A Perspective on an R&D Program for Spent Fuel Interim Storage Cask System

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1. INTRODUCTION

Cask systems for spent fuel interim storage should have sufficient capability to comply with both transport and storage requirements. In recent years, spent nuclear fuels (SNFs) discharged from commercial nuclear power plants have a higher burnup rate and are stored after a shorter cooling time in the pools. On the market side, the economy of interim storage is regarded as just as important as keeping its safety.

Mitsubishi Heavy Industries, Ltd. (MHI) has been developing a new “MSF” cask fleet for transport and storage of the SNFs, focusing on a large payload of high-burnup and short-cooled SNFs. For the development of the MSF casks, the research and development (R&D) program has targeted on improving their safety and reducing their manufacturing cost. This paper presents the approach and the results of the R&D program for the MSF cask fleet.

2. MSF CASK FLEET

The MSF storage and transport cask provides the capacity to satisfy the requirements with respect to commercial SNF, especially high burnup and short cooled SNFs. They are designed to meet Type B (U) fissile requirements of the IAEA Regulations for the Safe Transport of Radioactive Materials (TS-R-1) as well as other regulations, guidelines, standards, and authorizations for storage and transport. They are also in accordance with ASME Section III subsection NB for pressure and containment boundary and NG for basket structure.

The MSF cask consists of the following major components (See Figure 1).

- Containment vessel comprised of a monolithic low-alloy steel forging shell, a primary lid and a secondary lid with closure bolts, and metal O-ring seals
- Neutron shielding material installed around the cask body, base plate, and primary lid
- Two pair of trunnions for handling and tiedown
- Boron containing aluminum alloy fuel basket providing positions for spent fuel assemblies
- Impact limiters attached to each end of the cask during transport

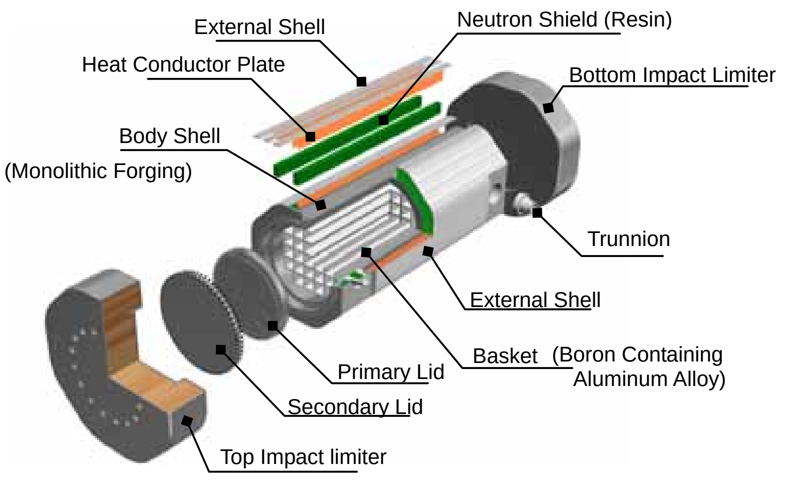


Figure 1. Overview of MSF cask fleet

The MSF casks are cylindrical in shape with a multi-layer structure consisting of a forged steel body shell and a carbon steel outer shell and a layer of neutron shield enclosed between the body shell and the outer shell. A double lid closure system with a metallic O-ring seal provides the containment boundary of the cask, and a pair of impact limiters is attached to each end of the cask. An internal basket consisting of boron-containing aluminum alloy provides compartments for accommodating spent nuclear fuel assemblies.

3. R&D PROGRAM

The period for interim storage is assumed to be 40-60 years. The cask's safety functions, which include Containment, Shielding, Subcriticality (Confinement) and Heat dissipation, should be maintained during long-term storage and transport after the storage. To secure these safety functions, the design, parts and materials of the cask should have appropriate integrity and be evaluated based on verification studies. Issues to maintain the safety functions are identified as follows:

1) Containment

The capability of the cask closure system during storage and transport should be evaluated to meet the requirements for storage and transport. The capability of the closure system under accident conditions such as the 9m-drop test should be confirmed. In addition, the deterioration of the sealing ability caused by relaxation of the metallic O-rings seal during the storage period should be evaluated.

2) Shielding

A deterioration of the epoxy-based neutron shielding material is caused by heating during storage. The loss of hydrogen content, evaluated as a reduction of its weight, should be limited to keep the shielding requirements.

3) Subcriticality (Confinement)

Subcriticality depends on the strength of the basket materials. For example, an aluminum alloy is used for the basket assembly, but the strength of the aluminum tends to be affected by heating. Materials for the basket should have enough strength and toughness under accident conditions and stability after long-term usage under heating conditions.

