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TESTING OF A TRANSPORT CASK FOR RESEARCH REACTOR SPENT FUEL

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ABSTRACT

Since the beginning of the last decade three Latin American countries which 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 reactors operated in the region. As a step in this direction, a packaging for the transport of irradiated fuel from research reactors was designed by a tri-national team and a half-scale model for MTR fuel constructed in Argentina and tested in Brazil. Two test campaigns have been carried out so far, covering both normal conditions of transportation and hypothetical accident conditions. Although the specimen has not successfully performed the tests, its overall performance was considered very satisfactory, and improvements are being introduced to the design. A third test sequence is planned for 2011.

1 INTRODUCTION

Research reactors have been in operation in Latin American countries since the late 1950 decade. As of today, Argentina, Brazil, Chile, Colombia, Peru and Mexico maintain a fleet of 16 active MTR and TRIGA research reactors [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 country have in the past repatriated American-origin fuel to the United States (Table 1), 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 IAEAsponsored project to devise regional strategies for the management of the reactors and the generated spent fuel.

Table 1 Spent Fuel Assemblies Shipped Back to the USA [3, 4].

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.

Two test campaigns have been carried out so far, covering both normal conditions of transportation and hypothetical accident conditions. Although the specimen failed the tests in both instances, in the second campaign due to a small leakage detected after the drops, its overall performance was considered very satisfactory.

A third test sequence is planned for the third quarter of 2011 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.

2 CASK DESCRIPTION

The cask was designed to meet the transportation criteria established by the IAEA for Type B packages carrying fissile materials [5]. 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 yielding at a temperature of 800^{o}C for 30 minutes, and submersion to 15 m depth of water.

Since no long term storage strategy has been defined in Brazil for this kind of spent fuel, the cask is regarded by the Brazilian participants also as a potential storage option. For that reason, some of its features were designed to attend long term storage requirements, such as long-term 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 set up 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 with a storage capacity to accommodate in exchangeable baskets either 21 MTR or 78 TRIGA spent fuel elements.

The cask consists of a sturdy cylindrical body with internal cavity to accommodate the basket that holds the spent fuel elements. The cask body has a sandwich-like shielded wall consisting of stainless steel outer and inner surfaces and lead in-between. At the top, a double lid system guarantees the required containment and the internal lid – which is part of the pressure boundary – has a double sealing system. The cask is provided with two access ports to the internal cavity, one for pressurization and sampling of the cavity filling gas, embedded in the internal lid, and the other for the cavity draining, located at the lower region of the cask wall. Both ports are equally equipped with two concentric seals. All double seals are metallic, whereas external lid seal is elastomeric.

The structure of the basket is made of square tubes. 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 an energy-absorbing filling material. The filling material chosen was an wood composite named Oriented Strand Board (OSB), which is an engineered, mat-formed panel product made of strands, flakes or wafers sliced from small diameter, round wood logs and bonded with a binder under heat and pressure. A schematic view of the cask is shown in Fig. 1. The main dimensions of the natural scale cask are: main body, ϕ 1,000 x 1,400 mm; overall dimension with shock absorbers, ϕ 2,160 x 2,010 mm.

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 [6] . 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 [7] were used in the calculation.

The maximum values found for surface dose rate were 186 and 367 μSv/h in the radial and axial directions, respectively. These values are well below the limits established by IAEA standards, which are 2,000 or 10,000 μSv/h, depending on whether the transport is under exclusive use or not [5].

The criticality safety analysis of the cask was carried out using the Monte Carlo transport code MCNP4B [8]. It was conservatively assumed that the fuel elements were fresh, that is, no burnup was considered, that the cask was completly submerged in water (water inside the cavity and surrounding the cask) and the calculated neutron multiplication factor (k_{eff}) required to be, for both normal and accident conditions, lower than 0.95. The maximum values found were 0.87165 ± 0.00070 for TRIGA elements and 0.89890 ± 0.00082 for MTR [6], 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.

