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Drop Testing of a New Package Design for the Transport of SNF from German Research Reactors

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Abstract

A new dual purpose cask design was developed for the safe transport and interim storage of spent fuel elements of German research reactors. In the framework of the safety assessment within the package approval procedure the Bundesanstalt für Materialforschung und –prüfung (BAM) as competent authority performed a series of drop tests according with the IAEA Transport Regulations.

The package consists of a cylindrical thick-walled ductile cast iron cask body closed by a bolted lid system with metallic seals. A lid and bottom sided impact limiter consisting of a wood/steel construction limit the mechanical impact loading. The full-scale test specimen was equipped with a basket and assembled with dummy-fuel elements. The package and test specimen, respectively have a total mass of approximately 24 metric tons.

The mechanical drop test program included three 9m free drop tests, in horizontal, vertical and oblique cask orientation onto the lid system. Additionally, a 1m-puncture bar drop test followed the horizontal drop test to consider an IAEA-drop test sequence. The horizontal and vertical drop tests were performed at a temperature of minus 40°C. During the oblique drop test the upper impact limiter was heated up to +80°C. The tests were conducted onto an unyielding target, fulfilling the IAEA requirements.

The test specimen was considerably instrumented with strain gauges and accelerometers. Transient strains at selected locations of the inner and outer container walls, of the primary and secondary lid, as well as of the corresponding lid bolts were measured during the drop tests. Furthermore, decelerations in different locations at the cask body and the lids were measured. The complex geometrical deformation of the impact limiters due to the impact were determined by optical 3D-measurements. Before and after the drop tests the leakage rate of the lid system was determined by helium leakage testing.

The experimental results contribute to the evaluation of the package response to mechanical tests, demonstrating safety under normal and accident conditions of transport and especially to the verification of the dynamic finite-element model of the package used in the package design safety report.

Introduction

In the framework of the German transport approval procedure for a new dual purpose cask CASTOR® MTR3 BAM performed drop tests with a full scale model of the cask. The corresponding test program was submitted by the applicant and assessed by BAM according to the IAEA Regulations [1].

The thick-walled cask was designed by Gesellschaft für Nuklear-Service mbH (GNS) for the transport and interim storage of spent fuel assemblies from German research reactors. It is of cylindrical shape and equipped with a double lid system. The basket is loaded with five spent fuel assemblies. Two impact limiters at each end of the cask shock limit the mechanical loading of the containment under normal and accident conditions of transport.

The drop tests were performed to prove the leak-tightness of the package containment and the functionality of the fastening system of the impact limiters. Furthermore, the acceleration and strain signals measured during the tests were the basis for the verification of the analytical and numerical models used for the safety analyses of the package design [2]. According with the maximum loads which were detected in the pre-calculations for the package and its components, four drop test configurations were derived for the test program. These drop tests differ in drop orientation, test temperature and package configuration. Two of them were performed as an IAEA drop test sequence.

Dependent on drop orientation and the occurring loads different measurement methodologies are used to characterize the mechanical behavior of the package and its structural integrity. The test specimen was instrumented with strain gauges and acceleration sensors. These measurements were complemented by optical measuring systems to analyze the impact events and the deformation of the packages components. The integrity of the cask before and after each drop test was evaluated by helium leakage testing.

Regarding the verification objectives within the approval procedure the measurement results were analyzed and compared with the analytical and numerical calculations of the package. The experimental results support the safety assessment under normal and accident conditions in the design safety report.

Strategy for Safety Assessment

In the safety analyses of the package design a combination of experimental testing and calculations were applied for demonstrating the design safety under normal and accident conditions of transport [2]. Two tests were carried out as a full IAEA drop test sequence consisting of a 9m-drop test onto an unyielding target and a 1m-puncture bar drop test. The other two drop tests were performed as single 9m-drop tests and completed by additional analyses in order to consider the effects of an IAEA drop test sequence. Further details of the assessment strategy are described in [13].

Drop Test Program

The program of the mechanical testing included four drop tests. Two tests were conducted as a drop test sequence consisting of a 9m horizontal drop test onto an unyielding target and a 1m-puncture bar drop test.

