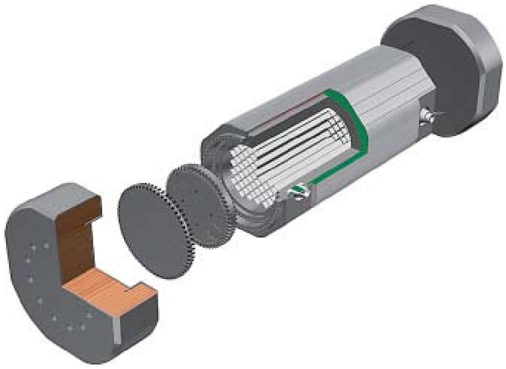


Developments in Spent Fuel Transport and Storage Casks

TOMOFUMI YAMAMOTO*1 HIROKI TAMAKI*2
SUGURU HODE*2 TOSHIHIRO MATSUOKA*2
YOSHIHARU KAMIWAKI*2 KIMINOBU HOJO*3

For spent fuel interim storage, safe and cost-effective storage and transport casks are demanded. To respond to this demand, Mitsubishi Heavy Industries (MHI) is proceeding with the strategic product development program of materials and manufacturing technology, including demonstration tests with a full-scale drop test model. Until now, MHI's technological developments in this field have focused on aluminum alloys for baskets, neutron shielding materials (resins), and a monolithic forging method for the main body shell. Through this research, MHI has also comprehensively demonstrated cask safety by conducting full-scale cask drop tests based on the Regulations for the Safe Transport of Radioactive Materials of IAEA. The MSF transport and storage casks (e.g. MSF-57B, MSF-26P) are the fruit of this technology.

1. Introduction

The high burnup of spent fuel with high decay heat in overseas nuclear power plants requires the use of high performance casks for transport and storage. The construction of the first commercial spent fuel interim storage facility (recyclable-fuel storage facility) in Japan is becoming a reality, and a safe and cost-effective cask is desired.

MHI has strategically developed the materials and manufacturing technology to be used for cask manufacturing to ensure full compliance with the requirements of domestic and foreign market environments. The safety of the developed casks has been demonstrated through drop tests with full scale and subscale cask models, based on IAEA Transport Regulations. These technological developments have culminated in the MSF dry type spent fuel transport and storage cask fleet (referred to below as the MSF cask).

In this paper, we report the features of the MSF cask and its technological development.

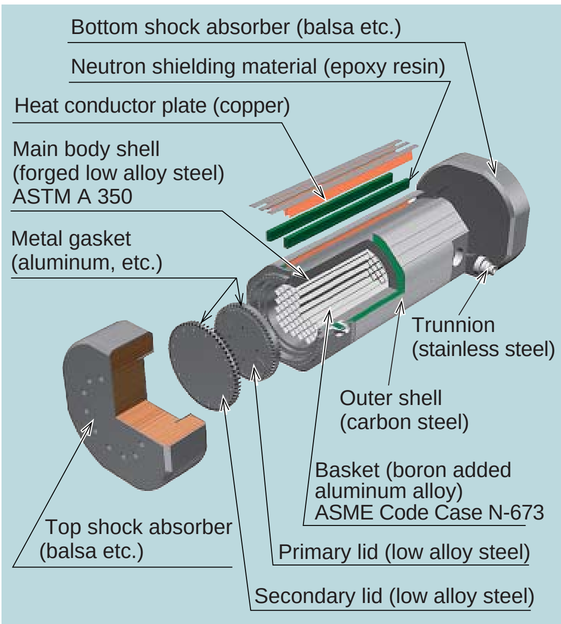


Fig. 1 An overview of the MSF Cast Fleet

2. Outline of the MSF cask

The MSF cask has been developed for the safe and cost-effective interim storage of spent fuel generated from domestic and overseas nuclear power plants. The cask is designed to comply with the requirements of both transport and storage, including IAEA Transport Regulations, and all laws, ordinances, and standards of the countries where it is used, also factors such as the design conditions specific to the site. **Figure 1** gives an overview of the MSF cask and **Table 1** lists its main specifications. Its main features are summarized as follows.

