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Options for the interim storage of IEA-R1 research reactor spent fuels

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Abstract

This paper presents an analysis of different options for the interim storage of research reactor spent fuels. The analysis' results showed a dual-purpose metallic cask as one of the most feasible options for the interim storage of the spent fuels of the IEA-R1 research reactor, located at IPEN-CNEN/SP, in Brazil. In case this reactor keeps its continuous operation at 5 MW in the next years, it will be necessary to transfer the spent fuels, today located in the reactor storage pool, to a spent fuels interim storage, until a definition of the Brazilian national policy on the final disposal of these spent fuels is established.

Keywords: Research reactors; Spent fuel elements; Dual-purpose metallic cask

1. Introduction

In most research reactors, the spent fuel discharged from the core is initially stored underwater in the reactor storage pool for long periods of time. This allows for heat dissipation and fission product decay.

Interim spent fuel storage facilities have been designed for the safe storage of spent fuels after their removal from the reactor storage pool and before they are reprocessed or disposed as radioactive waste. The design of such facilities must incorporate features that will be effective for their lifetime. Such features are (a) maintenance of subcriticality; (b) maintenance of fuel integrity; (c) minimization of fuel cladding corrosion; (d) removal of spent fuel decay heat; (e) provision of radiation protection; and (f) maintenance of isolation of radioactive material. The design must also consider the expansion of the facility capacity, and its eventual decommissioning.

The research reactor IEA-R1 is located at the "Instituto de Pesquisas Energéticas e Nucleares – IPEN-CNEN/SP", on the campus of University of São Paulo (USP), in São Paulo, Brazil. From 1957 to 1961, the reactor operated mainly for commissioning tests and some nuclear physics experiments, although designed to operate at 5 MW. The operation time was less than 8 h a day during week days, with power levels between 200 kW and 2 MW. In 1961, the reactor started to operate at a constant power of 2 MW, 8 h/day, 5 days/week. In 1995, a new program was established to increase the Brazilian production of radioisotopes, and the operational regime was changed to continuous 64 h/week, from Monday through Wednesday, keeping the reactor power at 2 MW. Furthermore, some modifications started taking place in order to increase the reactor power to 5 MW under continuous operation during 120 h/week complying with the applicable up to date Brazilian licensing requirements.

During the last years, the burn-up rate of the reactor has ranged between 120 and 240 MWD/year, and it was expected to reach 640 MWD in 2004. However, due to some problems in the primary cooling system heat exchanger, the reactor power was kept at 3 MW, instead of 5 MW as originally planned, and the burn-up reached only the value of 400 MWD. According to the original planning, at the end of 2006, the reactor power should be 5 MW, and the operational schedule should go from 64 continuous hours to 120 continuous hours per week.

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If this had been achieved, the burn-up rate of the reactor would increase to 1200 MWD/year, which would mean a burning up between 22 and 24 fuel elements per year.

When the IEA-R1 reactor fuel elements storage capacity is analyzed according to its expected operational condition, it can be observed that its storage scenario is not so comfortable, even considering that in 1999, 127 fuel assemblies were sent back to the United States of America. At present the available infra-structure for spent fuel in IEA-R1 are some metallic racks installed in the reactor pool, with total capacity for 156 fuel assemblies. According to the expected operational regime (5 MW, 120 h/week) 22–24 assemblies will be spent annually. Currently, 43 storage positions are occupied, and 24 are reserved to store a complete core according to operational procedures. This means that only 89 positions are available for the spent fuel storage, suggesting that in 5 years the IEA-R1 reactor wet storage facility will be full.

The present policy in Brazil does not foresee the reprocessing/recycling of spent fuel. In case where the construction of repositories for the final disposal of spent fuels in the next years will not be established by the government, IPEN will have to build a facility for interim storage of the research reactor IEA-R1 spent fuels. Therefore, an extended interim storage should be seen as the next step in the IEA-R1 reactor spent fuel management. The term ‘‘extended’’ takes into account that the facility should be designed for long-term storage, considering the uncertainty of the nuclear policy for the Brazilian research reactors spent fuels.

