

## **Testing of a Transport Cask for Research Reactor Spent Fuel – 13003**

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### **ABSTRACT**

Since the beginning of the last decade three Latin American countries that operate research reactors – Argentina, Brazil and Chile – have been joining efforts to improve the regional capability in the management of spent fuel elements from the TRIGA and MTR reactors operated in the region. A main drive in this initiative, sponsored by the International Atomic Energy Agency, is the fact that no definite solution regarding the back end of the research reactor fuel cycle has been taken by any of the participating country. However, any long-term solution – either disposition in a repository or storage away from reactor – will involve at some stage the transportation of the spent fuel through public roads. Therefore, a licensed cask that provides adequate shielding, assurance of subcriticality, and conformance to internationally accepted safety, security and safeguards regimes is considered a strategic part of any future solution to be adopted at a regional level. As a step in this direction, a packaging for the transport of irradiated fuel for MTR and TRIGA research reactors was designed by the tri-national team and a half-scale model equipped with the MTR version of the internal basket was constructed in Argentina and Brazil and tested in Brazil. Three test campaigns have been carried out so far, covering both normal conditions of transportation and hypothetical accident conditions. After failing the tests in the first two test series, the specimen successfully underwent the last test sequence. A second specimen, incorporating the structural improvements in view of the previous tests results, will be tested in the near future. Numerical simulations of the free drop and thermal tests are being carried out in parallel, in order to validate the computational modeling that is going to be used as a support for the package certification.

### **INTRODUCTION**

Research reactors have been in operation in Latin American countries since the late 1950 decade. As of today, Argentina, Brazil, Chile, Colombia, Jamaica, Peru and Mexico maintain a fleet of 17 active research reactors, mainly MTR (Materials Test Reactor) and TRIGA (Teaching Research Isotopes General Atomic) types [1]. Throughout their operational life hundreds of fuel elements have been generated and mostly stored at in-reactor wet and dry facilities. Although some of these countries have in the past repatriated American-origin fuel to the United States (Table I), the increase of the discharged fuel stock not eligible for repatriation and the desire to share solutions for common operational problems (e.g. fuel corrosion) led some of these countries - namely Argentina, Brazil and Chile – to join efforts in an IAEA-sponsored project to devise regional strategies for the management of the reactors and the generated spent fuel.

Table I. Spent Fuel Assemblies Shipped Back to the USA [2].

Country	Year	Number and type of spent fuel	Total
Argentina	2000	207, MTR HEU	249
	2007	42, MTR HEU	
Brazil	1999	127, MTR HEU and LEU	160
	2007	33, MTR HEU	
Chile	1996	28, MTR HEU	58
	2000	30, MTR HEU	

Despite no definitive solution regarding the back end of the research reactor fuel cycle has been taken so far by any one of the participating countries, any long term solution – either disposition in a repository or centralized storage away from reactor – will involve at some stage the transportation of the spent fuel through public roads. Considering this, it was decided by the tri-national team to develop a cask for the transportation of this kind of spent fuel. In view of the predicted cask weight and dimensions vis-a-vis the available test facilities, the team chose to test a half-scale model. A test unit was then built in Argentina and tested in Brazil. This unit is equipped with the MTR version of the internal basket, considered to be an envelope case, in that MTR fuel are more reactive than TRIGA ones.

Three test campaigns have been carried out so far, covering both normal conditions of transportation and hypothetical accident conditions. The specimen failed the tests in the first two instances, but, after some critical design modifications, successfully passed the third set of tests.

A fourth test sequence was conducted in the last quarter of 2012 and new improvements and design changes are to be incorporated to the cask. Numerical simulations of the free drop test have been carried out in parallel in order to validate the computational modeling that is going to be used as a support for the package certification.

## CASK DESCRIPTION

The cask was designed to meet the transportation criteria established by the IAEA for Type B packages carrying fissile materials [3]. Therefore, the cask has to be sturdy enough to resist the postulated transport accidents: a free drop from 9 m on a rigid surface, a one-meter drop onto a flat pin, a fire that generates a temperature of 800 °C for 30 minutes, and submersion to 15 m depth of water.

