure in the free drop test.

4.5 Choice of Boundary Conditions - Temperature

In designing a transport package, the Transport Regulations requires the designer to:

> *“take into account ambient temperatures and pressures that are likely to be encountered in routine conditions of transport.” (Paragraph [615]).*

And for Type B(U) packages,

> *“A package shall be designed for an ambient temperature range from -40°C to +38°C.” (Paragraph [664]).*

Commenting on this clause, the Advisory Material states:

> *“In assessing a package design for low temperature performance, the heating effect of the radioactive contents (which could prevent the temperatures of package components from falling to the minimum limiting ambient design temperature of –40°C) should be ignored. …. Conversely, in evaluating a package design for high temperature performance, the effect of the maximum possible heating by the radioactive contents, as well as insolation and the maximum limiting ambient design temperature of 38°C, should be considered simultaneously.” (Paragraph [664.3]).*

Although the Transport Regulations do not specify the temperature of the test specimen in the drop tests, if the drop tests are the sole demonstration of the package performance against the regulations, then the variation of its performance at the extreme ends of the temperature spectrum must be addressed.

Mechanical properties of some energy absorbing materials employed in impact limiters could vary quite significantly over the temperature range and the effect on the package performance over these must be demonstrated. The Advisory Material notes that the low temperature limit is particularly important *“because of pressure increases from materials which expand upon freezing (e.g. water), because of possible brittle fracture of many metals (including some steels) at reduced temperature and because of possible loss of resilience of seal materials” (Paragraph [664.1] of TS-G-1.1).*

It is recognized that testing at extremes of the temperature range – from a minimum of -40°C to a maximum arising from an ambient design temperature of 38°C – is costly and may be difficult to execute, especially for large transport packages. Because of this, most drop tests have been carried out at “ambient temperature”. This is likely to be sufficient for most cases provided that the performance at extremes of temperatures are demonstrated by other means, such as by reasoned arguments based on similar existing packages, or by FE analyses that have been benchmarked with the drop tests using material properties at the appropriate temperatures.

Even if drop tests at the extremes of temperatures are not carried out, mechanical behavior of all the materials over the operational range of temperatures, and stress/strain conditions must be known. This may require separate component level and/or material testing.

4.6 Pressure

During package operation, the containment could be subjected to different combinations of internal and external pressures. These are in part, related to the variation in temperatures as discussed above. The significance of these on behaviour in the drop tests depends on the design. For the drop test, the worst case pressurization is adopted and often, this is the maximum normal operating pressure (MNOP). Behaviour in other pressure scenarios can normally be demonstrated by calculations.

4.7 Bolt pre-stress

The level of pre-stress in the lid bolts could have a significant effect on the behaviour of the bolts and the lid-body interface in drop tests. The pre-stress in the lid bolts in the drop test specimen should be identical to that in the real package during operation. Pre-stress in the other bolted interfaces in packages should also correspond to those in the real package.

4.8 Logistics

For small packages, it is feasible to procure a number of test specimens and test each for a different combination of 9m drop, 1m drop onto a punch, and thermal test. For large packages, perhaps only one test specimen can be procured for economic reasons. For packages with bolt-on and removable impact limiters, in which the flask itself is designed to suffer negligible permanent deformation in the 9m drops and only local damage in punch drops, a number of impact limiters can be procured for the different drop tests. For packages with integral impact limiters which rely on metal flow to absorb the impact energy, the sequence of tests, and the impact attitudes, must be considered carefully, so that the damage is maximized, for each sequence of tests, without affecting the performance in later tests.

4.9 Normal Transport Drop Tests

Consistent with the requirements for accident drops, the Transport Regulations specifies for the normal transport drops that:

> *"The specimen shall drop onto the target so as to suffer maximum damage in respect of the safety features to be tested" (Paragraph [722]).*

The Advisory Material explains this in a slightly confusing way:

> *"all possible drop test orientations need not be considered when conducting the drop test for normal conditions of transport. Providing that it is not possible under 'normal' conditions for the package to be dropped in certain orientations, these orientations could be ignored in assessing the worst damage. It was envisaged that this relaxation would only be allowed for large dimension and large aspect ratio packages. In addition this relief would require documented justification by the package designer. Package designs requiring approval by the competent authority should be tested in the most damaging drop test attitudes irrespective of package size or aspect ratio." (Paragraph [722.6])*

This suggests that it is permissible to discount some package orientations from the drop test if it can reasonably be shown that it is not possible for the package to be dropped in a particular orientation in normal conditions of transport, or if it was, it would be considered as an accident. This latter consideration is particularly relevant to heavy packages. On the other hand, it could mean that for all package designs that require Competent Authority approval, the package should be drop tested in the most damaging orientation, irrespective of whether the package could actually be dropped in that orientation. The latter approach would be a more conservative approach, but, in any case, it is recommended that guidance be sought from the Competent Authority where there is any doubt on which approach to adopt.