Table 1 The specifications of the MSF Cask Fleet

	MSF-57 B	MSF-69 B	MSF-21 P	MSF-26 P
Type	B (U)	B (U)	B (U)	B (M)
Fuel type	10 × 10 BWR	10 × 10 BWR	18 × 18 PWR	17 × 17 PWR
Payload	57	69	21	26
Cooling period (years)	≧5	≧9	≧6	≧15
U-235 enrichment (%)	5	3.7	4.5	4.2
Maximum burnup (GWd/t)	63	45	60	48
Calorific value (kW)	49	22	41	20
Weight (t)	125/140*	126/141*	121/136*	119/140*
Dimensions (m)	ϕ2.5 × 5.3	ϕ2.5 × 5.3	ϕ2.5 × 5.7	ϕ2.6 × 5.1

* : Weight (including the shock absorbers for transport)

*1 Nuclear Energy Systems Headquarters
*2 Kobe Shipyard & Machinery Works
*3 Takasago Research & Development Center, Technical Headquarters

- Boron-containing aluminum alloy basket made with powder metallurgy (developed by MHI)
- Forged low alloy steel main body shell (monolithic forging for overseas cask, developed by MHI)
- Double lid closure system with metallic gasket (tertiary lid for Japan market)
- Epoxy resin neutron shielding material (developed by MHI)
- High performance shock absorber (developed by MHI, attached to the top and bottom of cask during transport)

3. Technology development program

The cask must satisfy four safety functions: (1) containment (containment of radioactive materials), (2) shielding (shielding of radiation), (3) prevention of criticality (maintenance of sub-criticality), and (4) heat removal (dissipation of decay heat). The appropriate structural strength is required to ensure that the safety functions maintain their intended purposes. An assumed interim storage period of 40 to 60 years will require the reliable maintenance of each function.

From the viewpoint of economy, the cask should accommodate an increased number of fuel assemblies and incorporate weight saving design features and safety function enhancements. The simplified cask design and structure realize the reduction of the man-hours required for manufacture and inspection.

The development items for the MSF cask were determined through the evaluation of several issues with respect to the above enhancements of safety functions and economy. **Figure 2** shows the relation between the safety functions and cask structure. **Table 2** shows the relation between the various issues considered, including economy and the development items.

The following section gives an overview of the development items selected.

(1) Containment

The containment system consists of lids, a main body shell and its flange, and metal gaskets. The performance and structural strength of the sealing system must be verified to meet the requirements for both transport and storage. In addition, the aging deterioration due to heat and corrosion needs to be considered from the viewpoint of long term integrity.

(2) Shielding

Gamma ray and neutron radiation are shielded with the thick forged steel of the main body shell and the neutron shield installed around the main body. The issue to be verified from the viewpoint of long-term storage will be the aging deterioration of