Since no long-term storage strategy has been defined in the region for this kind of spent fuel, the cask is regarded by the waste management implementers – at least in Brazil – also as a potential storage option. For this reason, some of its features were designed to attend extended storage requirements, such as stability of its constitutive materials and compatibility between them and with the radioactive contents. Also the access to its internal cavity has to be granted for periodical checks through gas sampling.

Additionally to the above criteria, the cask design features and constraints were determined taking into account the characteristics of the research reactor facilities in the participating countries. Therefore, the maximum cask weight, when loaded, was established as 10 metric tons and the maximum external diameter – to allow in-pool loading – as one meter. Likewise, as the main research reactor types operating in Latin America are MTR and TRIGA reactors, the cask was designed to accommodate, in exchangeable baskets, either 21 MTR or 78 TRIGA spent fuel elements.

The cask's main components are the main body, lids, fuel basket, shock absorbers and connection bars. The body consists of a sturdy cylindrical structure with an internal cavity to accommodate the basket that holds the spent fuel elements. Its bottom and sidewall are sandwich-like shielded barriers consisting of stainless steel outer and inner surfaces and lead in-between. Four lifting trunnions exist on the cask sidewall to allow its vertical handling and rotation. A draining port, equipped with quick-connect valve and protection lid is located at the side of the cask, close to its bottom rim.

The cask has a double lid system. The internal lid is also a stainless steel structure with lead filling; an access – similar to the draining port – is embedded to the lid, providing access to the internal cavity for gas pressurization, sampling and purging. The internal lid is part of the cask's containment system and is, therefore, provided with a double metallic sealing system. An access point to the annular space between the sealing gaskets is provided as a testing point of the cask's cavity containment. The internal lid is attached to the cask's main body by 24 bolts.

The external lid is made of stainless steel and has a circumferential groove to accommodate an elastomeric gasket, its main function being the protection of the internal lid<sup>1</sup>. The external lid is fixed to the main body by means of 16 bolts.

The internal basket is removable and consists of a structure of 21 square tubes, horizontal connection plates, side and bottom plates and foot supports.

For protection against mechanical and thermal loads, the cask is provided with top and bottom external removable impact limiters. These are structures made of external stainless steel skin and polyurethane foam filling for shock energy absorption and thermal protection<sup>2</sup>. The foam density is 165 kg/m<sup>3</sup> and, for enhanced thermal protection, fire retardant is added to its composition.

A schematic view of the cask is shown in Figure 1. The main dimensions of the natural scale cask are: main body,  $\phi$  1,000 x 1,400 mm; overall dimension with shock absorbers,  $\phi$  2,160 x 2,010 mm.

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<sup>1</sup> The external lid will be removed during the storage period. Therefore, the elastomeric gasket is acceptable as sealing material, which would not be allowed for long-term storage.

<sup>2</sup> The original energy-absorbing material was the wood composite OSB (Oriented Strand Board). It was replaced by polyurethane foam due to unsatisfactory results of drop tests.