To save time and cost, sometimes the argument is made that if the package can survive the tests for accident conditions of transport then it is automatically qualified for normal conditions, and this justifies omitting the specific tests for normal conditions. The risk with this approach is that the pass criteria for normal conditions of transport are fundamentally different. Convincing arguments for no loss of dispersal of the contents and for the dose rate at the external surface of the package not to increase by more than 20% will need to be made separately.

4.10 Drop Tests for Fissile Packages

For packages containing fissile material, the Transport Regulations require the package to be subjected to the combination of normal and accident conditions of transport i.e. cumulative damage. This is normally fulfilled in one of two ways:

a) drop the specimen for maximum damage under normal conditions followed by a drop of the same specimen under accident conditions

b) sum the drop heights for normal and accident conditions and drop the specimen from the combined height to represent cumulative damage

Wherever appropriate, the approach in (a) should be adopted as this approach is easiest to justify to the Competent Authority. However there may be situations that make the second approach most sensible such as when normal damage has been shown to be negligible, or where, with the agreement of the Competent Authority, the test programme can be simplified. When adopting the second approach, it is essential that a separate assessment and justification is made against the acceptance criteria for the normal transport drop, and that the approach is agreed in principle with the Competent Authority before testing.

5 Package Lifting and Manipulation

In order to rotate the test specimen to the required orientation, to lift the specimen to the required drop height, and to suspend the test specimen at the required orientation, lifting devices need to be attached to the test specimen. In the design of such lifting devices, the following should be noted:

- they must not interfere with the impact behaviour of the package,
- they must be designed taking into account the loadings, not only when the package is suspended at the required orientation, but during the whole rotation process from whatever is the original orientation
- they must only be attached to components on the test specimen that can sustain the load without permanent deformation and not onto components that are not load-bearing, e.g. thermal cladding
- the weight of the device including any chain, slings and links which will fall with the package, must be kept to a minimum, must not alter the centre of gravity of the package significantly, must not increase the susceptibility of the package to rotate during descent and must be weighed prior to each drop
- damage of the package from the falling chains, slings and links which fall with the package must be minimised. Cushioning and protective material may be added to the upper surfaces of the test specimen or wrapped around the chains, slings and links

Orientations of the test specimen, and location of the point of impact in the case of 1m drop onto the punch, must be verified when hanging freely above the target before it is lifted to the required drop height. Method of measurement may include careful measurement of distances from discrete points of the package vertically down to the target surface and the use of calibrated digital inclinometer.

Drop height of the test specimen must be verified before a drop, and the method of measurement and expected accuracy must be agreed between the test house and owner of the test programme.

6 Test Measurements

6.1 Instrumentation

Continuous monitoring of accelerations, strains, relative displacements, and pressures at selected locations on a package during a drop test, can provide significant insight into the behaviour of the package, and is indispensable in demonstrating the margin of safety. They are useful in demonstrating the test conditions and the reliability of the results, and they are a must for benchmarking and validating FE analyses against drop test results. Paragraph [727.18] of the Advisory Material (Ref. 2) gives the following reasons for such instrumentation:

> *“Instrumentation of test specimens and even of the target response to impact should be done for the following reasons:*

- *validation of assumptions in the safety analysis*
- *as a basis for design alterations*
- *as a basis for the design of comparable package,*
- *as a benchmark test for computer codes"*

Acceleration time history is probably the transient data that is most often measured. From this the following can be assessed where relevant:

- the inertia loading on a package
- the severity between different drop orientations
- velocity-time history (see Appendix B.2)
- drop height (see Appendix B.3)
- displacement-time history (see Appendix B.2)
- knockback distance (an important parameter for benchmarking FE analysis, providing an indication of energy absorbed)

The following are key considerations in employing accelerometers:

- to ensure availability of usable results, accelerometer and cabling should be duplicated. For each accelerometer position, at least two accelerometers should be mounted, with one as a backup (i.e. two separate channels at each measurement point). Each channel may need to be set to different measurement ranges to reduce the risk of the measurement being over or under range. Also, accelerometers with different sensitivities could be considered
- the most useful data is likely to be obtained by mounting them such that their axes are parallel to the direction of impact, i.e. in the direction of gravity. However, if an impact is to take place at an angle (e.g. drop onto lid edge), angled mounting blocks which can be securely attached to the test package and allow the accelerometers mounted on it to aligned in parallel to the target could be designed and used. Alternatively, tri-axial accelerometers could be considered
- they should be adequately protected against damage from falling cable, and chains, slings and links that form part of the lifting system
- cables must not interfere with the impact behaviour of the test specimen
- they should be mounted directly onto the containment of the package or via mountings. The mounting should be designed such that its dynamic vibratory response does not affect the measurement and it is sufficiently robust to remain firmly attached to the package (see Appendix B.1)
- single axis piezoresistive or piezoelectric accelerometers are normally used (tri-axial accelerometers could be considered as mentioned above)
- any connection between accelerometers and amplifiers should be of suitable quality to prevent signal degradation due to spurious earth loops or poor connections. Care should be taken to ensure that signal corruption due to cable vibration (triboelectric noise) does not occur
- prior to use, accelerometers should have been calibrated using an approved method (see Appendix B.5) and the Test House should make certificates available to the owner of the test programme. If accelerometers were used on previous work, they should be re-calibrated before use. In addition, the complete signal conditioning and recording system should have a continuity check immediately prior to each test. This check will vary depending upon the type of accelerator used.