Furthermore, a 9m vertical and a 9m oblique drop test, each onto the lid sided impact limiter, were conducted. The test specimen was equipped with a new impact limiter system for each single drop test and sequence, respectively. The metal seals and the screws of the entire lid system were also renewed. In the following the setup parameters of each drop test and the configurations of the test specimen are described:

9m-horizontal and 1m-puncture bar drop test

These two free drop tests were performed as an IAEA drop test sequence (Figure 1). The test specimen which was previously damaged by the 9m-horizontal drop test was used for the puncture bar drop test with a drop height of 1m. The drop height was measured in each case from the upper surface of the target to the lowest point of the impact limiter. The sequence was set to cause maximum damage to the test specimen regarding the objectives of the test.

Regarding the material properties of the cask body and the wood filled impact limiters the test specimen was cooled down to the minimal design temperature of -40°C. Maximum lateral displacement was expected for the lids in the horizontal drop test.

The puncture bar drop test was performed at ambient temperature of the package. The puncture bar was positioned in a way that the lid edge laid in line with the edge of the puncture bar. The impact zone of the horizonal orientated test specimen was located radial in the area of the lid system. The height of the bar, made of mild steel, was determined analytically in advance and is described in [3].

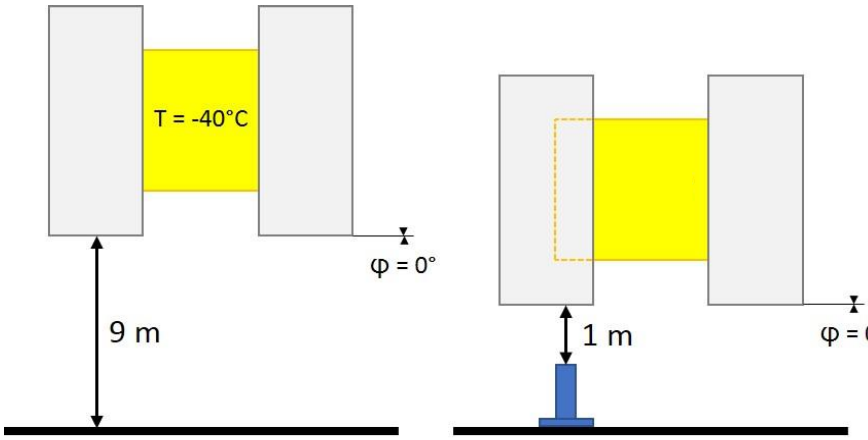

FIGURE 1. Schematically 9m-horizontal drop test and 1m- puncture bar drop test.

9m-vertical drop test

For the vertical drop test the entire test specimen was cooled down to -40°C and dropped on the lid-side of the package (Figure 2). The drop height of 9m was measured from the unyielding target to the underside of the lid impact limiter. Due to the drop orientation and the minimal design temperature the highest stress for the lid screws and seal system was expected. In order to realize a realistic load of the primary lid, expecting an internal impact of the content, the basket was equipped with dummy fuel assemblies.

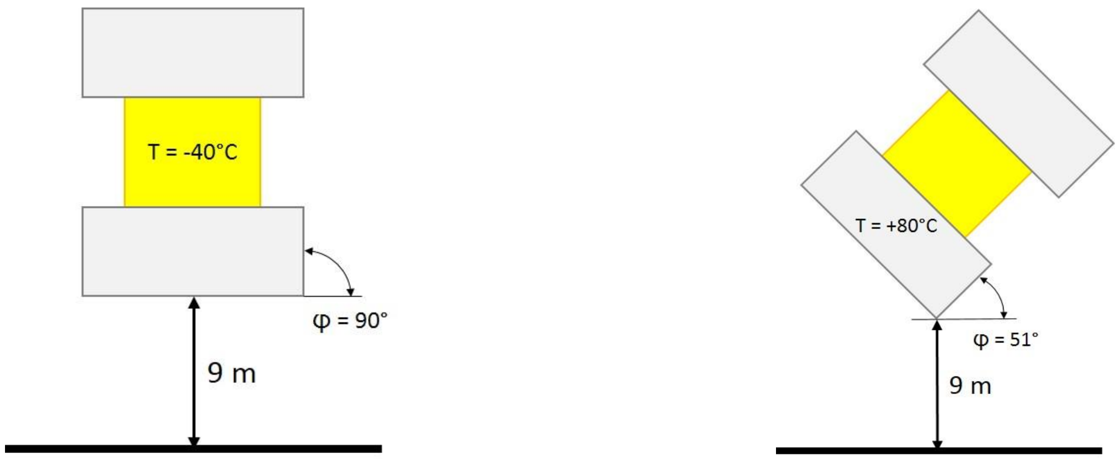

FIGURE 2. Schematically single 9m-vertical and 9m-oblique drop test on the lid side.