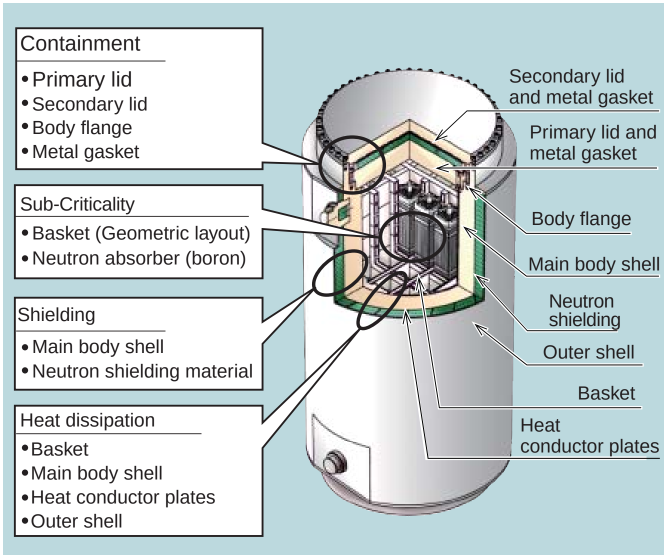
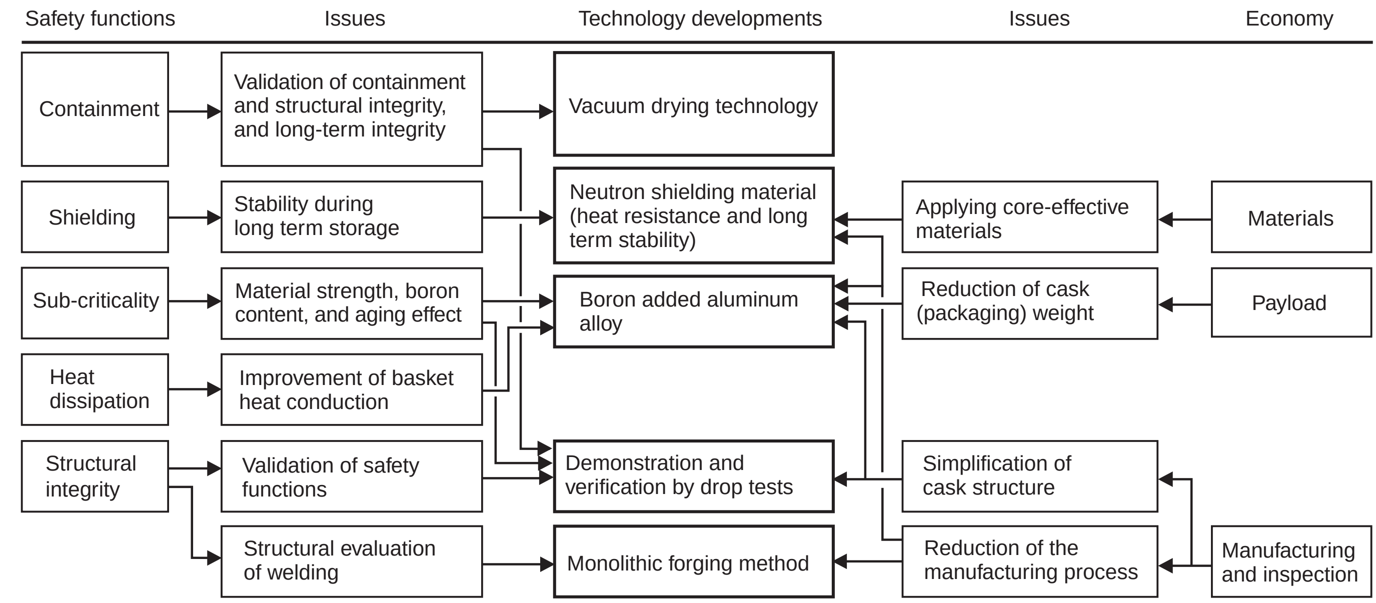


Fig. 2 Safety functions of the cask
Relation between the cask structure and safety functions

Table 2 Technology developments in relation to economy and safety functions



the high polymer materials used for the neutron shielding.

(3) Sub-criticality

The prevention of criticality is realized with the maintenance of the geometric layout of fuels by the basket and the neutron absorbing material contained in the basket. For this reason, the materials for cask basket are required to possess appropriate strength and toughness and contain the required amount of boron.

(4) Heat dissipation

The heat dissipation function is realized by dissipating the decay heat of the spent nuclear fuel from the outer surface of the cask. In order to obtain excellent heat transfer performance aluminum alloy is a good choice for the basket, and in addition, sub-criticality safety must be satisfied.

(5) Structural integrity

The cask must be designed to possess the appropriate structural strength in order to maintain its safety functions during transport and storage. The IAEA Transport Regulations (Regulations for the Safe Transportation of Radioactive Materials; representative transport requirements) provides various test conditions such as nine meter drops. Sufficient verification of the structural integrity is required for the containment system and basket.

(6) Economy

The economy of the cask can be improved by rationalizing the manufacturing and inspection processes and increasing the number of fuel assemblies that can be accommodated. Weight saving and enhancements in the respective safety functions are indispensable for increasing the payload. The simplification of the basket structure allows its fabrication process to be reduced. No welding line in the main body shell contributes to the elimination of inspection and strength evaluations of the welded sections.

4. Technological developments

MHI has been developing casks since the 1960s. The MSF cask fleet is the fruit of accumulated MHI cutting-edge technology and its strategic development program. Several of the typical technological developments of the MSF cask fleet are described below.