For piezoresitive accelerometers, a shunt calibration or voltage insertion calibration should be considered. It is useful to connect the accelerometer leads to a distribution box attached to the outside of the package away from the drop zone. The resistance of cabling from the distribution box to the control room can then be measured with a multimeter. The test house should be able to demonstrate this does not adversely affect signal accuracy

- signals should be recorded digitally using a PC based data acquisition system with a suitable amplitude resolution on the analogue to digital conversion (see Appendix B4). Anti-aliasing filters should be available in the data acquisition system if needed. Their use will depend upon the logging speed, and the expected amount of high frequency measured by the accelerometer at impact (see Appendix B.4)

Further information on accelerometer selection can be obtained from suppliers. Also the US Institute of Environmental Sciences and Technology (IEST) have produced a reference document *Shock and Vibration Transducer Selection RP-DTE011.1* (Ref. 8).

For all instrumentation:

- transducer specification, method of transducer installation, exact location of instrumentation attachment on the test model, cable location, machining required to install instrumentation and cabling, cable attachment technique, details of signal conditioning equipment and instrument settings should be agreed between the test house and the owner of the test programme, before each test
- instrumentation procedure should be in accordance with recognised good practice

In general, results should be presented by the test house as raw unfiltered data from each transducer (but note the comments on anti aliasing filters in Appendix B.4). Acceleration-time traces could also be filtered, with at least two filtering frequencies to assure the quality of the data. In some test programmes, it may be useful to obtain a velocity-time trace by integrating the acceleration-time trace (see Appendix B.2).

Where accelerometers are used to measure the global deceleration of a package they should be mounted on the rigid components or parts of the lid or body of the package and not on bolt-on impact limiters or structures that could suffer from high vibratory response, e.g. claddings of thermal insulation.

FE analysis of the package response in the time domain should be carried out prior to testing to inform the choice of accelerometer and the likely amplitude range for the data acquisition system as well as the ideal locations of the accelerometers. It is also important in selecting an accelerometer to ensure its resonant response does not affect the measurement. The test house should be informed on the likely frequency response of the package. This also helps in deciding the sampling rate on the data acquisition system.

The package temperature at the time of tests should be measured to ensure appropriate material properties are used in the FE analysis.

6.2 Photography

High speed video (HSV), typically with a frame rate of 500 to several thousand fps (frame per second), provides a complete record of the motion of the package during the impact event. Close-up views of impact areas provide information for detailed evaluation of the behaviour at the impact area, and overall views provide information from which global parameters like impact velocity, impact angle, impact duration, rebound velocity, rebound trajectory, etc can be verified.

The following are key considerations in employing high speed video:

- the view from the cameras should be designed prior to the tests taking into consideration distance and height of drop, and finalised just before the drop test with the package suspending at the impact position. The desired coverage should include a combination of close-up views and wide views. Cameras should view in the same direction (in the case of close-up and wide view), perpendicular to each other or at 45 degrees to each other
- adequate lighting should be available for each test depending on the frame rate chosen. It should be designed to provide sufficient light at the end of the test for the key interest points. Ideally the object should be placed in the drop position to set the lighting up for the best results. This will help eliminate any shadow or highlights.
- precautions shall be taken to ensure security and safety of lighting and power supply during the test
- a scale shall be placed at the background of each camera's view to enable vertical displacement measurements to be taken directly from the HSV files
- the HSV from the different cameras must be synchronised
- time value should be displayed in the HSV files,
- the files from the different cameras in each drop test must be synchronised using an event marker on the high speed video. The signal from the event must also appear in the acceleration, strain gauge and pressure time history displays
- the event signal should also trigger digital stopwatch displays capable of measuring milliseconds and a stopwatch display should be visible in each camera view
- grid line and bulls eye markers should be used on the surface of the package to facilitate motion measurement
- a plain background could be placed behind the object as the contrast with the package can make it appear clearer in the HSV images
- video and photographic equipment should preferably be outside the exclusion zone, if it is needed to film from inside the zone, it may be necessary to protect it from projectile damage

In addition to high speed video, normal speed video has also been found to be useful in giving an overview of the event.