9m-oblique drop test

The drop test with an oblique orientation of the test specimen was conducted with a heated lid impact limiter. It was heated up to the maximum design temperature of 80°C whereas the other components of the package still had ambient temperature. Due to the heating process the lid and seal area of the cask was lightly heated as well. The drop height was measured from the unyielding target to the lower edge of the impact limiter (Figure 2).

The potential damage of a preceding puncture bar drop was taken into account by the removal of one mounting rod of the impact limiter fastening system. For this reason, the 9m-oblique drop test can be considered as an enveloping IAEA drop test sequence.

Test Specimen

The dual purpose cask CASTOR® MTR3 designed by Gesellschaft für Nuklear-Service mbH (GNS) consists of a monolithic hollow cylinder and a double lid system (Figure 3). The cask body is made of ferritic ductile cast iron with a length of 1631 mm and an outer diameter of 1430 mm. Primary and secondary lid are made of stainless steel and are equipped with metal seals. In the lid area of the cask body are two flanges with the corresponding sealing surfaces for the primary and secondary lid. The cask including the lid system has a weight of about 18 metric tons.

Source: GNS, [4]

FIGURE 3. CASTOR® MTR3 by Gesellschaft für Nuklear-Service mbH (GNS), Germany, and relating test specimen in horizontal drop test configuration.

The radioactive inventory is stored in a basket made of aluminum which has five positions for the fuel assemblies.

During transport the cask is equipped with impact limiters which are mounted on each end of the cask (Figure 3). The impact limiters are a steel sheet construction filled with multi-layer wood to reduce impact loads to the cask under drop test conditions. The two impact limiters are fixed to the cask body by four mounting rods which are tightened with each other. The external dimensions of the package are 2969 mm in length and 2400 mm in diameter. In total the transport package has a weight of about 23 metric tons.

The test specimen corresponds to the original design and is almost identical in terms of its dimensions, mass and materials. In the frame of the assessment strategy, the following constructive adjustments were made on the test specimen:

1. Adjusting the constructive maximum radial gap between the primary and secondary lid and the cask body to guarantee the maximum lateral displacement of the primary and secondary lid.

2. Adjusting the constructive maximum axial gap between the inner side of the primary lid and the basket, in order to reflect the maximum loads on the lid system caused by the internal impact of the basket onto the primary lid during the 9m-vertical drop test onto the lid side impact limiter.

The radial and axial gaps were adjusted by reworking the primary and secondary lids. That means the height and diameter of the lower part of the primary lid and the diameter of the secondary lid. Based on the actual dimensions of the cask body and the basket, the needed conservative dimensions for the lids were calculated according with the tolerances indicated in the technical drawings.

Another difference to the original cask of the CASTOR®MTR3 was the installation of the lid screws. In contrast to the assembly of the original cask with a torque-controlled tightening procedure, the screws of the test specimen of the CASTOR®MTR3 were ultra-sonic based force-controlled tightened in order to get more exact pretension loads of the screws. Two screws of each lid were tightened with the maximum preload and all other screws with the minimum preload. The combination of minimum preload of the screws and maximum lateral gaps between the lid and the cask body led to a maximum lateral displacement of the primary and secondary lid during the 9m horizontal drop test respectively to a maximum axial displacement during the 9m vertical drop test onto the impact limiters.

Test Setup and Drop Testing

The drop tests were performed at the 200-tons drop test facility located at BAM's Test Site for Technical Safety (BAM TTS) near Berlin (Figure 4). The unyielding impact target of the drop test facility is built according to the IAEA-Regulations [1], [5]. It consists of a concrete block (German concrete quality B25/B35) with the geometrical dimensions 14 m x 14 m x 5 m 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 using 40 pieces of M36 anchor bolts to the concrete block. The total mass of the target is 2,600,000 kg [6].