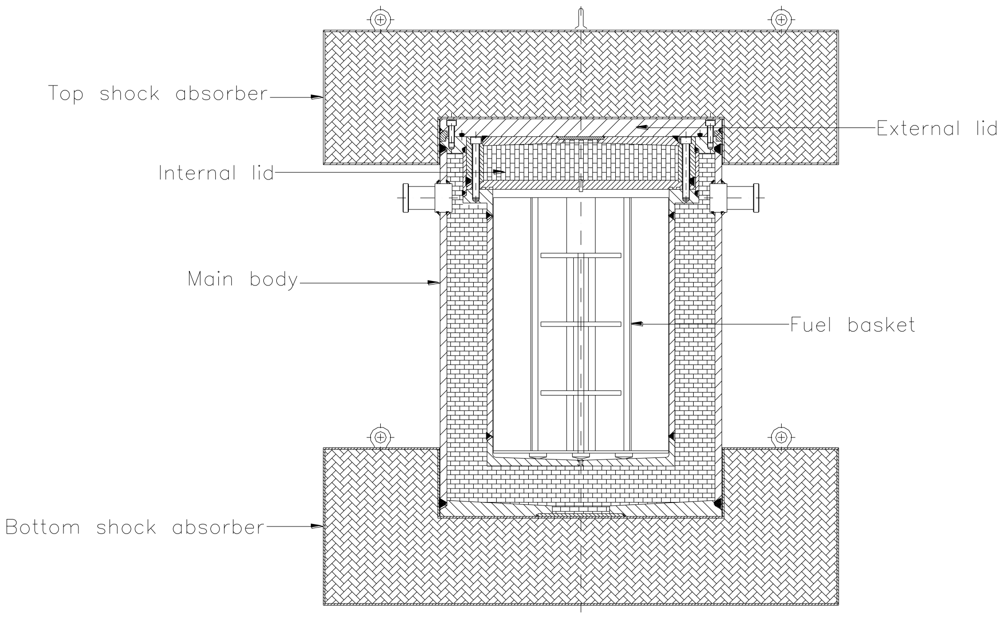

Figure 1. Transport cask for research reactor spent fuel

3 CASK MODEL TESTING

As part of the cask development program, the half-scale model was submitted in two instances to the sequence of tests prescribed at the IAEA´s standard for the safe transport of radioactive material [5]. The test campaigns took place on June 2008 and June 2010, 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 contamination release rate were translated into gas (helium) leakage rate. Therefore, a maximum helium leakage rate of 10^{-7} Pa.m^3/s was established as approval value. An initial helium leak test was carried out prior to any other test and the cask model 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 cask model side wall. The accelerometers orientation angles with respect to the model main axis were respectively 0^o, 45^o and 90^o. 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.

3.1 First Test Campaign

The first test campaign, carried out on June 2008, consisted of the tests shown in Table 2.

Table 2. 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[a] – corner, 43^o inclination to horizontal
	1.2m drop test II	Upside down
	1.2m drop test III	Horizontal drop position
	Penetration test	-
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	-

Sequence	Type of test	Remarks
-	Containment test	Final helium leak test
-	Gamma scanning	Shielding verification

[a] Center of Gravity

The methodology used to simulate the water immersion test consisted of checking the leak tightness of the cask model'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.

Figure 2. Electrical circuit at the top rim of the cavity

The sequence of 1.2 m drop tests that followed was intended to challenge the cask model'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 cask model 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 [5] 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 to it. In order to verify different responses to this test, the cask model 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 model. The numerical data collected will be useful in the validation of the numerical simulation of this test.

The test consisted of submitting the test model for 30 minutes to a temperature of 800 ^{o}C. The test was carried out in an industrial electrical furnace preheated to 804 ^{o}C and the model 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 ^{o}C;
Cask wall, 1/3 thickness:	436 ^{o}C;
Cask wall, 2/3 thickness:	405 ^{o}C;
Cask cavity:	254 ^{o}C.

The maximum temperature range registered by the labels on the basket and dummy fuel elements was 163 ^{o}C < T < 177 ^{o}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 cask model 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.

3.2 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 mainly 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, 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 2010, as seen in Table 3. 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 cask model (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 3. 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^o 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^o 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, cask model 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, cask model upside down
	Containment test	Leak above limit
	Containment test	Seals replaced, bolts re-tightened - Leak below limit
	9m drop test III	CG – corner, 48^o 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 cask model to 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.

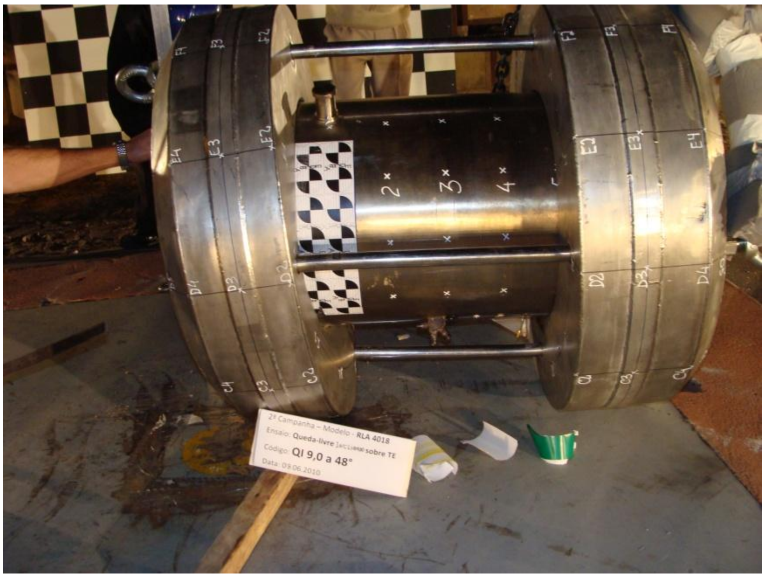

Figure 4. Cask model after 9 m CG-corner drop test: less damage observed

4 CONCLUSIONS

The results gathered in the two test campaigns suggest that the cask design is robust. The specimen has suffered several impacts without significant permanent deformations. However, the specimen failed the helium leak tests, although presenting only a small leak in the internal lid inner gasket. The external lid seal and both the pressurization and the draining ports remained leak tight.

The design modifications introduced between the two test campaigns brought good improvements to the overall cask model behavior, but, on the other hand, were a handicap during the drop tests in the upside down position. The energy absorption of the impact limiters during this test appears to be less than expected and then the cask suffered very high accelerations during the short duration impact. These accelerations were the cause of the lid displacement and the consequent loss of the sealing properties by the lid seals.
The impact limiters must then be re-designed in order to reduce the accelerations transmitted to cask body. The impact limiters behaved too rigidly, due both to the weld joints reinforcement introduced between the two campaigns and the re-orientation of the OSB boards in its central region. An alternative energy absorbing filling material – rigid polyurethane foam – will be considered as a substitute for OSB for the next test campaign.
Also an extremely high friction coefficient was observed during the lid bolts tightening, which is indeed expected when using stainless steel bolts. As an alternative, lubrication or high strength steel – or both – will be considered to ensure appropriate lid pressure on gaskets.

The recommended design enhancements will be completed and the model will be subjected to another test campaign in the third quarter of 2011.

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