High quality still photographs should be taken before the test series on the pristine test specimen, before each test to record the drop orientation and the pre-existing damage of the test specimen, and after each test to record the final resting position and the damages to the test specimen. Photographs should also be taken of the target and the punch after each test.

6.3 Metrology

In order to quantify the damage, the test specimen should be inspected before and after each test (or set of tests, e.g. a 9m drop plus a punch drop). It could include a combination of the following:

- measurement of knockback of impact limiters and shock absorbers
- non-destructive examination e.g. dye penetrant, magnetic particle, radiographic and ultrasonic tests
- destructive tests of replaceable components, e.g. sectioning of impact limiters,
- overall dimensional survey to assess permanent deformations. This could include the use of a co-ordinate measuring machine and/or an optical surface digitisation technique
- visual examination to identify and record any unusual features
- measurement of indentation and other damages (e.g. punch damage by indentation and tearing)
- lid-body gap if test ports for such measurements are designed into the test specimen

The accuracy of such measurements must be stated in the test specification and the accuracy of the method must be agreed.

Besides the damage to the test specimen, damage to the punch must also be measured and recorded in sufficient detail.

In drop tests of packages with “integral shock absorbers” in which the feature of the package that impacts the target can have similar hardness as the steel plate on the target, the plate is susceptible to indentation from the test specimen and such damage must be measured and recorded in detail.

The test house and owner of the drop test programme should agree that the impact target is adequate for the purposes of the tests and meets the requirements of Regulations [717], taking note of guidance provided in [717.1 and 717.2] (Ref 2). This may require the test programme owner to provide the test house with information on the predicted dynamic response of the package at impact, and the test house to provide evidence that the plate is fully bonded to the concrete block below, and the concrete is in good repair.

6.4 Bolt tightening and measurement of loss of bolt pre-stress

For those bolts used to form the containment boundary, e.g. bolts at the lid-body interface, maintenance of adequate pre-stress is an important requirement.

It is therefore important to tighten each bolt to the required specified torque and to record the torque used before each test (or test combination) and to record the torque to loosen each bolt after each test or test combination, to assess the amount of pre-stress loss.

6.5 Leak testing

Leak testing is probably the most common “acceptance test” for packages and can demonstrate directly whether a package satisfies the containment criteria.

Leakage rate through the sealing system at the lid-body interface, at the vent valve and other sealed openings, should be measured after each test or set of tests (i.e. 9m drop and punch drop combination). A test method commonly adopted is that defined in TCSC 1068 Appendix J (Ref. 9), which gives detailed requirements and good practice in leak testing.

7 Test Specification

The owner of the test programme should produce a test specification that defines the tests to be carried out. It is a key document in ensuring that the tests are carried out properly. It can be expected to include at least the following sections:

- Background
  This section provides background to the tests, introduces the packages and discusses the relevant test clauses in the Regulations (Ref.1) that are required for the licensing process

- Objectives
  This section states the objectives of the tests

- Description of the test specimen
  This section describes the test specimen(s) and spare parts that are provided for testing. This section also includes storage and assembly instructions, and schedules for part replacements – e.g. impact limiter change

- Weighing and measurement of centre of gravity
  This section defines the requirements for weighing test specimens and identifying the centre of gravity of the test assembly, including the accuracy required of these measurements

- Test sequence
  This section defines the sequence of tests that need to be carried out, including a list of work that needs to be carried out before and after each test (e.g. photography, metrology, data processing, bolt torque, pressurisation, leak testing, collecting and sieving of particulates, dismantling, part replacement, etc, details of which are specified in the following sections of the specification)

- Target
  This section defines the requirements for the design and construction of the flat unyielding target and the punch target

- Test conditions
  This section defines the drop heights, the orientation of the package in the drop tests, the point of impact in the punch tests, as well as pressure, bolt torque, fit-up requirements. In defining the orientation and point of impact, the specification needs to be specific regarding the exact edge, face, or corner of the test specimen that needs to be impacted

Accuracy of all these must be defined, e.g. drop height of 9m ± 50mm. For drop orientation and point of impact, the test specification must state the required accuracy at the time of impact

The test house should be required to provide a methodology to measure these and demonstrate how these can be checked before the test, and also at the time of impact in the case of drop orientation and point of impact

- Handling and manipulation instruction for the test specimen
  This section defines the methodology to lift, handle and manipulate the test specimen including the individual components of the test specimen e.g. lid, basket. Fragile structures on the surface of the package, e.g. thin clad thermal insulation, could be damaged by inappropriate lifting. This section also defines what can be used to suspend the package in the drop test orientation and what can be used to rotate the package into the drop test orientation, as well as requirements on the release mechanism