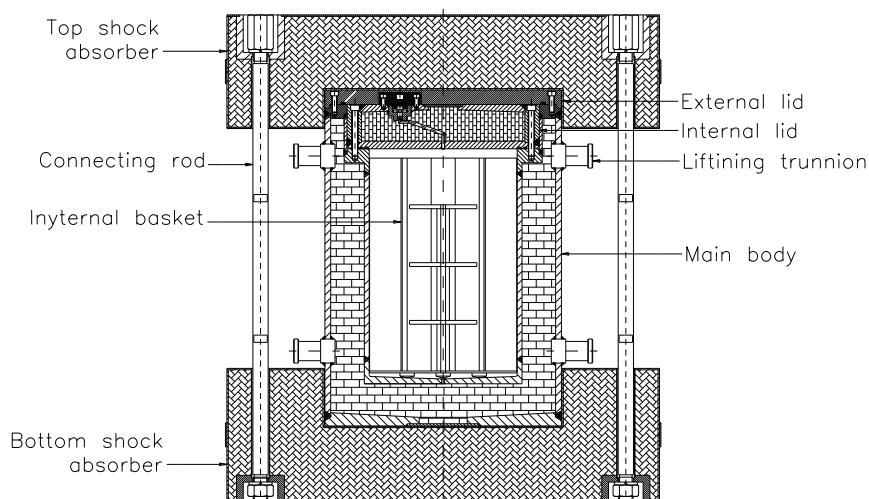


Figure 1. Transport cask for research reactor spent fuel

As part of the dual purpose cask design, both shielding and criticality analyses were performed for the most reactive MTR and TRIGA fuel elements in the region, considering the most conservative assumptions likely to be encountered [4]. For the shielding analysis, the gamma and neutron sources were estimated considering a burnup of 50% (U235 depleted) for the MTR fuel and 25% for the TRIGA fuel. Furthermore, a 5-year cooling time was adopted in the model. The QADS and SAS4 modules of the SCALE 4.4A package [5] were used in the calculation.

The maximum values found for surface dose rate were 0.186 and 0.367 mSv/h in the radial and axial directions, respectively. These values are well below the limits established by IAEA standards, which are 2 mSv/h for transport not under exclusive use or 10 mSv/h for transport carried out under exclusive use.

The criticality safety analysis of the cask was carried out using the Monte Carlo transport code MCNP4B [6]. It was conservatively assumed that the fuel elements were fresh, that is, no burnup was considered and that the cask was completely submerged in water (water inside the cavity and surrounding the cask). The maximum neutron multiplication factor ( $k_{eff}$ ), for both normal and accident conditions, was established as 0.95.

The maximum values found were  $0.87165 \pm 0.00070$  for TRIGA elements and  $0.89890 \pm 0.00082$  for MTR [4], demonstrating that the sub-criticality condition is guaranteed for the cask loaded with any one of the two types of fuel elements. Thus, the fuel elements can be stored and transported safely even in the hypothetical situation of the cask being completely flooded.

## CASK MODEL TESTING

As part of the cask development program, a half-scale model was submitted in three instances to the sequence of tests prescribed at the IAEA's standard for the safe transport of radioactive material. The test campaigns took place on June 2008, June 2010 and August 2011, respectively. The tests were carried out to simulate both normal conditions of transportation (NCT) and hypothetical accident conditions (HAC). During the first campaign, the first group of tests

consisted of free drops from 1.2 m height and a penetration test. The prescribed water spray and stacking tests were not performed, the former for being deemed to have irrelevant effects on the tested item and the latter because, due to its geometry, the cask is not stackable. The tests to simulate HAC were water immersion test, punch tests onto a vertical bar, free drop tests from 9 m height, and thermal test. The latter was carried out only for design development purposes, since scaled models are normally not submitted to real thermal tests. The practice recommends that if it is not possible to carry out thermal tests in a natural scale prototype, due to high cost or lack of a proper infra-structure, then numerical simulations should be used, since the thermal phenomena that occur during the test are not reproducible in a scaled model.

For the second campaign, the NCT tests carried out consisted only of 1.2 m drop tests. The penetration test carried out earlier caused only a small local dent at the point of impact and was considered to impart irrelevant effects on the cask and was therefore not performed. As for the HAC sequence, a series of punch and 9 m drop tests at different impact points and drop positions were conducted.

The approval criteria established in the regulations in terms of radioactive activity release rate were translated into gas (helium) leakage rate. Therefore, a maximum helium leakage rate of  $10^{-7}$  Pa.m<sup>3</sup>/s was established as the approval value. An initial helium leak test was carried out prior to any other test and the specimen was found to be leak tight. Subsequent leak tests were carried out at different stages of the test campaigns.

The test instrumentation for the drop tests consisted of three uni-axial piezoelectric accelerometers attached to an especially built fixture at the specimen sidewall. The accelerometers orientation angles with respect to the model main axis were respectively 0°, 45° and 90°. The thermal test instrumentation consisted of six thermocouples installed at different positions, including the internal cavity, and temperature indicating labels, fixed at various positions inside the cask cavity.