4.1 Boron-containing aluminum alloy

The basket material is the key to the prevention of criticality and the heat transfer performance, as well as improvements in economy through weight saving and simplified structure. To this end MHI has developed a boron-containing aluminum alloy using powder metallurgy. The developed material has the following features:

- Aging (overaging) doesn't influence the material strength and other properties, even over long periods of usage at high temperature (up to about 300C).
- Toughness can be ensured more easily than it can with the melting process.
- The thermal conductivity is equivalent to that of conventional aluminum alloy.
- The boron content is 1.5 wt% – 9 wt% (B_4C), with uniform boron dispersion (**Fig. 3**).
- The material has been already registered in ASME Code Case N-673 as core support structure for storage and transportation of spent nuclear fuel in Section III, Division I (**Fig. 4**).
- Various shapes such as square tubes can be formed by extrusion (**Fig. 5**).

MHI is now applying mechanical alloy technique to realize a boron-containing aluminum alloy with significantly improved strength in high temperature environments.

4.2 Neutron shielding material

Taking into consideration the long term stability and the handleability of filling-up in the cask fabrication

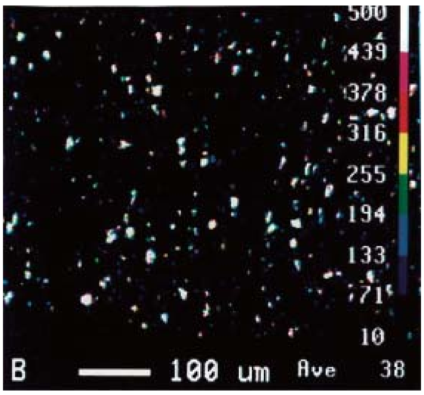


Fig. 3 Boron dispersion (ASME N-673 material)
The state of boron dispersion shown by an electron beam micro analyzer. White dots show boron.

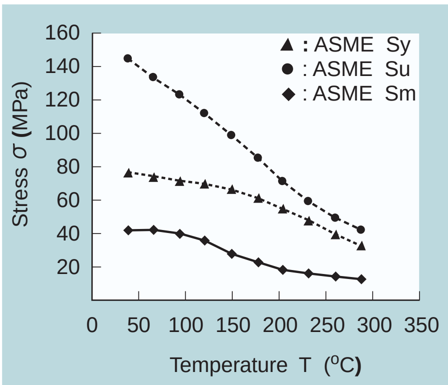


Fig. 4 Material Property (ASME N-673 material)

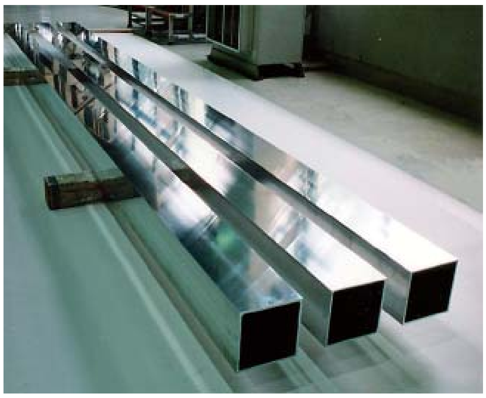


Fig. 5 BWR basket of ASME N-673 material
Square tube basket cells for the BWR fuel assembly.

process, MHI has independently developed MREX, a neutron shielding material (**Fig. 6**).

The features of this material are as follows:

- As epoxy resin is the base material, the material specifications such as specific gravity, hydrogen content and B_4C content, are equivalent to those of conventional products.
- The stability under long term high temperature conditions (weight loss characteristics) is equivalent to those of existing products.
- Internal tests have already been conducted to elucidate the material characteristics (**Fig. 7**).
  - Long term stability test for 5,000 Hr x 150C.
  - Deterioration test by neutron irradiation.
  - Fire testing at 800C x 30 minutes (50% resin residue or more has been confirmed).
- Mixing equipment with an automatic material accounting function has been developed. The traceability from material to final product is excellent.
- MHI has experience with the use of this material for the manufacture of actual transport casks.