- Instrumentation and data processing
  This section defines:
  - any instrumentation required to obtain transient information during the test, such as; deceleration, strains, and internal pressure
  - any information on predicted peak values for acceleration, strain, pressure, frequency, range etc
  - the location and orientation of accelerometers and strain gauges
  - requirements on the design of the accelerometer mountings
  - any specialised recording instruments
  - the required accuracy for the instrumentation specified

  It should be noted that different test houses will have different measuring equipments, data recording systems and in-house instrumentation and measurement procedures. The test specification should outline the requirements, and require the test house to develop the system, then provide the details of the set-up for agreement

- Leak tightness measurements
  This section defines the leak tightness measuring requirements

- Photography
  This section defines what high quality still photographs should be taken before the test series (e.g. of the pristine test specimen), before each test (e.g. of the drop orientation), and after each test (e.g. of the damages). It also defines the high speed photography that needs to be carried out during each test, including the method of synchronising this with instrumentation measurements. The test specification should be specific about the views of the high speed photography

- Metrology
  This section defines the measurements that need to be carried out before and after each test, e.g. knockback measurements, indentation measurements, lid-body gap measurements, overall dimensional change, deformation of the punch, target

indentation and damage, etc. Again, the accuracy of these measurements must be defined and consideration given to the use of co-ordinate measuring machines and optical surface digitisation techniques

- Reporting
  This section defines the extent, scope and format of reporting required, including the need for reporting of results after each test

- Quality Assurance
  The test house must be required to prepare and submit a quality plan for approval. This should include a programme of work identifying individual tasks and their scheduling, hold points, detailed work procedures for the various tasks, details of the checks, inspections, reviews that will be carried out to confirm that the requirements have been met, details of any elements of work that will be sub-contracted and the controls that will be applied to the sub-contractor.

The test specification should also specify criteria which would govern/determine the need for the test house to re-do certain tests if these criteria are not met.

The test specification should request a methodology statement from the test house, of the way they plan to fulfil the requirements of the test spec. That is, how will they carry out what has been specified. This document must be submitted for agreement and no test or preparation should be carried out until agreement has been reached.

8 Test Reporting

The quality of the test report is of paramount importance as it may form part of the submission to the Competent Authority.

Consideration should be given to specifying a period of time, or a hold-point, in the programme during which information is reviewed and the programme held until agreement to proceed is given.

8.1 Reporting after each test

Within an agreed period after each test, the test house may be required to submit:

- Instrumentation results as follows, with format agreed between test house and owner of the test programme:
  i. raw unfiltered acceleration-time traces, strain-time traces and pressure record from each transducer
  ii. acceleration-time traces, filtered if necessary (filtering frequencies to be agreed between the test house and owner of the test programme)
  iii. for each accelerometer output, if required, a velocity-time trace of the impact event obtained by integrating the acceleration-time trace
  iv. for each accelerometer output, if required, a Fourier spectrum over a suitable frequency range to be agreed

- impact orientation, location of initial contact with the punch in the case of the 1m drops, and drop height actually achieved
- knockback and indentation on the target from 9m drops, and punch deformation in 1m punch drops
- high speed video footage and still photographs

The above requirements should be agreed with the test house prior to the commencement of the tests as this will affect the programme duration.

8.2 Final reporting

The tests must be reported in detail. Beside the results already reported after each test, the report may also include the following:

- description of the tests and actual test conditions achieved
- complete copy of all detailed work procedures
- description of the test apparatus
- measurement techniques
- description of test model behaviour during the event
- description of deformations and damages
- instrumentation results, both raw and processed
- leak tightness measurements
- bolt torque measurements
- metrology results
- photographic record and high speed video footage

All the results should be presented with sufficient text and diagrams to enable clear and unambiguous interpretation to be made. Comments should be provided on invalid data and their causes.

Instrumentation settings and technical specifications for all the instrumentation used shall be included in the appendices of the report. Calibration certificates for all the measuring equipment should also be included in the Appendix, or in the Quality Plan.

Instrumentation measurements, photographic records and high speed video footage should also be submitted as electronic files as part of the report, (format to be agreed between test house and owner of the test programme).

9 References

1. IAEA, Regulations *for the Safe Transport of Radioactive Material*, 2005 Edition, IAEA Safety Standards Series No. TS-R-1, 2005

2. IAEA, *Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material*, IAEA Safety Standards Series No. TS-G-1.1 (Rev. 1), 2008

3. TCSC, *Good Practice Guide - The Application of Finite Element Analysis to Demonstrate Impact Performance of Transport Package Designs*, TCSC 1087

4. Donelan PJ and Dowling AR, *The use of scale models in impact testing*, from the resistance to impact of spent Magnox fuel transport flasks, 1985

5. Quercetti T et al, *Comparison of experimental results from drop testing of a spent fuel package design using a full-scale prototype model and a reduced scale model*, Patram 2007, Miami, USA, 2007