The shock absorber energy-absorbing material used during the first and second test campaign was the wood composite OSB. After the second campaign, it was replaced by high-density rigid polyurethane foam.

### First Test Campaign

The first test campaign consisted of the tests shown in Table II.

Table II. Tests carried out during the first campaign

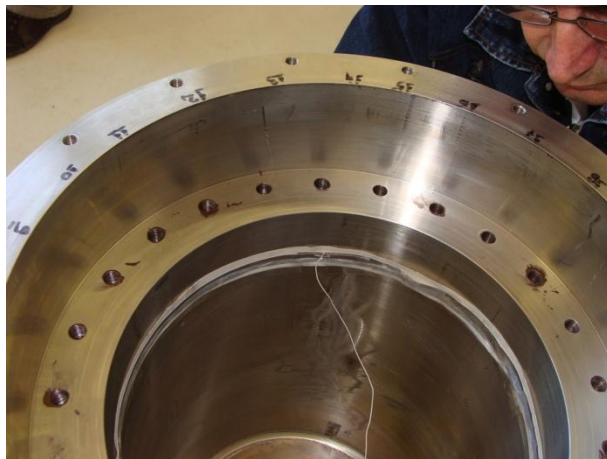
Sequence	Type of test	Remarks
-	Containment test	Initial helium leak test
HAC	Water immersion test	Simulated by electrical resistance circuit
NCT	1.2m drop test I	CG* – corner, 43° inclination to horizontal
	1.2m drop test II	Upside down
	1.2m drop test III	Horizontal drop position
	Penetration test	-

Sequence	Type of test	Remarks
HAC	Punch test I	Directed to lower surface of top shock absorber
	Punch test II	Onto cask body mid-section
	9m drop test I	CG-corner
	9m drop test II	Upside down
	9m drop test III	Horizontal drop position
	9m drop test IV	Horizontal drop position
	Thermal test	-
-	Containment test	Final helium leak test
-	Gamma scanning	Shielding verification

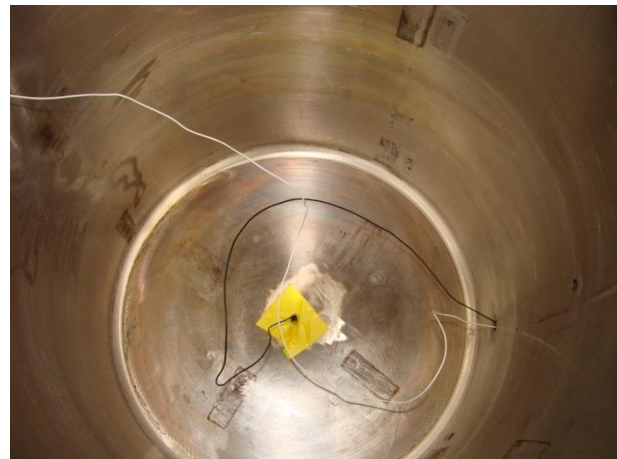
\* CG – Center of Gravity

The methodology used to simulate the water immersion test consisted of checking the leak tightness of the specimen's critical features – the double seals of the internal lid and pressurization/sampling and draining ports – through the variation of the electrical resistance of a circuit properly mounted around these regions. The test consisted in applying a hydraulic pressure of 150 kPa to the annular space between each set of seals and recording the variation of its resistance (Figure 2). Any water intrusion would reduce the electrical resistance of the circuit, which was originally open (infinite resistance) in the absence of water.

The cask failed this test, possibly due to lack of gasket compression deformation.