The punch target was 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. The material of the puncture bar had a yield strength (R_e) of 220 N/mm² and a tensile strength (R_m) of 360 N/mm². The length of the bar was 369 mm and 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 [3].

The drop tower, a 36-meter high steel frame construction, is placed over the assembling hall on four separate pile foundations. The hoist is located in a height of 33 meter. The lifting capacity is limited to a mass of 200,000 kg - the maximum lifting height belongs to 30 meters. The release of a specimen is performed by momentum free working release systems. Here, an electro-mechanical system for masses up to 50 tons was used [7].

FIGURE 4. Drop test facility with test specimen ready for 9m-drop test.

Measurement Methodologies

Acceleration and Strain Measurements

Instrumented measurements especially transient acceleration and strain measurements are one of the accepted standard measurement methods in drop testing of packages for radioactive materials. These methods are dedicated to answer questions in regard to the structural integrity of a package, the behavior of a package's components (closure lid, lid bolts, handling parts, etc.) as well as of the content behavior under impact conditions [8].

Acceleration measurement is providing characteristics of the package response to impact in form of continuous acceleration-time histories at the monitored locations of the container and target, rigid-body impact acceleration, rigid-body impact kinematics of the container during impact (velocity- and displacement history), impact duration, vibration frequencies and response spectra.

Strain measurements during cask drop testing give continuous strain-time histories at the monitored locations (cask walls, closure lids, lid-bolts, contents, etc.) and the structural response of the cask due to impact. Acceleration and strain measurements constitute the main basis for the validation of assumptions in the mechanical container safety analysis and for the evaluation of finite-element calculations [8].

The test specimen was instrumented at the cask body as well as on primary- and secondary lid with in total 22 units of three-axial foil strain gauges (gauge length 6 mm, resistance 120 Ohm) in order to determine the principle strain/stress histories and their belonging directions. Additionally, four lid screws at the 0°-, 90°, 180° and 270°- position of each closure lid were instrumented with uni-axial strain gauges in order to determine the screws' pretension after tightening and the remaining pretension after a drop test. Further, bending strain and normal strain-time histories during the impact were intended to be measured. In summary, a drop test was performed with a number of up to 100 pieces of single strain gauges, 16 units of accelerometers and 26 thermocouples. The thermocouples were mainly used to control the cooling and warming process of the shock absorbers and to confirm the required end temperature of the impact limiters for the drop test, -40°C and +80°C, respectively.

All strain gauges were 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. At the exterior long side of the outer cask body a terminal merges all cables coming from the sensors. This terminal is connected by means of 50 m long and shielded measuring cables to the data acquisition systems were the sensors are connected to wideband differential bridge amplifiers with an analogue bandwidth up to 300 kHz. The transient recording was done with a sampling frequency of 400 kHz for each channel and a digital 24-bit vertical resolution was applied.

Leak Testing

The CASTOR® MTR3 has a double-barrier closure lid system. Both lids, the primary and secondary lid are sealed against the cask body flange by metallic O-rings. The leak tightness of each barrier was determined by measurement of its helium leakage rate according to DIN EN ISO 20485 [9] using a helium leak detector.

The principle of a helium leak detector bases essentially on a selective mass spectrometer. Inflowing gas diffuses against the gas flow, called counter flow principle, is pumped by a turbomolecular pump into the mass spectrometer, there it is ionized. Depending on the mass of helium and stressed by the voltage helium is turned round in a specific curve, so only helium hit the surface of the “counter”. On each side of a seal which has to be checked a sealed cavity is needed. For the measurement one cavity must be evacuated, the other must be filled with helium under well-defined partial pressure, so that the standard-helium-leakage rate, which is related to 1013 mbar of helium, can be calculated after measuring.

High Speed Video

The high-speed video technique with motion analysis of an impacting specimen under drop test conditions can be an advantageous tool for the analysis of the impact event and the kinematic behavior of the package and seeks to complement measurements of acceleration [8].

The chronological synchronization of high-speed video recording with corresponding acceleration time histories using adequate signal analysis software gives the opportunity for better mechanical interpretation and understanding while analyzing acceleration signals as well as strain signals. Significant signal parts of the acceleration time curve during impact can be possibly related to visual mechanical events occurring at the impacting package or the target. The cask adjusted drop orientation can be validated by the high-speed video e.g. in the moment just before impact and possible deviations from that orientation can be quantified. Besides other aspects, this could be one important aspect in context with the validation of numerical calculations of drop tests using the method of finite elements considering that already small deviations from the defined impact orientation can change expected results significantly.