2. Analysis of options for the IEA-R1 research reactor spent fuel interim storage

In 2001, IPEN started the first discussions on the necessity of an interim storage of IEA-R1 research reactor spent fuels looking for developing a specific storage facility in the next 10 years. Between 2001 and 2004, IPEN has also participated with CDTN-CNEN/BH and other Latin American institutions in the IAEA Latin American Regional Project RLA/4/018 entitled ‘‘Research Reactor Spent Fuel Management Options in Latin America’’ (IAEA-TECDOC-1508, 2006). One of the interests of IPEN in this project was to identify possible options for interim storage of the reactor spent fuel, in order to define the most convenient option in a further period.

The most common way of wet storage consists of storing spent fuel elements in water pools, usually supported directly on racks or baskets. Sometimes, before storing, the fuel elements may be inserted inside sealed canisters used to isolate the nuclear fuel. Racks and baskets are open frames with functions including heat transfer, criticality control and structural support for the spent fuel elements but the baskets may be removed from the reactor pool and used as an open container or inside a cask for handling and transportation operations of the spent fuel. In the wet storage facility, the pool water surrounding the spent fuel provides the heat dissipation and the radiation shielding, and the racks or the baskets ensure the geometrical configuration which maintains the subcriticality and the heat transfer required conditions. A number of features of this technology are (IAEA-TECDOC-1508, 2006) as follows: (a) the technology is identified, mature and well established; (b) experience to store even damaged fuel; (c) international experience indicates that aluminum cladding spent fuel may be kept underwater over 50 years in pristine conditions, provided that high quality water, environmental conditions and a proper surveillance program are ensured. On the other hand, aluminum cladding fuel degrades almost immediately in poor water quality or bad environmental conditions; and (d) the resources, both human and financial, required to implement this technology may well be higher than those of dry interim storage alternatives.

Interim dry storage is a good approach to allow the continued use of the reactor facilities, as either an alternative or a complementary option to the interim wet storage. At present, dry storage is likely to be a competitive alternative to interim wet storage and may be the best option to store aluminum-based fuel. The major features of this technology are the following (IAEA-TECDOC-1508, 2006): (a) eliminates corrosion degradation of the fuel clad providing that the storage is truly dry and the fuel has been properly dried prior to storage. This allows, in principle, a much longer period for interim storage, while the country studies and comes to a decision on final options; (b) can be implemented through modular designs, e.g., metal casks, concrete containers, dual-purpose (transport/storage) metal casks, etc. and (c) could be used to reduce the pressure to build new wet facilities, avoiding modifications inside reactor sites, which could generate problems in fulfilling contracts for radioisotope generation. However, the need to encapsulate each fuel element (e.g., in canisters) before its deposition in the spent fuel storage is an important factor when considering dry interim storage options as it could modify the economical features.

In the dry storage facility, the spent fuel is surrounded by a gas such as air or inert gas. Dry storage facilities include the spent fuel storage in vaults, silos and casks (IAEA Safety Series 116, 1994).

Vaults consist of above- or below-ground reinforced concrete buildings containing arrays of storage cavities suitable for containment of one or more fuel units. Shielding is provided by the exterior structure. Heat removal is normally accomplished by forced or natural convection of air or gas over the exterior of the fuel containing units or storage cavities, and subsequently exhausting this air directly to the outside atmosphere or dissipating the heat via a secondary heat removal system.

Silo or concrete canister is a massive container comprising one or more individual storage cavities. It is usually circular in cross-section, with its long vertical axis. Isolation and shielding are provided by an inner, sealed liner and the massive concrete of the canister body. Heat removal is accomplished by radiant transfer, conduction and convection within the body of the canister and natural convection at its exterior surface.

Cask is a massive container that may be used for transport, storage and eventual disposal of the spent fuel. It provides shielding and containment of spent fuel by physical barriers which may include the metal or concrete body of the cask

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and welded or sealed liners, canisters or lids. Heat is removed from the stored fuel by radiant heat transfer to the surrounding environment and natural or forced convection. Casks may be located in enclosed or non-enclosed areas. The spent fuels are loaded vertically in the casks that are stored in vertical positions. They are placed in baskets or sealed metal canister that provides structural resistance, subcriticality and closing through a double cover. The casks can have single-, dual- or multiple-purposes. The spent fuel transport option by cask is called a single-purpose and the transport and storage options are called dual-purpose. The multi-purpose term is reserved for the casks that are designed with the transport, storage and disposal options. The IPEN studies are concentrated only in dual-purpose casks.