(a) Circuit for internal lid



(b) Circuit for draining port

Figure 2. Set up for water detection

The sequence of 1.2 m drop tests that followed was intended to challenge the specimen's ability to withstand impact efforts in the three classical drop positions for cylindrical test specimens: CG –corner, vertical upside-down and horizontal. The visible effects of the CG-corner and horizontal drop tests were dents on the impact regions of the shock absorbers and a slight bulging of each impact limiter's flat surfaces, whereas the vertical drop caused no visible effect on the tested

model. As for the accelerations developed during the impact, the maximum g-level – approximately 33 g – was registered during the CG-corner drop. It shall be mentioned that, due to the scaling physical laws, the acceleration levels in the natural scale cask are expected to be half of the values observed for the half-scale model.

The penetration test consisted of a drop from one-meter height of a cylindrical metallic bar weighing 6 kg onto the most vulnerable region of the specimen. The specimen was positioned lying in the horizontal position so that the bar would impact its central point. As expected, the impact caused only a small indentation in the point of contact.

The HAC test sequence started with the performance of the punch tests. The IAEA standard establishes that the specimen shall be released from 1 m distance onto a sturdy vertical bar in such a position that the maximum damage is inflicted [3]. In order to verify different responses to this test, the specimen was submitted twice to this test. In the first test, the drop angle was selected to make the bar impact the top impact limiter in an attempt to remove it. As a result, the targeted impact limiter was torn open at the welded joint near the point of impact but was not removed.

In the second drop, the specimen was released on the horizontal position so that it would be hit flatly in the middle of its side. The effect of this drop was an indentation with a depth of 11.8mm to the cask body at the point of impact, but no tearing to the cask body outer wall. Nevertheless, an increase in the contact dose rate at the impact region was later observed during the shielding verification test.

Four 9 m drop tests were then carried out in sequence, according to the same release positions as above. The horizontal drop test was carried out twice, the second time with the draining port facing down, in an attempt to damage this critical region. Due to the extensive damages sustained by the shock absorbers, the most affected ones were replaced after each drop. The different damages sustained by the shock absorbers were indentation along the impacted edges; bulges on the surfaces near the impact regions; opening of the most stressed weld seams; tearing of the impact limiter skin due to impact of the lifting trunnions, and bending of the tensor bars which connected the top and bottom shock absorbers (Figure 3). The maximum g-level recorded was 272 g, recorded during the drop at the upside down position. Half of this value is expected to be observed in the natural scale cask.

The last test of the HAC group carried out was the thermal test. The objectives of this test were to have a general feeling of the behavior of the cask under high temperature conditions and register the temperature distribution along the specimen. The numerical data collected will be useful in the validation of the numerical simulation of this test.

The test consisted of submitting the specimen for 30 minutes to a temperature of 800 °C. The test was carried out in an industrial electrical furnace preheated to 804 °C and the specimen was equipped with temperature indicating labels and thermocouples. The labels were installed in different positions inside the cask cavity, including the cavity walls, basket and some of the dummy fuel elements. The thermocouples were mounted in the following positions: two inside holes existing on the external lid; two inside the cask cavity and two inserted into especially designed passages through the cask body wall (one inserted 1/3 deep on the wall thickness and

one 2/3 deep on the wall thickness). The two last sensors were meant to record the temperatures of the lead during the test.



Figure 3. Top shock absorber after the CG-corner 9 m drop test

After soaking in the furnace for 30 minutes, the cask was removed and suspended in air for about 10 minutes and then laid to rest on thermal insulating pads. The maximum temperatures indicated by the thermocouples at each monitored position were:

External lid:	395 °C;
Cask wall, 1/3 thickness:	436 °C;
Cask wall, 2/3 thickness:	405 °C;
Cask cavity:	254 °C.

The maximum temperature range registered by the labels on the basket and dummy fuel elements was  $163\text{ °C} < T < 177\text{ °C}$ .

These values indicate that, although the lead might have partially melted, a suspicion corroborated by a bulge observed on the bottom of the cask, the cask wall as a whole provided good thermal insulation, preventing the fuel elements to reach excessive temperatures.

A leak test after the above-described tests was carried out to verify the specimen's containment capacity. A helium leak test was initially performed, but it was soon evident that the tested model presented gross leakages. The helium test equipment was disconnected, a compressed air line attached to the cask and a soap bubble test performed. Leaks through the lid rim were then observed and the test interrupted with unsatisfactory results.