MHI has also developed high performance neutron shielding material with outstanding stability under high temperature conditions for longer periods.

4.3 Forging technology for the main body shell of the cask

Main body shell is a key factor whose appropriate structural strength is required to assure the safety functions of the cask. MHI has accumulated a number of material utilization techniques for plant components such as pressure vessels for the nuclear industry. This technology has been applied to the joint development of the "monolithic forging method" in collaboration with the Japan Casting & Forging Corporation (JCFC). This method is a process which forges the cask main body shell into a cup shape. **Figure 8** outlines the work process to fabricate the main body shells, and **Fig. 9** shows examples of the results with this process. The features of this method are described below:

- Elimination of welding between the shell and bottom plate, and of welding inspections (RT, etc.)
- The fracture toughness of the welds does not need to be evaluated.

The material of the main body shell of the cask also must be maintain appropriate toughness under the lowest working temperature, or at −40C. Thus, manufacturing control technology has been established to ensure the required strength and low temperature toughness.

4.4 Other technological developments

The casks used for interim storage are dry type casks with an inner atmosphere of helium. The water inside the cask is drained and dried after the cask is loaded with spent nuclear fuel in the power plant. Two important elements of this drying process must be established: first, a drying procedure which satisfies the temperature limit of the fuel cladding; second, a standard drying value to avoid corrosion inside the cask. MHI research on these items has led to the establishment of the following techniques:

- Temperature evaluation during vacuum drying (including the evaluation of the temperature of the fuel cladding)
- Countermeasures against corrosion of the sealing system and establishment of a drying standard

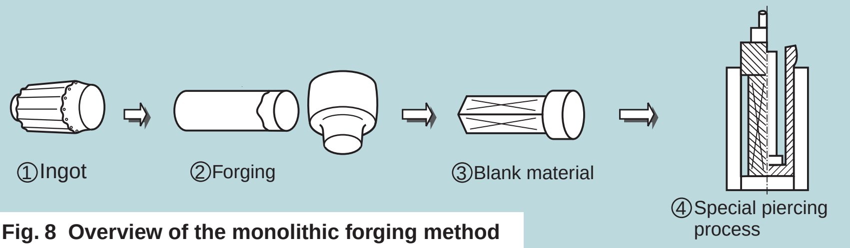


Fig. 8 Overview of the monolithic forging method

Fig. 6 Neutron shielding material, "MREX"
Execution of the filling work between the main body shell of the cask and outer shell.

Fig. 7 Fire testing for the neutron shielding
Verification of the self extinguishing ability after fire testing at 800°C × 30 minutes.

Fig. 9 Fabrication of the main body shell of the cask by the monolithic forging method

5. Drop test and structure evaluation

5.1 Drop test

The demonstration by tests and the validation of the analysis technology are required, as well as evaluation by analysis, in order to evaluate the structural integrity of the cask. MHI has carried out a number of drop tests based on IAEA Transport Regulations in the 10-ton class, in-house drop test facility (refer to **Fig. 10**).

In regard to MFS casks for overseas markets, MHI has collected a multitude of useful data from drop tests with both full-size and scale model casks performed by MHI and later by the Bundesanstalt fuer Materialforschung und -pruefung (BAM), which is the responsible German government institute for mechanical and thermal safety assessment and quality assurance issues within the approval procedure of packages for the transportation of radioactive materials.

Below are the dates and a summary of the drop tests conducted in connection with the development of the MFS cask:

- 1998 - 1999: Tests of a 1/2.35 scale model cask (MHI tests)
- 2003 - 2004: Tests to determine the performance of impact limiters mounted on a 1/2.35 scale model cask (MHI tests)
- 2004 - 2005: Tests on 1/1 and 1/2.5 scale model casks by BAM at the BAM drop test facility in Horstwalde, within the German approval procedure of packages for transportation of radioactive materials.

Figure 11 shows the full scale drop test model used for the German licensing testing. **Figure 12** shows a testing scene.

5.2 Dynamic structural evaluation technology

The progress of computation technology has facilitated three-dimensional dynamic structural analyses to evaluate the behavior of casks during drop test conditions. The 3-D analysis enables the actual behaviors of the cask structural response to be simulated. The principal considerations for the models and required analysis conditions are shown below.