The dual-purpose cask option can be found as cask-based or canister-based systems (Mattar Neto, 2004). For the cask-based system, one integral unit serves all purposes for which the system is designed. For canister-based systems, a sealed canister contains the spent fuel, and is a common component or subsystem to the storage and transport system, as applicable to the design. Typically, canister-based systems will use overpacks to house the canister for the purposes of storage and transport. The container system for spent fuel storage and transport shall be designed to satisfy specific radiological safety functions. In general, it shall contain the radioactive material, limit emission of ionizing radiation, dissipate internal heat, and assure subcriticality.

The container shall also be designed to assure structural integrity and thermal performance that allow proper functioning of the systems' radiological safety features. Cask-based systems have been developed for storage and transport of spent fuel. These have generally been metal systems. For these cask designs, the same integral cask unit provides all radiological safety functions needed for storage and transport. For canister-based systems, the specific overpack along with the canister provides the level of performance for each safety feature for each purpose. The canister may provide one or more of the required safety functions. For example, the canister includes a fuel support structure or basket, which generally provides criticality control for storage, transport, and disposal, as applicable. The canister may also provide confinement of radioactive material for storage, but the transport overpack is generally used for containment of radioactive material during transport. The shielding required for storage and transport is typically provided by the appropriate overpack.

Besides the features above indicated, other general characteristics are important in the choice of an option for spent fuel interim storage. These characteristics include (Mattar Neto, 2004): (a) mobility; (b) the possibility of fuel retrievability; (c) modularity; (d) the reduction in the spent fuel handling operations; (e) public acceptance; and (f) economics.

Mobility is the ability to move a system from place to place. Retrievability will be defined as the ability to remove the cask, package, canister or spent fuel from its enclosure or emplacement. Mobility can be considered as a part of retrievability. The retrieval is always possible. The concern is whether retrieval, if necessary, will be easy or difficult to accomplish. Modularity is the ability to separate into distinct and standard units. The feature allows the designer to select canisters or casks of some chosen standard size and configuration. The utilization of dual-purpose casks, for example, will reduce the number of the fuel handling operations in comparison with the single-purpose casks. Although attempts to predict public acceptance are subjective and speculative, there are several factors that should be considered in such an assessment. A common public concern related to temporary storage is that temporary storage measures may be extended and eventually become permanent. Although canister-based and cask-based systems are regulated in the same way, and are expected to be equivalent from a radiological safety standpoint, the public perception of safety might be enhanced when canister-based systems are used. The canister might be perceived to provide an additional barrier of containment. Concerning economical advantages, wet storage facilities require continuous operation of cooling, filtration, cleaning and sampling systems which depend upon mechanical components such as pumps, valves and filters. The chemical and temperature control of water require continuous monitoring and sampling. Such operational requirements increase with the amount of fuel in the pool and are particularly high when pools are near to capacity. Siemens engineers have stated that dry storage facility construction costs are considerably lower per tonne of fuel stored than those of the wet storage facility, particularly in the case of small facilities (Peehs and Banck, 1993).

3. Option proposed for the spent fuel interim storage of the IEA-R1 research reactor

The choice of an option to be proposed for the IEA-R1 research reactor spent fuel interim storage was conducted in a way to supply a solution inside the technological and economic realities of Brazil. For the IEA-R1 reactor, it was not defined a decommissioning date. The reactor has been operating safely since 1957 and there is no plan to build a new research reactor to replace its research activities and radioisotope production. It is also not defined in the country the policy to be adopted for the spent fuel management after the operational storage. These uncertainties raise difficulties to define the type of interim storage facility to be built in the country.

Wet storages are made in pools, whose systems should be sized according to their capabilities in safe support of the storage of a certain number of spent fuels. The uncertainties in the quantity of spent fuels to be stored and in the period of time of storing could overestimate or underestimate the dimension of the needed pool. The modularity of some dry storage facilities becomes attractive. Besides, the construction and operational costs per tonne of fuel for wet storage facilities have been shown to be higher than those for dry storage facilities. Pools can give to the public the perception of a permanent facility, without mobility, which should be decommissioned in the future, complicating the licensing procedures. The wet storage facility construction near the reactor building could bring interruptions in reactor operation, hindering the execution of radioisotope production contracts.

