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Division V

FULL-SCALE DROP TESTING WITHIN THE SAFETY EVALUATION OF A PACKAGE FOR RADIOACTIVE WASTE

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ABSTRACT

Packages for the transport of radioactive materials shall fulfil the requirements of the IAEA regulations for the safe transport. The requirements define mechanical and thermal test conditions including criteria ensuring the package design's ability to withstand severe accidents and provide a high level of technical safety. Different methods can be used for safety demonstration showing compliance with the regulations.

The central part of a safety demonstration which is presented in this paper was a comprehensive drop test program with a full-scale model of a transport package accompanied by pre- and post-test FE analyses. Using full-scale drop test models allow the benefit that similarity and scaling issues become a significant smaller issue, additional material investigations can be limited and analyses for transferring test results to the original package design are reduced. Additionally, experience for the future serial packaging manufacturing and handling procedures can be collected in a very early state of the design approval process. The pre-test finite element analyses derived and justified the drop test program consisting of several drop sequences with different drop orientations of the specimen. The performance and the results of the drop test sequences shows the manageability and the advantage e.g., in view of the direct availability of test results for the package licensing. On the other hand, the drop test performance shows the difficulties during handling and the need for additional equipment during preparation of the specimen.

The package presented was intended for the transport and storage of compacted radioactive waste from reprocessing of spent nuclear fuel assemblies - designed and applied for approval by the AGC consortium. The project ended in 2021. The package design was characterized by a cask body made of a forged thick stainless-steel shell, a bolted double lid system with metallic gaskets and wood filled shock absorbers at both ends. The total mass of the entire transport package including content was 120.000 kg, the total length was about 7000 mm and the diameter approximately 3000 mm, both measures include the shock absorbers.

The paper provides an insight into the performance of a full-scale drop testing campaign within the package safety evaluation and shows some selected test results.

INTRODUCTION

Packages for the transport of spent nuclear fuel or high-level waste shall fulfil the requirements of the IAEA regulations (IAEA, 2018) for the safe transport. The requirements define mechanical and thermal test conditions including criteria, which ensure the package design's ability to withstand severe accidents and provide a high level of technical safety.

Over recent decades the Bundesanstalt für Materialforschung und -prüfung (BAM) developed test and measurement concepts and performed fire and drop test campaigns with accident safe package types. The tests are part of the package licensing procedures. One of the last campaigns which ended in 2021 was the investigation of a package design for the transport and storage of compacted radioactive waste, which results from the reprocessing of spent nuclear fuel assemblies. The cask consists of a forged thick stainless-steel cylindrical shell with a welded bottom. The complete containment is built by a bolted double lid system with metallic gaskets. The cask is equipped at both ends with shock absorbers (aluminium/steel/wood sandwich construction) for protection against mechanical loads mainly in accident conditions. The total mass of the entire transport package inclusive the radioactive content is about 120.000 kg, it has a total length of about 7000 mm and a diameter including shock absorbers of approximately 3000 mm. The package was designed and applied for licensing by the AGC consortium.

The central part of the safety demonstration of this package type was a comprehensive drop test program with a full-scale model. This paper provides an insight into the safety evaluation concept and the reasoning why in some cases it makes sense to perform full-scale test and what the advantages in comparison to small-scale tests are.

PACKAGE SAFETY EVALUATION CONCEPT

Scale Model or Full-Scale Testing

In principle the IAEA regulations (IAEA, 2018) allow both, small-scale and full-scale testing to show an appropriate level of safety of the package and the fulfilment of the requirements. If scale models are used, the adjustment of certain properties of the specimen and the test parameters has to be considered. Additionally, the pre-test calculations and the derivation of appropriate model parameters, e.g., gaps, tolerances, scaled dimensions, specific component behaviour, and test configuration (Wille, 2007; Wille, 2015) are influenced by the proper application of similarity theory. But not every parameter and material or component behaviour is scalable, e.g., gravitation, complex components as like metallic gaskets or casted components.

To get the similar mechanical response of the full-scale and the small-scale model all general principles of similarities, i.e., geometric, kinematic, dynamic, gravitational, and material similarities have to be taken in account. But it is impossible to consider all similarities in one model. For example, there is an incompatibility of geometric, dynamic, and material similarities in view of the impact time and the strain rate effect. In general, leakage rates of scaled containment systems are not scalable with typical methods. Therefore, the IAEA (IAEA, 2012) advises: “In many cases, it may be simpler and less expensive to test a full-scale model rather than to use a scale model or demonstrate compliance by calculation and reasoned argument.”