4) Heat dissipation

The materials and parts of the cask which maintain the cask safety functions may deteriorate by heating from the stored SNFs, decay heat. The heat dissipation capacity should be secured adequately.

Structural integrity related to securing the cask safety functions also has to be preserved during storage and transport. One approach is the use of materials which have good properties for long-term service. The other is the reduction of the load on the cask structure under normal and accident conditions. The reduction of the impact load is especially effective to maintain the structural integrity under 9m-drop test conditions.

From the economical point of view, a larger payload is desirable. To increase the number of stored fuels in a cask, the weight of the cask itself and its heat dissipation capability need to be improved. Improvements of the manufacturing process also contribute to the reduction of the cask's own cost. An overview of the R&D items and their relation to the safety functions and the cost reduction for the MSF cask is shown in Figure 2. The MSF cask fleet has been developed according to this R&D program.

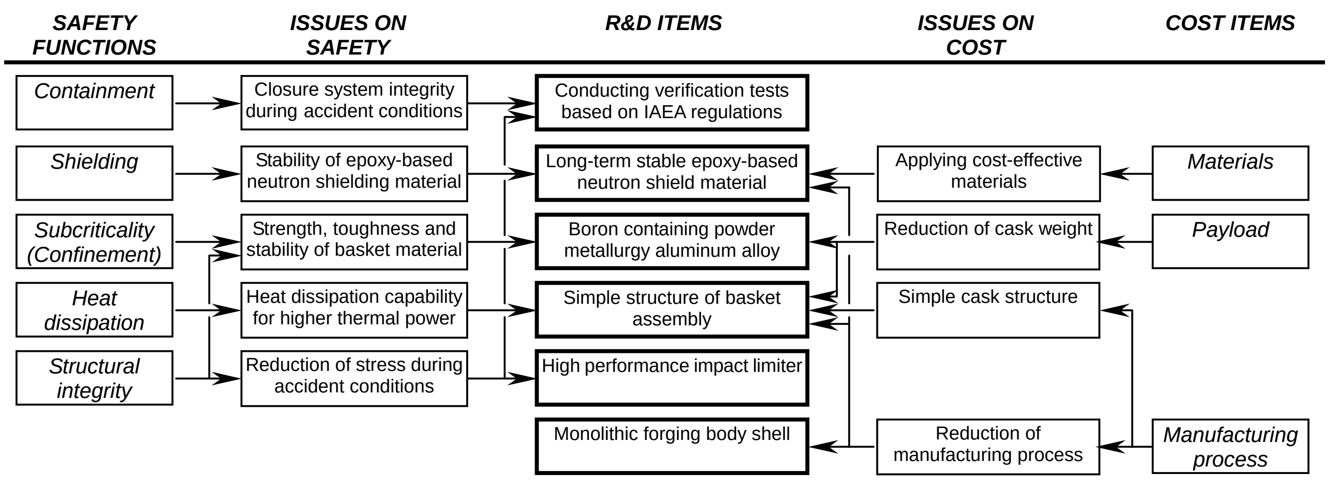


Figure 2. Overview of R&D items

4. DEVELOPMENTS

(1) Closure system

The containment capability of the cask system depends on its closure system and body shell. The closure system of the MSF cask consists of the primary lid and secondary lid with a metallic O-ring seal. The sealing capability of the closure system under normal and/or accident conditions, which can be evaluated by the leak rate, need to be confirmed basically by testing with a full-size cask. However, as it seemed that the leak from the closure system is caused by motion between the lid and its flange, the sealing capability can be estimated by testing with a scaled cask model.

MHI has conducted a series of drop tests using a 1/2.35-scaled cask model and confirmed its sealing capability. The closure system, including the O-rings and their grooves, is scaled down low. The leak rates after the drop test were less than approximately 10^{-9} Pa·m^3/sec, and no damage was observed in the closure system.

In addition, the elastic recovery and sealing force (= pressure) of the O-ring are reduced by thermal relaxation. MHI has developed an FEM analysis method to evaluate the adequate sealing force and elastic recovery during long-term service.

(2) Neutron shield material

Epoxy resin-based material (resin) is used as a neutron shield. In case of accommodation of a high burnup and short cooled SNFs, its service temperature goes up to 170 deg. C. Non-flammable and self-extinguishing properties are required under IAEA regulations, too. The resin has a characteristic to reduce its own weight under heating conditions by mainly releasing the contained molecules of H_2O. This phenomenon affects the safety evaluation of the shield. Based on our research, weight reduction of the resin is caused by deterioration in the filler that is added to supply the non-flammable and self-extinguishing properties.