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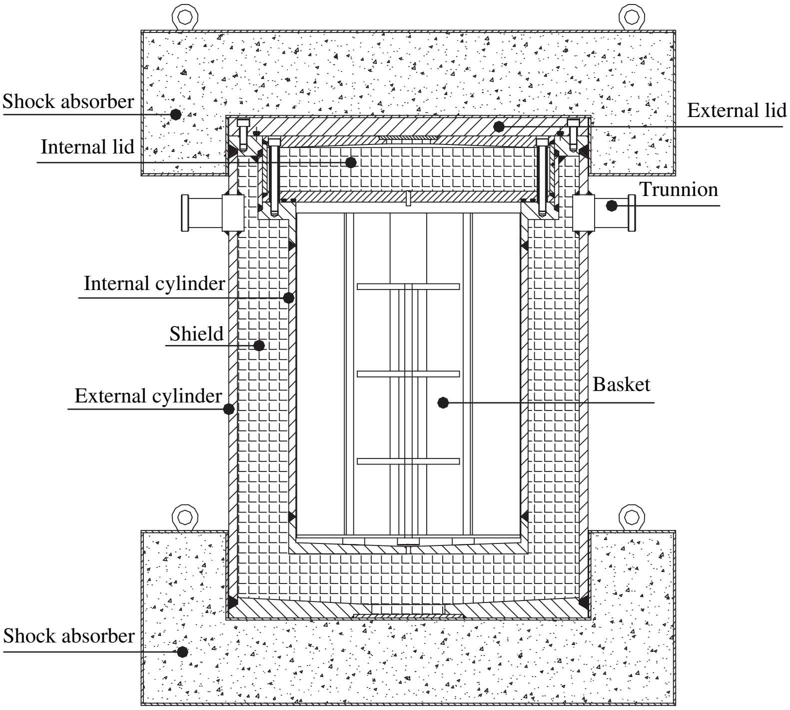

Fig. 1. Overall view of the dual-purpose metallic cask.

These aspects lead that the chosen option for the spent fuel storage of IEA-R1 reactor was directed to dry storage facilities. Among the existing dry storage, the first to be evaluated was the construction of a vault type facility near the reactor building, where the cavities for the dry storage of the spent fuels would be lodged internally. In order to attend this specification, it will also be necessary to build a transfer cask and a transport cask for the spent fuel. The transfer cask would be used to transfer the spent fuel from the reactor pool to the transport cask. The latter one would allow the spent fuel transport to the dry storage facility. It was also discussed the necessity of building a hot cell, where each fuel element would be encapsulated in canisters before its placement in the storage cavities. Again, the uncertainties in the quantity of spent fuels to be stored and the period of time of this storage complicate the establishment of the vault option, mainly in the definition of the building dimensions and the number of cavities for the intended storage. The vault option was relegated to a second plan, and the choice of casks and silos, in distinct and standard units, was considered the best alternative. Besides, inside the IAEA RLA/4/018 project, it was on-going the conception of a dual-purpose cask for transport and storage of the spent fuel from research reactors in Latin America (IAEA-TECDOC-1508, 2006). This metallic cask can accommodate 21 MTR fuel elements, as those of IEA-R1 reactor, and 78 TRIGA fuel elements. Based on these considerations, the dual-purpose cask is being considered as the most feasible option for the IEA-R1 reactor spent fuel storage. This option presents advantages against other options as it shows characteristics like mobility, modularity and reduction capacity of the fuel handling operations.

Table 1
Cask materials

Main body	Stainless steel ASTM A 240 grade 304 and lead grade ASTM B 29-92
Internal lid	Stainless steel ASTM A 240 grade 304 and lead grade ASTM B 29-92
External lid	Stainless steel ASTM A 240 grade 304
Shock absorber	Liners of stainless steel ASTM A 240 grade 304 filled with wood composite OSB – Oriented Strand Board
Internal basket	Stainless steel ASTM A 240 grade 304
Primary seal	O-rings – stainless steel ASTM A 321 with silver cladding
Elastomeric seal	Neoprene
Threads	Stainless steel ASME SA 193/193-95 – B8M
Nuts	Stainless steel ASME SA 194/194M-95a – 8M

4. Dual-purpose metallic cask description

The cask was designed to meet transportation and long-term storage criteria. The requirements for transportation are defined in an IAEA guide (IAEA TR-S1, 2001), where the cask must be structurally qualified for the normal conditions of transport and the hypothetical accident conditions which are critical in relation to the cask mechanical sizing. It must be demonstrated that the cask has to be sturdy enough to resist:

- a drop onto a rigid target so as to suffer maximum damage, and the height of the drop measured from the lowest point of the cask to the upper surface of the target shall be 9 m;

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Table 2
Comparison of some characteristics of MTR fuel elements from research reactors in Latin America

	Argentine	Chile	Brazil	Peru
Maximum number of plates	20	16	18	16
Composition	U–Al; U_3O_8–Al; U_3Si_2–Al	U–Al; U_3Si_2–Al	U_3Si_2–Al	U_3O_8–Al; U_3Si_2–Al
Maximum mass per assembly (kg)	5; 6.3; 7	5.5	6.13	6.79
Maximum thickness of the active plate (cm)	0.07	0.061	0.082	0.1
Clad minimum thickness (cm)	0.04	0.046	0.038	0.045
U-235 maximum initial mass per assembly (g)	425.6	214.5 (U_3Si_2–Al) 183 (U–Al)	280	240
Maximum burn-up (%)	50	50	50	50
Minimum cooling time (years)	2	5	5	5

- a puncture resultant from drop so as to suffer maximum damage onto a bar rigidly mounted perpendicularly on a rigid target. The height of the drop measured from the intended point of impact of the cask to the upper surface of the bar shall be 1 m. The bar shall be of solid mild steel of circular section, 15.0 ± 0.5 cm in diameter and 20 cm long unless a longer bar would cause greater damage, in which case a bar of sufficient length to cause maximum damage shall be used. The upper end of the bar shall be flat and horizontal with its edge rounded off to a radius of not more than 6 mm;
- a fire resulting in a temperature of 800 °C for 30 min;
- a submersion to a 200 m depth of water.

On the other hand, the cask constitutive materials have to present long-term stability and compatibility – among them and to the radioactive contents – and access to its internal cavity has to be granted for the usual storage period checks, as gas sampling, draining or pressurization.

Additionally to the above criteria, as the cask has been developed in the scope of a project involving Latin American countries operating research reactors, it has to follow the operational limitations of the region reactor facilities related to available handling systems and access doors. So, the cask design must satisfy two conditions, i.e., its maximum mass was set to 10,000 kg and its maximum diameter to 1 m. These operational limitations plus the other design requirements determined the final cask dimensions and its resultant maximum capacity of 21 MTR fuel elements (or 78 TRIGA fuel elements, using another internal basket).

The main components of the cask are the main body, internal and external lids, internal basket and shock absorbers. The body has a sandwiched wall with internal and external stainless steel layers and the intermediate space filled with lead for biological shielding. The internal lid has external stainless steel surfaces and lead filing, being provided with double metallic seals and pressurization and inspection ports. The external lid is basically a protection to the internal one. The basket structure is made of square tubes. The shock absorbers, sacrificial items added externally to the cask main body to absorb energy in case of impacts and to provide thermal barrier, are made of thin stainless steel covering filled with the wood composite OSB – Oriented Strand Board.

The cask main features are shown in Fig. 1.

The main dimensions of the cask are as follows:

- maximum diameter (with shock absorbers): ∅ 1800 mm;
- total height (with shock absorbers): 1996 mm;
- main body maximum dimensions: ∅ 984 mm × 1326 mm;
- internal cavity dimensions: ∅ 616 mm × 928 mm.

The cask materials are shown in Table 1.

Table 3
Dose rates for basket with MTR fuel (Dalle, 2003a,b)

	Dose rate (μSv/h)		
	Cask surface	1 m distance	2 m distance
Cask side	233.5	30.7	10.5
Cask end	1519.4	240.8	72.4
Allowable limit	10,000		

5. Shielding and criticality safety analyses

5.1. Shielding analysis

A shielding analysis of the cask was carried out with SCALE4.4A (ORNL/RSICC, 2000). Neutron and gamma contributions were taken into account.

Fig. 2. Model main body.

Fig. 3. Internal lid.

A comparison between some characteristics of the MTR fuel elements from Latin America research reactors is shown in Table 2 and, from it, the reference fuel element used for this analysis was selected. It is the MTR standard type manufactured by CNEA (Argentinean Atomic Energy Commission) for its RA-3 reactor, the most critical one amongst the region research reactor fuel, including the IEA-R1 reactor.