Another important point is that full-scale testing improves the public acceptance of nuclear related technical solutions. In addition, the package manufacturer can develop and verify manufacturing and inspection methods from the beginning of the licensing procedure on. The methods used for the full-scale model are the same or easier transferable to the original package design.

Mechanical Evaluation Concept

The IAEA regulations (IAEA, 2018) define in para 104 four measures for ensuring the safety objectives: containment of the radioactive contents, control of external dose rate, prevention of criticality and prevention of damage caused by heat.

Experience and reasoning lead to certain assessment objectives for accident conditions of transport, which typically include:

- closure system including lids, lid bolts, gaskets, and flange
- shell performance
- welding seams
- shock absorber performance incl. different temperatures
- basket and content behaviour
- shielding components
- interactions such as internal impacts.

The most severe mechanical loads for these components result from the IAEA test conditions according to para 727: Test sequences consisting of 9-m drop tests onto an unyielding target and 1 m puncture bar drop tests. The drop test orientations to be tested are, considering the specific package construction, derived by reasoning, deduction and most important, a set of pre-test calculations.

A full-scale model cannot be conservative in every regard of the assessment objectives. Therefore, similarity evaluations are performed to directly demonstrate the serial package design performance with the results of the drop testing. These evaluations include effects of temperature, gaps, material properties, bolts, and the gasket behaviour – all considering the mechanical performance and the general leakage rate. The above-mentioned assessments lead to a drop test model in a specific condition and a set of drop test sequences with different drop orientations (slap down, oblique drop etc., drop test model characteristics, e.g., adjusted shell, lid and bolt properties, conservative axial, and radial lid gaps) and drop model temperatures (from -40°C till maximum package operating temperature). The measured leakage rate shall then be conservative for the serial package design.

Pre-Test Analyses

Multiple calculation variants or variations for each drop test are performed during the pre-test analyses. The aim is to evaluate the most penalizing drop position and configuration of the mock-up for the experimental drop test program. In this context it is required to model the package sufficiently with an appropriate numerical method. Here, the use of explicit dynamic finite element (FE) analyses as provided by the commercial FE-codes LS-DYNA and ABAQUS/EXPLICIT is well established. These calculations allow the approximation of the impact event with the whole package (Figure 1).

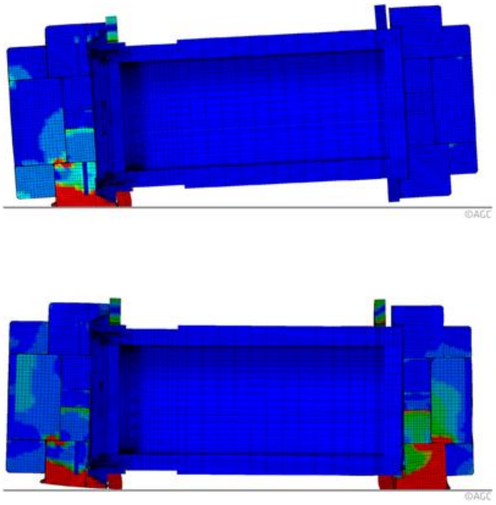

Figure 1. FE analysis of the package in a 9-m slap-down drop (source: AGC)

The calculation variants to be examined depend on the specific drop test position and its goal in the assessment strategy. For example, the most severe transversal loads on the lid system in the campaign presented, result from a 9-m lateral drop with a slight angle, the so-called slap down. Here the variation of the drop angle in multiple calculations helps to identify the severe drop test position.

The consideration of tolerances in manufacturing and the material behaviour is another issue for the pre-test calculations. Manufacturing tolerances, e. g. gap sizes, are usually included by calculations variants with minimum and maximum gap sizes. Variants with minimum and maximum material properties are used to cover material uncertainties. An equivalent approach is used for friction coefficients and bolt pretensions. Here one should keep in mind that each additional aspect doubles the total number of calculation cases. Consequently, it is useful to reflect, if some of the variants can be neglected or may be linked together. A common example in this context is the link assumed between the friction for a bolt connection and resulting the pretension of the bolt. It is usually expected that the maximum friction results in the minimum pretension of the bolt and vice versa.