6. Wille F et al, *Suggestions for correct performance of IAEA 1m puncture bar drop test with reduced-scale packages considering similarity theory aspects*, Patram 2007, Miami, USA, 2007

7. Neumann M et al, *Using scale model impact limiter in the type assessment of transport casks for radioactive material*, Patram 2007, Miami, USA, 2007

8. US Institute of Environmental Sciences and Technology (IEST), *Shock and Vibration Transducer Selection RP-DTE011.1*

9. TCSC, Leakage tests on packages for transport of radioactive materials, TCSC 1068

Appendix A
Drop Test Sites in the UK and major facilities in Europe

A list of drop test facilities within the UK and major facilities in Europe have been complied. This provides a brief overview of their testing capabilities. It is important to note that this is not an exhaustive list, but provides at a glance the recognised drop test sites used by the nuclear industry.

Sites

Drop test sites and their respective operators:

- Waste Management Technology, Winfrith, Dorset, UK
- Croft Associates Limited Didcot, Oxfordshire, UK
- Taylor Woodrow Technology, Leighton Buzzard, Bedfordshire, UK
- GE Healthcare Ltd, Amersham, Buckinghamshire, UK
- Gravatom Engineering Systems Ltd, Bishops Waltham, Hampshire, UK
- Defence Test & Evaluation Organisation, Shoesburyness, Southend On Sea, UK
- Health and Safety Laboratory, Buxton, Derbyshire, UK
- BAM, Horstwalde, Germany and Berlin, Germany
- TN International, Zi L'Ardoise, Laudun, France

Capabilities

Site	Country	Max Drop Height	Maximum Test Mass	Site Description
Waste Management Technology, Winfrith	UK	55m 10m	90t 200kg	700t target, 6x6m x 75mm steel plate, mobile crane, outdoor 1.6m x 1.6m x 50mm steel plate, mobile crane/guided, indoor
Croft Associates Limited, Didcot	UK	10m	5t	50t target, 2.5x3m x 50mm steel plate, mobile crane, outdoor
Taylor Woodrow Technology, Leyton Buzzard	UK	25m	20t	200t target, 3x3m x 60mm steel plate, mobile crane, indoor
GE Healthcare Ltd, Amersham	UK	10m	500kg	8t target, 1.5x1.5m x 50mm steel plate. Fixed platform, outdoor

Gravatom Engineering Systems Ltd, Bishops Waltham	UK	3m 9m	800kg 400kg	8t target, 2.4x1.2m x 40mm steel plate, 3m under crane (up to 6m using FLT) 8t target, 2.4x1.2m x 40mm steel plate, jib crane, outdoor
Defence Test & Evaluation Organisation, Shoeburyness	UK	25m	2500kg	50t target, 4x2m steel plate, rigid jibbed crane, outdoor
Health and Safety Laboratory, Buxton	UK	25m	15t	150t concrete block (4m x 4m x 3.8m deep) with a 4m x 4m x50mm steel target plate grouted to the surface and attached with 25-off pre-stressed steel studs each of 3.3m length. A punch of length 600mm is available for attachment to the plate centre or corners. Outdoor.
BAM, Horstwalde	Germany	30m	200t	14m x 14m x 5m reinforced concrete foundation with 10m x 2.5m x 0.22m steel plate on top. Total mass of target, 2630t. Indoor
BAM, Berlin	Germany	11m	5t	6m x 6m x 3m reinforced concrete foundation with 4m x 2m x 0.3m steel plate on top. Total mass of target, 280t. Indoor
TN International, Laudun	France	9m	10t	3m x 5m x 0.15m steel plate on a concrete slab target. Facilities available to cool test specimen down to -40°C

References

- Waste Management Technology, Winfrith, Dorchester, Dorset DT2 8DH. Tel: 01305 203324 Dr P Powell.

- Croft Associates Ltd, Drop Test Facility, Didcot. Tel: 01865 408640 Dr R A Vaughan.

- Taylor Woodrow Technology, Technology Centre, Stanbridge Road, Leighton Buzzard, Bedfordshire, LU7 4QH. Tel: 01525 859111. Mr N McDonald.

- GE Healthcare Ltd, The Grove Centre, White Lion Road, Amersham, Buckinghamshire, HP7 9LL. Tel: 01494 54 3443 Mr A Lewis

- Gravatom Engineering Systems Ltd., Bishops Waltham, Hampshire. Tel: 01489 897300 Mr G Holden.

- Defence Test and Evaluation Organisation, Shoeburyness, Blackgate Road, Southend On Sea, Essex. Tel: 01702 292 271 ext. 3596 Mr C Lincoln.