MHI has developed a new resin-based neutron shield material which is mixed with $Mg(OH)_2$ as a non-flammable and self-extinguishing filler. With its high hydrogen content, it has good neutron shielding properties and is stable over a high range of operating temperatures for long-term service. The weight loss of the resin could be restricted to less than 0.1 % at a service temperature of 170 deg. C during the 60-year storage period. The result of the long-term heating test is shown in Figure 3.

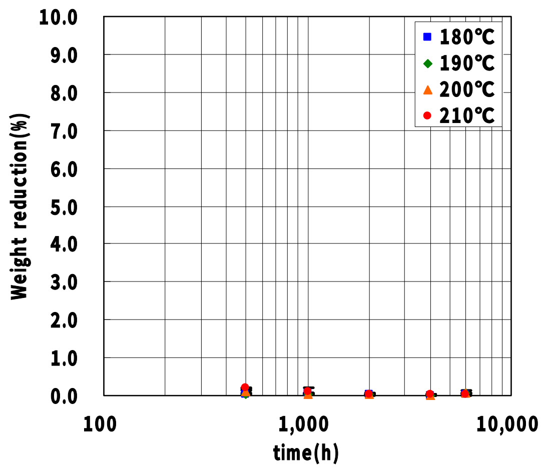


Figure 3. Weight reduction vs. heating time

A layer of the resin is enclosed between the body shell and the outer shell of the cask. With the conventional process of casting into neutron shielding layers, the volume of a casting batch is about 100 kg, and it takes 2 weeks to completion. MHI has improved the casting process and facility, developing a simulation code for hardening of the resin due to optimizing the one-batch volume. The new casting facility can cast 600 kg of the resin per batch.

(3) Basket and basket materials

Aluminum alloy is suitable for the cask basket material, because it has low density and good heat dissipation properties. A higher boron content in aluminum is desired to provide criticality control. However, the boron contained in a conventional aluminum alloy is limited within a maximum of 1 wt% due to its lower toughness property.

MHI has developed a new boron-containing aluminum alloy (B-Aℓ) manufactured by a powder metallurgy process for baskets of the MSF cask fleet. In comparison with the conventional method, this powder metallurgy method has good features, as follows:

1) Uniform boron distribution
2) Avoidance of needle crystallization of “Al-B_2” which affects the brittleness of the material
3) No degradation of the strength due to annealing (over-aging)

This B-Aℓ alloy has been registered as ASME code case "N-673," which can be used in the construction of Section III, Subsection NF, Class 1 supports, and Subsection NG, Class CS, core support structure for storage and transportation of spent nuclear fuel in Section III, Division 1. The key features of N-673 alloy are as follows:

1) Higher stability and high-temperature strength for long-time service
2) Higher toughness than that of conventional boronated aluminum alloys
3) High thermal conductivity equal to or higher than that of conventional aluminum alloys
4) Higher boron content: 1.5 wt% - 9 wt% B4C.

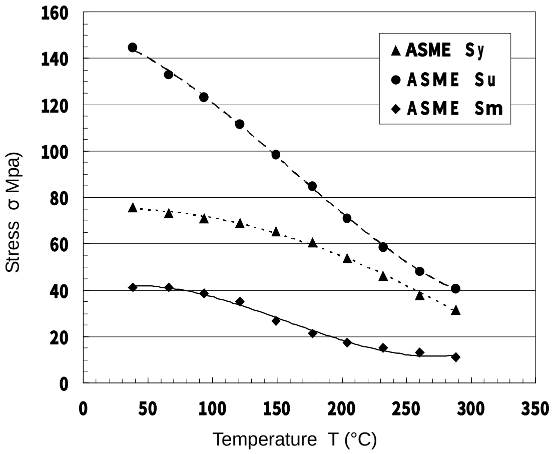
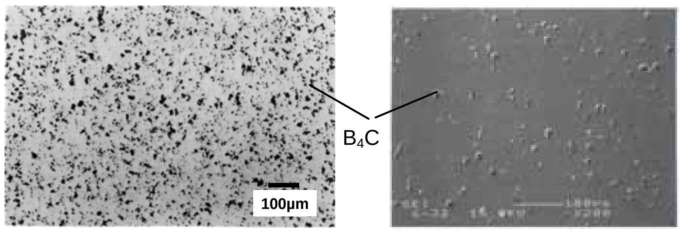


Figure 4. Mechanical Properties of ASME N-673

The mechanical properties of N-673 are given in Figure 4 and the microstructure showing B_4C distribution is given in Figure 5.