Since the pre-test analyses serve the definition of the boundary conditions for the experimental drop tests one should keep in mind that possibly not all assessment objectives can be addressed equally within a drop test. For example, one certain configuration with specified gap sizes and bolt pre-tensions can lead to maximized bolt loads, whereas another configuration may result in maximized lateral lid displacements. Since both issues can be relevant for the approval strategy one has to decide which assessment aim should be focused for the experimental testing. Additional post-test analysis may be required to cover the remaining issues. It should be emphasized that full scale drop tests are usually more extensive than physical tests with scale models. Consequently, the number of drop tests shall be kept to a minimum required.

The pre-test analyses for 1-m puncture bar drops shall also consider the position of the puncture bar under the package and therefor the impact target at the package. Common target areas are the lid system and the protective covers for the orifice lids.

The drop test model does not comply with the serial package design completely as already mentioned in the previous paragraph. Consequently, additional pre-test calculations comparing the serial package design and the drop test model are required to ensure that a selected drop test covers the possible equivalent serial cask configurations.

In summary, the pre-test calculations performed for the campaign presented were rather extensive, but they lead to the development of a comprehensive drop test program with well-defined assessment aims for each drop sequence, which is described later in this paper.

Post-Test Analysis

Post-test analyses may be required to assess specific questions which are not or cannot be addressed in the drop test program. Such a question may e. g. result from the decision that another issue is prioritized for the physical testing. Additionally, there are some assessment properties which can hardly be measured during the drop tests. For example, the irreversible openings of the lid system in the sealing area are usually derived numerically and the values are used to estimate the cumulative openings of the drop sequences and the thermal test. This value is required for the activity release calculation.

It was also decided to assess the impact of the trunnion and loads of the shell-bottom-welding by post-test analyses. Generally, the confidence about the plausibility of post-analyses is required. This can be achieved by comparing the numerical calculations with the drop test results. The extent of the plausibility testing is usually seen in the context of the specific questions of approval.

DESCRIPTION OF THE FULL-SCALE SPECIMEN

One full-scale drop test specimen and a dedicated set of impact limiters and waste canisters for each sequence was manufactured according to the relevant manufacturing system in Germany for packages for the transport of radioactive material (BAM-GGR 011, 2018). The specifications for serial package designs include masses, geometrical dimensions, and relevant material properties. Therefor the full-scale drop test specimen was – with certain adaptions – in general compliant with the specification of the serial cask design. These include among others basket, gaskets, canisters, resin, and trunnions.

Adaptions are integrated where specific assessment objectives are concerned: The shell and the lids were manufactured using a steel with lower mechanical properties (yield and ultimate strength), therefore maximising possible plastic strains. For primary and secondary lid bolts the last heat treatment step was omitted for reducing the yield strength and therefore maximising the lid opening relevant for leak tightness. Tolerances for manufacturing of lids were adjusted to maximise or minimise radial and axial gaps in the lid region. The wood for the shock absorbers was sorted into hard and soft – at the lower or upper boundary limits regarding mechanical performance for the serial cask design, dependent on the assessment objective. Certainly, the content of the canisters was not low-level radioactive waste, but a substitute made of steel. Additional adaptations such as grooves for instrumentation of the model were also performed.

The total mass of the full-scale model was above 120.000 kg, it had a total length of about 7000 mm and a diameter including shock absorbers of approx. 3000 mm. Figure 2 shows a schematic view of the package design.

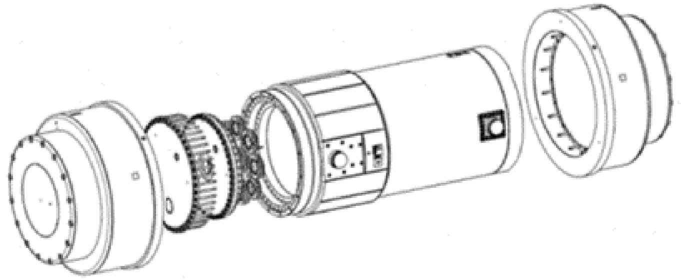

Figure 2. Schematic view of the package design

DROP TEST PROGRAM

The drop test program includes in total four separate drop test sequences. Each sequence consists of a 9-m free drop test followed by a 1-m puncture bar drop test with different and most penalizing drop orientations of the test specimen in accordance with the IAEA regulations (IAEA, 2018). In each test sequence, the test specimen is equipped with new shock absorbers. Further metal seals and bolts of the closure lids, the basket and the internal canisters are renewed. After each drop test sequence, the specimen was nearly completely disassembled and re-assembled for the next sequence.