- Health and Safety Laboratory, Harpur Hill, Buxton, Derbyshire SK17 9JN. Tel: 01298 218240 Dr Michael Stewart

- BAM, Unter den Eichen 44-46, D-12203 Berlin, Germany. Tel: +49 30 8104-1331, Dr.-Ing. Karsten Müller, e-mail: Karsten.Mueller@bam.de

- TN International Laudun test facility, Zi L'Ardoise, 30290 Laudun, France. Frédéric Patalagoïty, e-mail: frederic.patalagoity@areva.com and Gwenaël Mauras, e-mail: gwenael.mauras@areva.com

Appendix B
Test Instrumentation

B.1 Accelerometer Specification

Aspects to consider in choosing an accelerometer are:

- peak acceleration values
- length of impact pulse (secs)
- frequency range of interest
- mounting considerations[1]
- cable length between the accelerometer and the logging equipment
- environmental conditions (humidity, dirt and dust etc.)
- accelerometer robustness (survivability)[2]
- resonant frequency of the accelerometer[3]

Two basic types of accelerometer are most commonly used for shock measurement[4]:

- piezoresistive accelerometers
- piezoelectric accelerometers

Piezoresistive accelerometers usually consist of a silicon strain gauge (a wheatstone bridge of resistors) bonded to an inertial mass. The majority of piezoelectric accelerometers use ceramic sensing materials, and there are two designs: one design has a charge amplifier external to the accelerometer which takes the electrostatic charge (via a cable) from the accelerometer, and converts the signal to a usable voltage for logging purposes. The other type has the amplifier built in to the accelerometer, and converts the charge from the sensing element into voltage signal within the accelerometer itself (integral electronics piezoelectric (IEPE)).

A list of advantages and limitations of piezoresistive, and the two types of piezoelectric accelerometers is shown in Table B1. Manufacturers should be aware of the technical limitations of each type of accelerometer, and design modifications have been applied to reduce these limitations in some cases. The more information provided to the suppliers on the above bullet points, the better the chance of getting the most suitable type of accelerometer for the test programme.

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[1] High frequency response is affected by the mounting method. Rigid stud mounting is the only reliable method for measurements above 10kHz. Silicon based grease can be used between the accelerometer and mounting surface to improve the bond (ref Endevco TP 291).

[2] In high shock loads, physical damage to the sensor can occur. If possible, over-estimate the maximum shock level when selecting the range of a shock accelerometer

[3] If the shock pulse is analysed in the frequency domain, and considerable frequency content is found above one-fifth of the accelerometer’s resonant frequency, the accelerometer is probably operating outside of its flat frequency response range, and errors will exist in the measurement (ref PCB Piezotronics Technical Note 24).

[4] There are other types of accelerometers such as variable capacitance and servo accelerometers but these are not normally used for shock measurements

Table B1 - Advantages and Disadvantages of Accelerometer Types		
High impedance Piezoelectric Accelerometers	**Low Impedance (internal amplifier) Piezoelectric Accelerometers**	**Piezoresistive accelerometers**
Can measure to low frequencies but not 0 Hz	Can measure to low frequencies but not 0 Hz	Can measure down to 0 Hz (DC).
More at risk of signal corruption in contaminated environments and from electrical and RF interference	Better system reliability	Better system reliability
Requires additional charge amplifiers which adds cost	Amplifiers built in to the accelerometers	
No external power supply needed	Requires an external power supply (normally constant current)	Requires an external power supply (normally constant voltage)
Capacitive effects from accelerometer and cable increases noise and reduces resolution	Can drive long cables without significant noise increase or loss of resolution [7]	Can drive long cables without significant noise increase or loss of resolution[5]
Can be interchanged in existing systems	May not be interchangeable if power requirements are different between accelerometers	May not be interchangeable if power requirements are different between accelerometers
Needs special purpose low noise cable	Uses standard coaxial cable or ribbon wire	Uses standard coaxial cable or ribbon wire
Can be prone to temporary DC shift if the shock signal contains a significant amount of high frequency	Can be prone to temporary DC shift if the shock signal contains a significant amount of high frequency	DC shift not normally a problem. If it does occur, it is an indication the accelerometer is permanently damaged.
		Has a higher resonant frequency than piezoelectric accelerometers. However, if the resonant frequency is excited (e.g. very high, transient decelerations above the range for the accelerometer) it can permanently damage the accelerometer

[5] If the cables are very long and changes in cable resistance with temperature during the test programme are likely to be significant, a system requiring a constant current power supply will be less affected by these variations.

B.2 Obtaining velocity-time and displacement-time data from the acceleration measurement

An approximation of the velocity time history (*v(t)*) could be obtained from the acceleration using the equation

$$v(t) = \int a(t)dt + C_1 \text{ (m/s)} \quad (1)$$

where C_1 is a constant of integration. As the deceleration event begins at the point of impact, C_1 is simply the velocity at this point, which can be calculated from

$$C_1 = \sqrt{2gh} \text{ (m/s)} \quad (2)$$

where *g* is acceleration due to gravity (m/s^2)
h is the drop height (m)

The displacement (*d(t)*) is obtained from velocity

$$d(t) = \int v(t)dt + C_2 \text{ (m)} \quad (3)$$

C_2 is a second constant of integration. However, by assuming displacement is zero at the point of impact, C_2 is zero.