- Appropriate modeling of cask structure and establishment of calculation meshes
- Appropriate consideration of physical property data and velocity effects
- Appropriate consideration of the friction factor and gaps between elements
- Optimization of input conditions such as impact energy

The above items are to be validated (benchmarked) through the tests. Theoretical explanations of the preconditions and assumptions of the analyses based on the test results are required. Now, having executed all of the drop tests outlined in the precedent paragraph, MHI is proceeding with the evaluation and validation of the application of the 3-D dynamic structural analysis code, LS-DYNA (**Fig. 13**).

Fig. 10 9 m drop test with 1/2.35 scale drop model
In-house drop test site in the Takasago Research & Development Center.

Fig. 11 Full scale drop test model (MSF-69B)
At the BAM drop test facility in Horstwalde, Germany.

Fig. 12 Certification test with full scale model
At BAM drop test facility in Horstwalde, Germany.

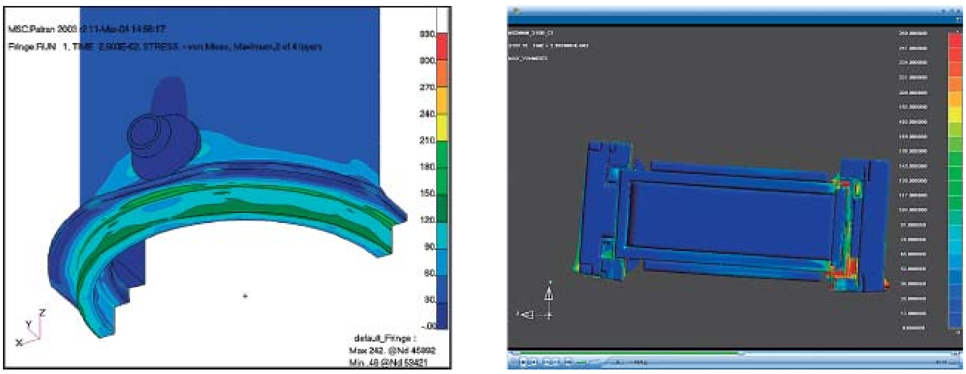


Fig. 13 Analysis by 3D dynamic structural analysis code, "LS-DYNA"
Stress profile of the cask flange during a 9 m drop test (an example).

6. Conclusion

MHI has continued to develop its technology for improving the economy and safety of interim storage casks for spent nuclear fuel using strategic approaches. The accumulation of this technology has culminated in the MSF cask fleet.

The burnup of spent nuclear fuel has been rising in recent years not only in foreign countries but also in Japan. To accommodate this trend, MHI will continue to promote its policy of developing technology for the supply of optimal products with excellent safety and economy in the future.

In closing, we express our gratitude to the Federal Institute for Materials Research and Testing of Germany (BAM) for allowing us to photograph the BAM drop test facility in Horstwalde, Germany. All remarks about the test results which appear in this report represent the opinions of this writer, not BAM. It should be noted that these results are subject to examination by competent German authorities.

References

(1) Regulations for the Safe Transport of Radioactive Materials, IAEA Safety Requirements No. TS-R-1

(2) S.Kuri, Y.Funakoshi, et al., Development of Manufacturing Technology on Body-Base Monolithic Cask Forging, 15th International Forgemasters Meeting (2003)

(3) T.Yamamoto, et al., A Perspective on an R&D Program for Spent Fuel Interim Storage Cask System, PATRAM2004 (2004)

(4) S.Kuri, H.Tamaki, et al., Development of Transport and Storage Cask for High Burn-up Spent Fuel of German Nuclear Power Plant, PATRAM2004 (2004)

(5) T.Yamamoto, et al., Results of Full-Scale Drop Tests for "MSF" Spent Fuel Transport and Storage Cask in Germany, INMM Spent Fuel Management Seminar (2006)


Tomofumi Yamamoto


Hiroki Tamaki


Suguru Hode


Toshihiro Matsuoka


Yoshiharu Kamiwaki


Kiminobu Hojo