The first drop test sequence, performed by BAM in autumn 2019, is schematically shown in Figure 3. The sequence consisted of a 9.3-m drop test with a 4 degrees inclined lateral drop orientation of the mock-up causing a slap-down impact on the top shock absorber. This test was followed by a 1-m horizontal drop on a puncture bar striking the mock-up laterally in the plane of the sealing surface of the secondary lid. The tests were performed under ambient temperature conditions. The aim of the drop test sequence was the maximum damage of the closure lid system due to a maximum possible lateral movement of the lids with a subsequently demonstration of the leak tightness of the mock-up in accident and normal conditions of transport.

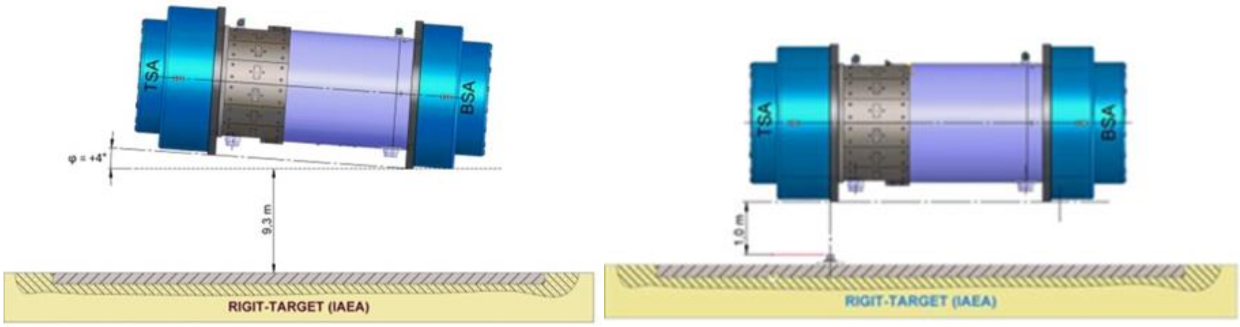

Figure 3. First performed drop test sequence including a 9.3-m free drop test followed by a 1-m puncture bar drop test (source: AGC).

Other examples from the drop test program are the 9-m vertical drop test with the mock-up's lid system downwards onto the top shock absorber under minus 40 degrees Celsius temperature conditions. Further, the 9-m oblique drop test also with the lid system downwards in the impact zone under plus 70 degrees Celsius temperature conditions for the impacting top shock absorber. Each test is combined with a relating 1-m puncture bar test within a test sequence. The aim of the vertical drop test is to obtain a maximum axial impact loading at the lid system, also by internal impact of the content (Ballheimer et al., 2018), also in this case with a subsequently demonstration of the leak tightness of the mock-up. Due to the cooling of the top shock absorber to minus 40 degrees Celsius a minimal deformation of the shock absorber during the impact is expected with a maximum deceleration and impact loading, respectively. The aim of the oblique drop test with an angle of 30 degrees is to evaluate the fixation of the top shock absorber.

The drop test program comprised an extensive measurement program before, during and after each drop test and drop test sequence, respectively. Besides strain and acceleration measurements at the mock-up various other measurements as leak testing, digital optical measurements, high speed video, etc. were used.

In order to answer questions in regard to the structural integrity of the mock-up and the behaviour of the components (e.g., shock absorbers, closure lids, lid bolts) under impact conditions, strain and acceleration measurements are generally performed during the drop tests. For each drop test specific measuring points are activated relating to the safety criteria to be evaluated. The acceleration measurements provide characteristics of the mock-up response to impact in form of continuous acceleration-time histories at the monitored locations. From the analysis of this data, the rigid-body impact acceleration, rigid-body impact kinematics (velocity- and displacement history), impact duration, vibration frequencies and response spectra can be derived. Strain measurements provide continuous strain-time histories determining the structural response of the mock-up at the monitored locations (e.g., cask, closure lids, lid bolts, contents, etc.). The acceleration and strain measurements constitute the main basis for the validation of assumptions in the mechanical package safety analysis and for the evaluation of relating finite-element calculations (Quercetti, 2009).