Although the integration can be done relatively easily post-test, it is essential to have an acceleration signal with good resolution and low noise, and it must be free of DC shift. This will not be known for certain until after the test has been carried out. If a piezoelectric accelerometer is going to be used, care should be taken to ensure it is suitable due to its limitations in measuring DC deceleration.

B.3 Obtaining the drop height from the acceleration data

Although drop height is normally determined by a tag line attached to the package, it can also be estimated from an accelerometer as a check.

To obtain the drop height from the acceleration measurement, triggering on the data acquisition system must start at or before the release. The time taken from the release to the impact is obtained from the measurement, and the drop height can be obtained from the equation

$$h = \frac{1}{2}gt^2 \quad (4)$$

t is the time obtained from the data acquisition system between release and impact (secs)

The Data Acquisition system has to be sensitive enough to measure the 1g change in acceleration signal as the package starts to fall, and the acceleration at impact, which could be many thousands of g. So logging data on two different amplitude ranges may be necessary.

It should be possible to use a piezoelectric or piezoresistive accelerometer for this task as both should register a 1g change at the point the package is released[6]. However, discuss this with the supplier as they often recommend different types of accelerometer for sensing motion, and for measuring shock. Shock accelerometers are low sensitivity so a 1 g change in acceleration will need amplification to be detected on the Data Logger. Also, background noise levels could mask the signal.

If the distance the package 'bounces' after impact is to be assessed, then the accelerometer must have a DC response (piezoresistive) (ref Endevco TP 321 *Acceleration levels of dropped objects*).

B.4 Signal Filtering, Sampling and Analogue to Digital Conversion

The main aim of filtering the signal is to remove high frequencies that introduce errors. Anti aliasing filters are normally required for this task. Also, higher frequencies may contain more unwanted noise components. If integration to obtain velocity is proposed, then anti-aliasing filters are probably essential.

A realistic high frequency limit of 20kHz for acceleration measurements has been suggested in PCB Technical Note 25 *How high in frequency are accelerometer measurements meaningful?*[7] Many Finite Element software packages have filters in the post processing software that can be used to filter the measured data. So both test measurements and analysis results are filtered using the same filters.

Digital sampling of data requires a minimum of two samples per cycle for a sine wave to preserve its frequency content[8]. However, for more accurate knowledge of the sine wave (e.g. knowledge of its peak value) then frequency sampling should occur at not less than ten equally spaced intervals/cycles. This ensures that the peak error is no greater than 5%. So sampling rates should be a minimum of ten times faster than the highest frequency of interest.

In the Data Acquisition system, the analogue input voltage is converted to a digital number. The accuracy of this number is dependent on the 'bit rate'. For example, a resolution of 12 bits can 'encode' the amplitude of an analogue input at 2^{12} different

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[6] The difference is that the piezoresistive accelerometer will show a 1g step change in acceleration at the point of release that remains constant after release. The piezoelectric accelerometer signal will show a 1g change at the point of release, but the signal decays back to zero

[7] Reasons are: **1**. Accelerometer performance above 20kHz is currently precluded in National systems of calibration standards. **2.** Structural modelling of drop test packages to very high frequencies becomes increasingly inaccurate and therefore cannot be used confidently to compare with measured data with confidence. **3.** The physical size of the accelerometer is significant compared with the wavelength and begins to provide a spatial average of the structural response rather than a 'point' acceleration value. **4.** At very high frequencies, the physical presence of the accelerometer modifies the response of the structure

[8] Based on the Shannon theorem. Sampling that satisfies this theorem is referred to as Nyquist sampling (ref PCB Technical Note 25)

levels = 4096. A low 'bit rate' can introduce integration errors when obtaining velocity and displacement. 12 to 24 bit are typical of the amplitude resolutions with modern data loggers and should be acceptable for most drop test work.

B.5 Accelerometer Calibration

Accelerometers are typically calibrated across a frequency range of 10Hz to 10kHz using an electro-dynamic shaker driven by a sinusoidal vibration that is 'swept' through the frequency range. The vibration amplitude is in the order of 10g.

However, this is not adequate for complete calibration as shock accelerometers are low sensitivity devices designed to measure in the 'thousand g' range. Therefore shock calibration techniques such as the 'hopkinson bar' and pneumatic exciters have been developed to apply a calibrated shock pulse typically in the 1000 to 10,000g range. This covers the likely measurement range in drop testing. The techniques are described in ISO 16063 *Methods for the calibration of vibration and shock transducers.* The calibration test house should be able to demonstrate competence in carrying out calibration work as described in BS EN ISO 17025 *General requirements for the competence of testing and calibration laboratories.*