Furthermore MHI has been improving the powder metallurgy method by adding "Mechanical Alloying (MA)" process. The MA process provides finer crystal grain size to improve its strength. The high strength B-Aℓ has enough properties (0.2 % proof stress of over 100 MPa at 250 deg. C) to be applied for the basket at higher service temperature such as high burnup fuels and/or short cooling period in the reactor pool.



Microstructure (Optical Microscope)

Secondary Election Image (Electron Microscope)

Figure 5. Microstructure of ASME N-673

The cask cavity is fitted with a basket designed as a structural support for the fuel assemblies. Fuel compartments for PWR fuel are provided by assembling rectangular hollow plates into lattices. The basket for BWR fuel assemblies with channel boxes consists of square tubes to provide the fuel compartments. Each type of the basket is made of the boron-containing aluminum alloy manufactured by powder metallurgy and formed by hot extrusion. These simple basket assembly structures contribute to be reduction of manufacturing steps.

(4) High Performance Impact Limiter

Under the requirements for the transport package, the most critical event is the 9m-drop test conditions. Saving the generated acceleration is effective for cask structural safety. The size of the impact limiter is restricted by transportation facilities.

MHI has developed a high performance impact limiter that has stable compression characteristics against deformation, optimizing the wooden materials and their arrangement. In order to verify the adequacy of the design, drop tests using a 1/2.35 scale model have been performed. The generated acceleration, structural integrity and closure system capability have been confirmed by the series of drop tests.

9m-Drop Test (Slap down) 9m-Drop Test (Vertical) 1m-Puncture Test

Figure 6 A series of drop tests based on IAEA regulations using a 1/2.35 scale model

(5) Monolithic forging body shell

The cask body is usually constructed using a cylindrical shell and bottom plate. By conventional manufacturing methods, the bottom plate is joined to the cylinder by welding. This process requires higher welding skills and periodic inspection of the welds.
A monolithic forging method has been developed by MHI that forms the cask body shell with its bottom plate in a single process. This method achieves a reduction of manufacturing steps and no inspection of a plate-to-cylinder weld during the manufacturing, service, and maintenance stages.

The manufacturing process for monolithic forging and a full-scale forging body manufactured as a trial are shown in Figure 7.

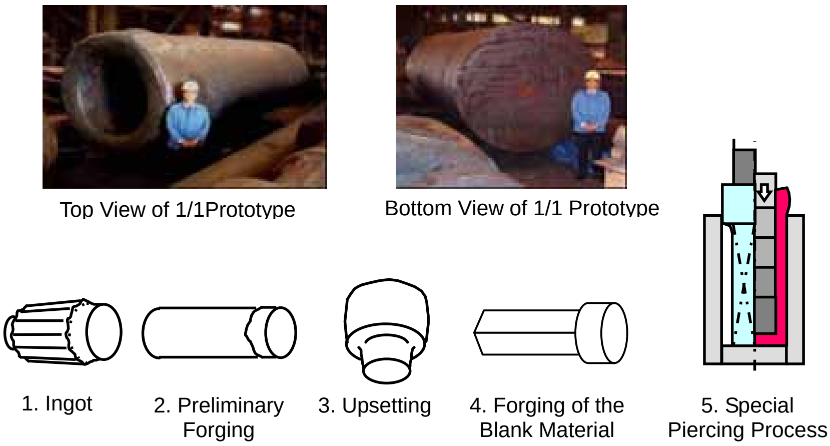


Figure 7 Overview of the monolithic forging method

5. CONCLUSIONS

The SNFs subject to interim storage are of a higher burnup rate and cooled for a shorter period of time in recent years. A large payload cask is desired to reduce the storage cost. Under these circumstances, the targets of MHI's R&D program are the improvement of cask safety and reduction of cask manufacturing cost. MHI has developed new materials and improved the manufacturing process as follows:

(1) With regard to subcriticality and heat dissipation, new boron-containing aluminum alloys manufactured by powder metallurgy have been developed for a basket assembly. One of them has been approved as an ASME Code Case. The basket assemblies formed by hot extrusion implement a simple and cost-effective structure.

(2) With regard to shielding, new neutron shielding materials have been developed to improve stability under high temperature conditions. The materials are made of epoxy-based resin and $Mg(OH)_2$ as a non-flammable and self-extinguishing filler. A casting plant for these shielding materials has also been improved to save casting costs by shortening the casting period, and to improve its quality too.

(3) With regard to containment and structural integrity, impact limiters have been improved by optimizing the woods used and their arrangement. The performance of the impact limiters has been verified by material property tests, a series of drop test on IAEA regulations and numerical analysis. The closure system has also been confirmed by these tests.

Based on the above program, the new "MSF" cask fleet, which can accommodate a large payload of SNFs with a high burnup rate and a short cooling period, has been established.

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