For the first drop test sequence, the mock-up was instrumented with in total 18 units of three-axial foil strain gauges at the cask and the secondary lid to determine the principal strain/stress histories and their belonging directions. Additionally, six lid bolts of the secondary lid were instrumented with each four uniaxial strain gauges to determine the pretension after tightening and the remaining pretension after the drop test. Further, bending strain and normal strain-time histories during the impact were intended to be measured. In summary, the first drop test sequence was performed with 78 pieces of single strain gauges and 10 units of three-axial accelerometers occupying a total amount of 108 measuring channels.

The strain gauges are connected in a three-wire Wheatstone Quarter-Bridge circuit, a commonly used technique in experimental stress analysis – the piezoresistive accelerometers in a corresponding six-wire circuit (Quercetti, 2009). A terminal merges all cables coming from the sensors at the exterior long side of the outer cask body. This terminal is connected by means of 50 m long and shielded measuring cables to the data acquisition systems where the sensors are connected to wideband differential bridge amplifiers. The transient recording was done with a sampling frequency of 400 kHz for each channel and a digital 24-bit vertical resolution was applied.

After each drop test sequence, leak tightness testing of the closure lid system is performed. Both lids, the primary and secondary are sealed against the cask body flange by metallic O-rings. The leak tightness of each barrier is determined by measurement of its helium leakage rate according to the relevant ISO (DIN EN ISO 20485, 2018) using a helium leak detector. Therefore, a sealed cavity for the inner and outer side of the metallic O-ring is needed. For the leak measurement one cavity must be evacuated and the other must be filled with helium under well-defined partial pressure. The helium leak detector is connected to the evacuated cavity.

In order to get detailed information about the complex geometry changes of the shock absorbers due to impact, they were geometrically measured by the 3d-fringe projection method (Gründer, 2008). A further important result of the drop tests, especially of the 9.3-m slap-down drop test was to determine the possible lateral displacement of the closure lids. Lid sliding, mostly caused in drop tests by horizontal or slightly inclined drop orientations can often not be perfectly excluded by the cask design and is able to effect a change of the leakage rate. Here, in order to determine a lateral displacement, the method of the close-range photogrammetry was used by measuring the position of the lid relating to the cask body's flange area.

Another important aspect of the drop test program and test performance is the handling of the mock-up. The drop orientation of the mock-up which is defined by its impact point and impact angle is usually derived from the requirements of maximum damage regarding the safety criteria to be reviewed (IAEA, 2018). Complex handling operations are required for the exact positioning of the 120.000 kg mock-up into the drop orientation which is defined in the drop test program by the drop angle. These handling operations have also to be seen under the aspect of current working safety regulations. In the case of the 9.3-m drop test for example, the mock-up had to be rotated by 4 degrees. This was done by a specially built heavy steel frame, the handling frame with an inner turning device, a steel basket which takes the test specimen. This construction allows tilting the cask axially for inclined drop positions. Figure 4 shows the mock-up lying in the turning device of the handling frame in the moment of rotation. Various other types of handling devices are necessary to supply the different drop positions, but also to perform the related drop tests themselves and for all the other assembly work which has to be done at the mock-up such as assembly/disassembly of shock absorbers, lids, basket, contents, etc.

Figure 4: Positioning of the test specimen into a horizontal 4° drop orientation with a handling device

The drop tests were performed at a 200-tons drop test facility located at BAM's Test Site for Technical Safety (BAM TTS) near Berlin. The unyielding impact target of the drop test facility is built according to the IAEA regulations (IAEA, 2018).

The target is built of a reinforced concrete block with the geometrical dimensions 14m x 14m x 5m and an embedded steel plate as impact pad. This 220 mm thick, 4.5 m wide and 10 m long steel plate is form- and force-fitted fixed with 40 pieces of M36 anchor bolts to the concrete block. The total mass of the target is 2,600,000 kg.

The punch targets are also built-in correspondence to the IAEA regulations as a bar of circular section with a diameter of 150 mm and an edge radius of 6 mm at his upper end (IAEA, 2018). The bars are connected rigidly and perpendicularly to the IAEA-target using a mounting plate which again was welded to the steel impact pad. Then, the punch bar was screwed into the thread in the middle of the mounting plate until the lower end contacts the IAEA-target and finally fixed by welding spots (Scheidemann, 2018).