Finally, a gamma scanning was performed after all tests. An Ir-192 point source with 2.2 TBq (59 Ci) activity was positioned at the center of the specimen cavity and the contact dose rate recorded at points at the specimen surface according to a 5 x 12 mesh on the external lateral surface and at six point on the specimen bottom. The results were compared with similar measurements taken previously at the cask manufacturing premises as part of the test acceptance tests. An increase of 44% from the first measurement was observed at the region directly impacted by the bar during the punch test, showing that the crushing of the lead filling affected the shielding performance of the cask. This value is however below the limit established at the IAEA transport regulations.

## **Second test campaign**

The examination of the test results suggested that the root cause of prototype failure in the final helium leak test was the plastic deformation of the internal lid bolts, probably due to lack of sufficient tightening force and engagement length. In order to improve the prototype performance, some design changes were implemented for the second test campaign. The modifications included changes in the shape, dimensions or material of some of the components of the prototype and in some fabrication specifications.

As for the internal lid bolts, the engagement length was increased and the material class changed. The original engagement length/diameter ratio was increased from 1.2 to the recommended 1.5. The bolt material – previously stainless steel ASME specification SA-193 B8M Class 1 – was changed to Class 2 [7], which presents yield strength three times higher.

Coming to impact limiters, their shape, welding scheme of the metallic cover and arrangement of filling material (OSB) were modified. The change in shape consisted of introducing a chamfer at its rim – the one to be hit in a CG-corner drop – to avoid stress concentrations during the impact that could lead to welding seams failure. Also the welding scheme was changed to allow full penetration in all critical welds. And finally the OSB wood boards were arranged in two directions: vertically in the absorber's central region and horizontally in the periphery. The objective of this change was to avoid the elastic response observed during the 9 m drop impact in the upside down position, when the boards were compressed perpendicularly to their medium plane. The energy absorption of the OSB when compressed in a direction parallel to its fibers showed to be prevalently plastic during laboratory tests.

Other modifications introduced were the reinforcement of the engagement of the external lid to the cask body, with the introduction of a shear lip to the border of the lid, and the protection of the draining port to prevent damages in case of a direct impact of the vertical bar during the punch test.

The modified cask model has then undergone a second series of tests in June 2010, as seen in Table III. As can be seen, many of the tests had to be repeated, sometimes more than once, as part of trial and error attempts to eliminate the leaks observed in the containment tests carried out after the mechanical tests. Most of the work done between the tests to get rid of leaks was directed to the lid sealing system: seal groove machining, smoothing of the cask body contact surfaces, replacement of seals, etc. Also two operational changes were introduced: increase of the internal lid bolt's tightening torque and lubrication of the bolt's thread.

The structural damages inflicted to the specimen (Figure 4), much less severe than those observed during the first campaign, demonstrated that the modifications introduced improved the overall mechanical strength of the specimen.

Table III. Tests carried out during the second campaign

Sequence	Type of test	Remarks
-	Containment test	Initial helium leak test
NCT	1.2m drop test I	CG – corner, 48° inclination to horizontal
	1.2m drop test II	Upside down
	Containment test	Leak above limit
	Containment test	Seals replaced, bolts re-tightened - Leak below limit
	1.2m drop test III	CG – corner, 48° inclination to horizontal
	1.2m drop test IV	Upside down
	Containment test	Leak above limit
	Containment test	Seals replaced, bolts re-tightened - Leak below limit
HAC	9m drop test I	Upside down
	Punch test I	Onto top shock absorber, specimen upside down. Considered not valid, bar bent laterally
	Containment test	Leak above limit
	Containment test	Seals replaced, bolts re-tightened - Leak below limit
	9m drop test II	Upside down
	Punch test II	Onto top shock absorber, specimen upside down
	Containment test	Leak above limit
	Containment test	Seals replaced, bolts lubricated re-tightened - Leak below limit
	9m drop test III	CG – corner, 48° inclination to horizontal
	Punch test III	Onto draining port
	Containment test	Leak below limit
NCT	1.2m drop test V	Upside down
	Containment test	Leak above limit
-	Gamma scanning	Shielding verification