Table 3 shows the dose rates for MTR fuels. It can be noted that the highest dose rates occur at the top and bottom ends of the cask. These values are within the regulatory limit applicable to undamaged Type B packages transported under exclusive use, 10,000 μSv/h (IAEA TR-S1, 2001).

5.2. Criticality safety analysis

The Monte Carlo transport code MCNP4B (Briemeister, 1997) was used in the criticality safety analysis. Three scenarios were considered regarding neutron moderation (Dalle, 2003a,b):

Fig. 4. Internal lid – bottom.

Fig. 5. External lid.

- the cask is fully dry, air surrounds the fuel elements;
- the cask is totally filled with water, air surrounds the cask, as may occur during the cask loading;
- the cask cavity is flooded with water and the whole cask is surrounded by a 30 cm thick layer of water, corresponding to an accident condition where the cask is fully submerged in water.

Furthermore, a case was simulated in which the dimensions of the internal basket cells were reduced from 10.0 cm to 8.74 cm in order to simulate a situation in which the fuel elements were as close as possible to each other.

Fig. 6. Basket.

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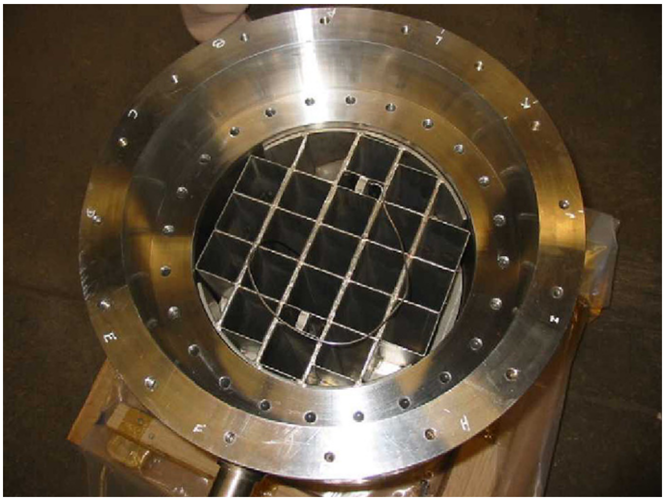

Fig. 7. Main body and basket.

The highest k_{eff} value was verified for the cask flooded and surrounded by water, with reduced dimensions of the internal basket cells:

$$\left(k_{\mathrm{eff}} \pm 2\sigma\right) = 0.89890 \pm 0.00082 \qquad (1)$$

The results obtained guarantee that, as for criticality, the cask can be loaded and unloaded safely.

6. Ancillary equipment

An assortment of items necessary for the proper cask manipulation, connection to site services (water, gas, etc.), per-use leakage tests, and tie down to the transport vehicle has to accompany the cask.

Some pieces of the needed ancillary equipment are as follows:

- transfer cask;
- lifting fixture;
- tie-down fixture (cables, crib);
- water tank adapted to the top of the cask or mirrored surface to avoid the direct operators exposure to radiation;
- connectors to facility services (e.g., air, water, inert gases);
- diverse tools (torque wrenches, pressure gauges, etc.).

Fig. 9. Shock absorbers.

Fig. 8. Complete model.

Fig. 10. Gamma scanning test.

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Fig. 11. Helium leakage test.

7. Test model

The cask licensing will be based on the IAEA guide (IAEA TR-S1, 2001). This guide contains "…performance standards, as opposed to specific design requirements. While this means greater flexibility for the designer, it presents more difficulties in obtaining approval. The intent is to allow the applicant to use accepted engineering practice to evaluate a package. This could include the testing of full scale packages, scale models, calculations, or a combination of these methods".

Considering that it is very difficult and more expensive to test the cask in its natural size (full scale), the adopted strategy for cask licensing is a combination of half scale model development and testing plus calculations.

7.1. Model description

As stated previously, the cask is expected to resist accidental conditions unlikely to occur during transportation without permitting any dispersion of its radioactive contents or a significant increase in its surface dose rate.