The drop tower, a 36 m high steel frame construction, is placed above the assembling hall on four separate pile foundations. The hoist is located in a height of 33 m with a lifting capacity of maximum 200,000 kg (Müller et al., 2004). The release of a specimen is performed by momentum free working release systems. Here, an electro-hydraulically working system for masses up to 200,000 kg was used.

RESULTS OF THE FIRST DROP-TEST SEQUENCE

In the following, some selected experimental results from the first drop test sequence are presented. The photos in Figures 5 and 6 show the test specimen directly before and after the drop test. The shock absorbers deformed in the regions of the directly impact areas according to their defined function absorbing the impact energy. They avoided any contact of the trunnions with the impact target (Figure 5) and protected the lid region in the puncture bar test (Figure 6).

One of the main objectives of this drop test sequence was to demonstrate the integrity of the mock-up and its safety against release of radioactive material. Pertaining to the accumulative loading from the 9.3-m and 1-m drop test within the drop test sequence, the measurements of the leak tightness of the lid showed no change of the standard helium leakage rates at all between the values determined before and after the drop test sequence. The first tests proved the required leak-tightness of the mock-up closure system.

Figure 5. Test specimen ready for the 9.3-m free drop test and after the 9.3-m drop test (source: BAM)

Figure 6. Test specimen ready for the 1-m puncture bar drop test and after the 1-m puncture bar drop test (source: BAM)

The kinematic behaviour of the cask during the drop tests could be determined by analysing data from accelerometers. In the 9.3-m declined drop test, the test specimen showed the typical kinematic behaviour of a slap-down with an increasing impact velocity of the secondary impacting end (Quercetti et al., 2002). After a primary impact onto the test specimen’s bottom shock absorber, the specimen is set into rotation which causes a secondary impact to the top sided shock absorber and the lid side, respectively. The diagram Figure 6 shows the measured and low-pass filtered deceleration-time histories of the test specimen bottom (dashed curve) and top side (continuous line) as well as the related velocity-time curves during the impact. The curves show the acceleration of the specimen’s top side during rotation from an initial velocity due to the 9.3-m free fall (13.5 m/s) to a significantly higher impact velocity with a subsequent deceleration of the top side caused by the secondary impact.

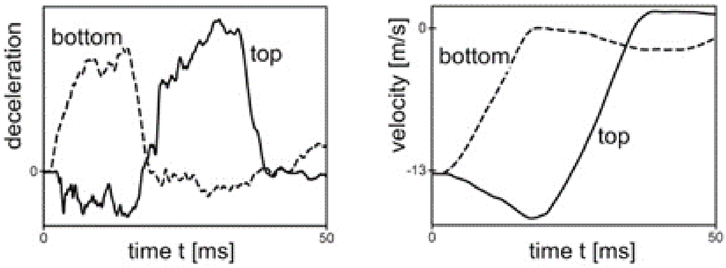

Figure 6. Deceleration and velocity time histories (source: BAM)

CONCLUSION

Packages for the transport of radioactive materials shall fulfil the international IAEA regulations. The regulations define requirements and criteria and specify the mechanical and thermal test conditions. Different methods are allowed for the test performance in order to demonstrate compliance with the regulations. The safety evaluation concept containing physical testing with a full-scale model and pre- and post-test analyses were introduced for the specific licensing procedure of a waste package design. In this case the use of a full-scale drop test model has several advantages. Similarity and scaling issues do not occur, additional material investigations can be limited and analyses for transferring test results to the original package design are reduced in number and complexity. Additionally, experience for the future serial design manufacturing and handling procedures can be collected with the test model in a very early state of the approval process.

The pre-test finite-element analyses derived and justified the drop test program consisting of several drop sequences. At the same time the analyses are the basis for comprehensive post-test analyses to cover the complete safety requirement parameter field.

The performance and the results of the first full-scale drop test sequence show the manageability and the advantage e.g. in view of the direct availability of test results for the package licensing. On the other hand, the drop test performance shows the difficulties during handling and the need for additional equipment during preparation of the specimen.

Discussions with the public underline that among all technical advantages and disadvantages of full-scale testing, the performance of physical tests with a specimen in original size improve the public understanding and acceptance of the safety of packages for nuclear material.

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