A deleterious effect however was detected as a consequence of the change in the orientation of the OSB boards in the central part of the shock absorbers. During the impact at the upside down drop test, the OSB boards in this region were compressed in the direction of their medium plane and were expected to enter the plastic region and be crushed without major elastic response, therefore preventing the specimen from rebound significantly. The stresses developed however in both 1.2 m and 9 m upside down drop tests were not high enough to bring the material to the plastic region and only a small amount of the impact energy was dispersed in the targeted shock absorber, the major part being transmitted to the cask itself. Furthermore, due to the rigid response of the shock absorber, the impact duration was very small, between 4 and 6 ms. As a consequence, the stress levels at the cask were exceedingly high, with recorded accelerations peaking at around 300 g.

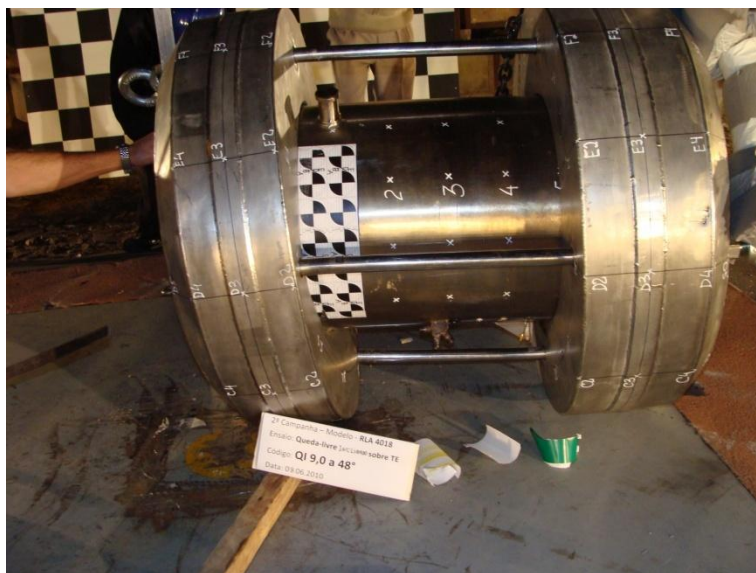


Figure 4. Specimen after 9 m CG-corner drop test: less damage observed

### Third test campaign

Based on the results of the previous tests, the following modifications and refurbishment were implemented:

Shock absorber energy absorbing material – the former shock absorber filling material (wood composite *Oriented Strand Board*, OSB) was replaced by high density –  $165 \text{ kg/m}^3$  – rigid polyurethane foam;

Shock absorber shape – the external chamfered corner was replaced by squared corner;

Gasket size– the internal lid seals were replaced by seals with smaller tubing diameter. New gaskets provide enhanced sealing properties.

Bolts lubrication – lubrication was used in the internal lid bolts to reduce friction and to better control the applied torque.

The tests sequence carried out is shown in Table IV

Table IV. Tests of the third campaign

Sequence	Type of test	Remarks
HAC	Containment test	Leak rate below limit
	9m drop test I	Upside down
	Containment test	Leak rate below limit
	Containment test	Seals replaced, bolts re-tightened - Leak rate below limit
	9m drop test II	Slanted, 51 degrees to horizontal
	Containment test	Leak rate below limit
	Immersion test	No water penetration

The results of the tests are as follows. No major damage was observed on the model due to the first 9 m drop test, only an inward curvature of the upper surface of the impacted shock absorber and a partial rupture of a secondary weld (Figure 5). A peak acceleration of 182 g was observed during the impact, having a duration of approximately 18 ms. The model rebounded approximately 560 mm into the air before landing on the horizontal position on the platform. It is worth mentioning that, due to scaling laws, the accelerations developed during the half-scale model are two times higher than those for the life-size cask.