To verify this requirement, a half scale model for testing purposes was designed and manufactured. The design followed basically the guidelines of the Oak Ridge National Laboratory *The Radioactive Materials Packaging Handbook* (ORNL/M-5003, 1998) and the ASME B & PV Code, Section III, Division 1, Subsection NB (ASME, 1998). The most relevant items for safety were calculated analytically. The model's external wall thickness was calculated to resist the penetration of a flat pin, whereas the cavity wall thickness was verified against buckling due to the radial pressure resulting from the contraction of the lead due to its cooling during the model fabrication. Also the internal lid, which is part of the cask containment system, was dimensioned to resist an internal cavity pressure of 7 bar, established as the maximum pressure the cask should resist. The verification included the 24 bolts connecting the lid to the model's main body. Another critical feature was the model welding parameters and quality. The welds were designed according to ASME Code. All welds belonging to the containment system (basically the welds of the internal cavity) were submitted to radiography test.

The main parts of the model are shown in Figs. 2–9.

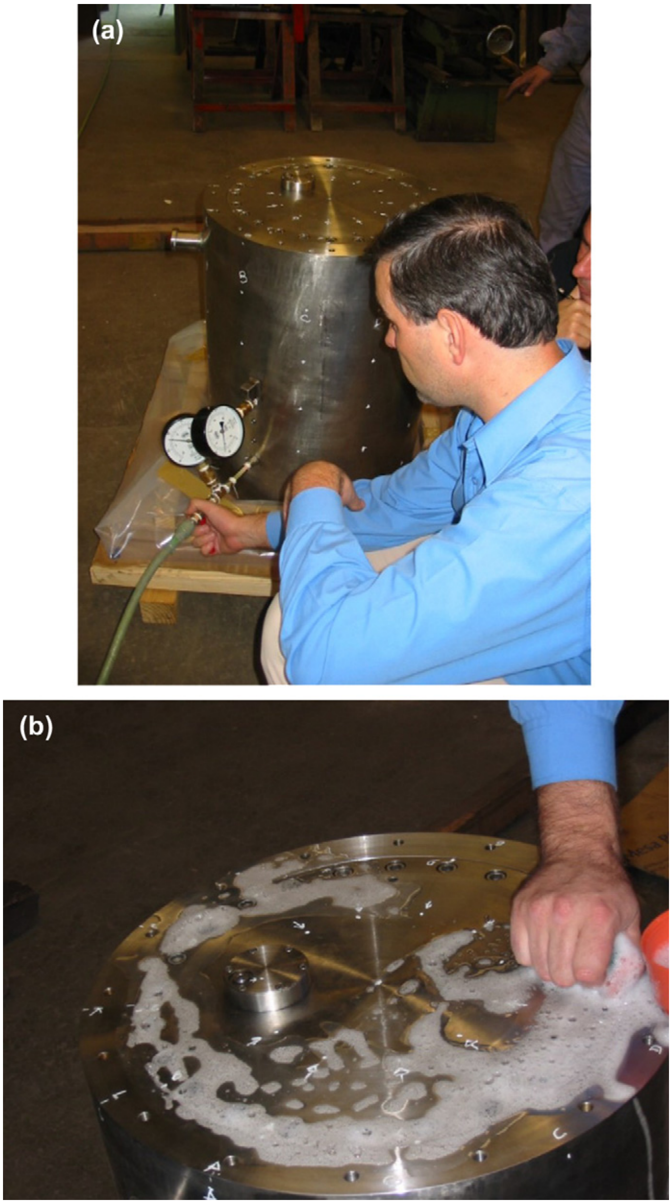

Fig. 12. Pneumatic pressure test.

7.2. Model acceptance tests

The model was submitted to acceptance tests carried out at the supplier's premises. The tests, detailed in the technical specifications for fabrication sent to the manufacturer at the beginning of the manufacture, consisted of gamma scanning test, helium leakage test and pneumatic pressure test. The test sequence was deemed to prove that the model shielding and containment features met the required quality and its mechanical strength attended the specifications. Some aspects of gamma scanning test, helium leakage test and pneumatic pressure test are shown in Figs. 10–12, respectively.

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8. Conclusion

The conceptual design of a dual transport cask for the interim storage of IEA-R1 spent fuels was finalized and a scale prototype was manufactured in Argentina for qualification tests to be held at CDTN-CNEN/SP, Brazil, in October 2007. The dual-purpose cask Safety Analysis Report (SAR) is being prepared for submission to the licensing authority in Brazil. IPEN is now developing the general requirements and the design aspects of the conceptual project of a spent fuel storage facility that will accommodate the dual-purpose casks.

Acknowledgments

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