The impact events during the drop tests were high speed video-taped with 4000 frames per second and let determine exactly the performed impact orientation of the package. Further, the IAEA conformity of the 1m puncture bar drop test could be proved by analyzing the high-speed video in combination with the measured decelerations.

Digital Optical Measurements

In order to get detailed information about the complex geometry changes of the impact limiters due to the drop test, they were geometrically measured by an optical 3d-laser scan method. This data was of interest in context with the evaluation process i.e. as data basis for FEA validation.

In the run-up of the assembly of the test specimen, the sealing surfaces of the cask closure systems were also geometrically measured. Here, with the method of projected fringes in order to provide very detailed and accurate reference data for comparison with possible post-measurements after the drop test [10]. The performance of the post-measurements depended on the results of the leak tightness measurements, but weren't necessary due to the unchanged leak tightness status of the closure lid systems after the drop tests.

A further important result of the drop tests, especially for the horizontal drop was to determine the possible lateral displacement of the closure lids. Lid sliding, mostly caused by horizontal or oblique drop positions of the cask can often not be perfectly excluded by the cask design and is able to effect a change of the leakage rate.

In order to determine a displacement, the method of the close-range photogrammetry was used by measuring the position of the lid relating to the cask body [11]. The close-range photogrammetry is an optical method of geometrical measuring 3d-objects by digital images within a finite distance of some meters. The objects to be measured have to be marked with special circular adhesive markings on their outer surface area, here lid and the cask body flange. Then, pictures are taken from different directions with a high resolution digital camera. These pictures are analyzed with the method of spatial image triangulation and the 3D-coordinates of all markings are calculated. The comparison of the coordinates between the status before and after drop test results in a difference vector, which describes the relative movement of the lid relative to the flange of the cask body.

Force-controlled tightening

According to the assessment strategy, the lid screws of both closure lid systems should be tightened with the minimum allowable preload. In order to provide an accurate and reliable preload status of the lid screws, a force-controlled tightening method [12] was used for the assembly of the primary- and secondary lid of the test specimen. This method is based on an ultrasonic system which sends an ultrasonic impulse longitudinally through the screw during the tightening procedure. By the runtime of the ultrasonic pulse the current length of the screw is measured and the relating preload derived. Therefore the screw heads have a sputtered transducer and each screw was calibrated with a force standard before and labeled to measure a reliable preload.

Experimental Results

In the following some selected experimental results from the drop tests are presented.

One of the main objectives of the drop tests described was to demonstrate the integrity of the package and its safety against release of radioactive material. Pertaining to all performed drop tests, the measurements of the leak tightness of the cask closure system showed no change of the standard helium leakage rates at all regarding to the values determined before and after each drop test. Although, a lateral displacement of the primary lid and consuming the whole available gap between lid and cask body occurred due to the accumulative effect of the horizontal 9m and 1m-puncture bar drop test. The secondary lid showed negligible remained lateral movement. The small lateral movements were detected for oblique drop test as well. The vertical drop test didn't effect any lateral movements of the lids as the maximum possible lateral displacement of the primary lid really occurred in the horizontal drop test. The maximum tightened screws also showed the maximum possible stress for this drop orientation.

Another objective of the tests was to show the functionality of the fastening system of the impact limiters. The fastening system consists of four mounting rods which tighten the lid- and bottom-sided impact limiters to the cask. The impact limiters remained at their foreseen place at the cask and the fastening system wasn’t unallowable affected by any of the drop tests, so that no damage occurred. According to their actual purpose, the impact limiters absorbed the impact energy by deformation, but no other parts of the package were affected by any other deformation or damage. Also, in the oblique drop test with the removed mounting rod the impact limiters remained at the cask and limited the mechanical impact loading.

The instrumented lid screws of the primary and secondary lid showed mainly bending stress in the 9m horizontal drop caused by the lid’s lateral movement during the impact. In the vertical and oblique drop test situation the screws of the primary and secondary lid showed combined bending- and normal-stress. The stress of the lid screws was within the elastic range of the material during all drop tests.