For the second drop test, the model was dropped at angle of 51 degrees with the horizontal surface, lid down. The targeted shock absorber experienced severe deformation at the contact region. All four tensor bars were bent to different degrees, the one closest to the impact region suffering the largest deformations (Figure 6). The package bounced back approximately 420 mm, rotated in the air approximately 80° and came to rest in the horizontal position. The maximum registered acceleration was 51 g.

The helium leak tests were carried out before and after each drop test. The adopted acceptance criterion was a maximum leak rate of  $1 \cdot 10^{-7}$  Pa m<sup>3</sup>/s. The specimen was found to be leak tight in all tests conducted. The maximum leakage, recorded after the first 9 m drop test, was  $7.1 \cdot 10^{-8}$  Pa m<sup>3</sup>/s.

The shock absorbers were removed for the immersion test. The model was tested in a pressurized tank. A hydrostatic pressure of 1.5 bar was established, thus simulating the immersion of the specimen at the required 15 m water depth. The test duration was 8 hours.

After removing the model from the tank and taking the external lid away, water was observed on the top of the internal lid and on the top surface of the cask. It was verified however that water did not penetrate the internal cavity and therefore the model was considered approved in the immersion test. The same water-sensitive electrical circuit described earlier was installed inside the cask's cavity.



(a) Model in position



(b) Small damages on the impacted shock absorber

Figure 5. First 9 m drop test – vertical, upside down



Figure 6. Second 9 m drop test – 51°, lid down

## DISCUSSION

The results of the last test campaign showed that the design modifications and refurbishment described earlier largely improved the cask capability of withstanding dynamic impacts, thus allowing it to pass the prescribed mechanical tests.

As a result of this test campaign, the design modifications below will be incorporated to the cask design.

Regarding the cask main body:

- increase of the threaded length of the holes at the body recess that receives the internal lid bolts, thus increasing the engagement length to 18 mm (this length corresponds to 1.5 times the bolt diameter);
- installation of a protection cover to the drain port;

Regarding the internal lid:

- addition of a guiding system for easier positioning and installation of the internal lid;
- machining a clearance on the outer diameter of the internal lid bottom to avoid interference during the lid tightening;
- operational aspects: lubrication of the bolts will be mandatory

Concerning the external lid:

- redesign of the elastomeric o-ring and groove (use a seamless gasket);
- operational aspects: lubrication of the bolts will be mandatory;

As regards the shock absorbers:

- absorbing material adopted: high density rigid polyurethane foam, with density of 165 kg/m<sup>3</sup>. This density will be confirmed by numerical modeling, in which different shock absorber thickness versus density combinations will be studied;
- shock absorber shape: the external chamfered corner will be replaced by a square corner;
- modifications to be implemented to the shock absorber for cask lifting and handling:
  - deepening of the lodge for the nuts on the top shock absorber to allow the nut to be flush to the shock absorber top surface;
  - reinforcement of the welding between the passage tubes and shock absorber metallic cover. This region failed during the 9 m drop tests;

The critical features to be controlled during the cask model fabrication are the parallelism and the flatness of the contact surfaces of the internal lid and cask's body. The perfect match of these surfaces will guarantee the model leak tightness.

## CONCLUSIONS

The results gathered in the test campaigns carried out so far suggest that the cask design is robust. The specimen was extensively tested, being submitted to a long series of free drop and punch tests without presenting significant damage to its containment or shielding systems. Although the specimen initially failed the helium leak tests, the design modifications introduced brought good improvements to the overall cask model behavior.



The impact limiters were re-designed in order to reduce the accelerations transmitted to cask body. A major enhancement was the replacement of the original shock absorber filling material – the wood composite OSB – by high-density rigid polyurethane foam, which significantly added to the energy absorption capability of these protection items.

Also the extremely high friction coefficient originally observed during the lid bolts tightening – which is indeed expected when using stainless steel bolts – was successfully reduced by the use of lubrication of the bolts.

A second test specimen was subjected to another test campaign in the fourth quarter of 2012.

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