The kinematic behavior of the cask during the drop tests could be determined by analyzing data from accelerometers and high-speed video recordings. The recordings of the impact onto the unyielding target were used to analyze and verify the adjusted drop orientation of the cask which has significantly effect on the measurement results. The drop orientations which were determined with a tolerance range in the test program were obtained in all performed drop tests.

Furthermore, it could be clearly shown that the length of the puncture bar was appropriate according to the IAEA-Regulations [5]. This evaluation was necessary due to the eccentric drop position of the cask relating to the puncture bar.

Conclusions

A new dual purpose cask design developed for the safe transport and interim storage of spent fuel assemblies of German research reactors was drop tested by BAM within a German transport approval procedure according with the IAEA-Regulations. The experimental testing of the cask was part of the safety assessment strategy showing compliance with the regulatory accident conditions and normal conditions of transport.

The relating drop test program included three 9m free drop tests, in horizontal, vertical and oblique cask orientation onto the lid system. Additionally, a 1m-puncture bar drop test followed the horizontal drop test to consider a full IAEA drop test sequence. The horizontal and vertical drop tests were performed at a test specimen temperature of minus 40°C. During the oblique drop test the upper impact limiter was heated up to +80°C. The main objectives of the drop tests were to demonstrate the integrity of the package and its safety against release of radioactive material as well as the proof for the fastening system of the impact limiters. Further, measurement data which was collected by the drop tests such as i.e. strain- and deceleration-time-histories as well as 3D-deformation data of the impact limiters, etc., created the basis for the verification of the numerical models of the corresponding FEA.

The tests proved the required leak-tightness of the cask closure system and the functionality of the fastening system of the impact limiters.

References

[1] International Atomic Energy Agency (IAEA), Regulations for the Safe Transport of Radioactive Material, 2012 Edition, Specific Safety Requirements No. SSR-6, Vienna, 2012

[2] Technical Guide, Package Design Safety Reports for the Transport of Radioactive Material, European PDSR guide, ISSUE 3, December 2014

[3] Scheidemann, R., et al., “Approach for determining the length of the bar in compliance with the IAEA 1m puncture test”, 11th International Conference on the Transport, Storage and Disposal of Radioactive Materials, paper no. 18562, London, UK, May 15-17, 2018.

[4] GNS, Das Unternehmensmagazin, Ausgabe 7, 11/2014, Seite 5

[5] IAEA Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (2012 Edition). Specific Safety Guide No. SSG-26, International Atomic Energy Agency, Vienna, 2014

[6] Müller, K. et al., “Impact target characterization of BAM drop test facility”, Packaging, Transport, Storage and Security of Radioactive Material, Volume 19, Number 4, pp. 217-221(5), 2008.

[7] Müller, K. et al., “The New BAM 200 Ton Drop Test Facility - Construction and Operation Experiences”, Packaging, Transport, Storage and Security of Radioactive Material, Volume 17, Number 3, pp. 131-135, Maney Publishing (2006).

[8] Quercetti, T. et al., “Instrumented Measurements on Radioactive Waste Disposal Containers During Experimental Drop Testing”, Proceedings of the 14th International Conference on Environmental Remediation and Radioactive Waste Management, paper no. 59142, ASME 2011, Reims, France, September 25-29, 2011.

[9] Non-destructive testing - Leak testing - Tracer gas method (ISO 20485:2017); German version EN ISO 20485:2018

[10] Gründer, K. et al., “Characterisation of shock absorber deformation by optical surface digitisation”, Packaging, Transport, Storage and Security of Radioactive Material, Volume 19, Number 3, pp. 155-159(5), Maney Publishing (2008).

[11] Gründer, K. et al., „Determination of Lid Displacements by Photogrammetry in Full-Scale Cask Drop Tests”, SENSOR+TEST 2005, 12th International Trade Fair for Sensorics, measuring and testing technologies with concurrent Conferences, Nuremberg Exhibition Centre, Germany, 10-12 May 2005

[12] Intellifast GmbH, Germany, Intelligent Fastener Technologies, www.intellifast.de

[13] Komann, S. et al., “Design Assessment by BMA of a New Package Design for the Transport of SNF from a German Research Reactor, PATRAM 2019, August 4-9. 2019, New Orleans, LA, USA