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Safety evaluation of MSF-type dual-purpose cask under severe accidents

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ABSTRACT

Safety concerns about storage system for spent nuclear fuels have been increased. A dry cask storage system is considered as a realistic and feasible option for the safe management of spent fuels. Mitsubishi Heavy Industries, Ltd. (MHI) has established transportable storage (dual-purpose) casks, MSF-type cask. MHI performed several full-scale drop tests with the MSF prototype cask, and demonstrated compliance with the containment requirements specified in the IAEA Safety Standards (No.SSR-6). The MSF-24P dual-purpose cask for storage and transport of PWR spent fuel was designed by employing the structural evaluation method verified based on the full-scale drop test results. In order to establish severe accident management scenarios, we evaluated the safety of the MSF-24P cask against severe accidents in storage facilities. This paper describes the outline of preliminary evaluation results for the safety of the MSF-24P cask under severe accident conditions.

1. INTRODUCTION

Many spent fuel storage pools in nuclear power plants are now nearing their full capacity, and the needs for storage have to be growing rapidly in Japan. Safety concerns about storage system for spent nuclear fuels have been increased. A dry cask storage system is considered as a realistic and feasible option for the safe management of spent fuels, because it possesses passive safety which does not require electric power for decay heat removal. Especially, a dual-purpose cask, which can store and transport spent fuels before and even after storage without reloading, is robust and safe against accidents in both storage and transport. Therefore, MHI are working on the development of dry storage facilities with the MSF-type dual purpose cask.

Dual purpose casks shall be designed to meet the requirements for the storage license as well as the transport license. As for the transport license, the drop, thermal and water immersion tests specified as accident conditions of transport in the IAEA Safety Standards (No. SSR-6) [1] must be considered. As for the storage license, the new safety standards for nuclear fuel storage facilities have been discussed in Japan, and countermeasures against severe accidents such as earthquake, tsunamis, aircraft crash, etc. will have to be required in the near future.

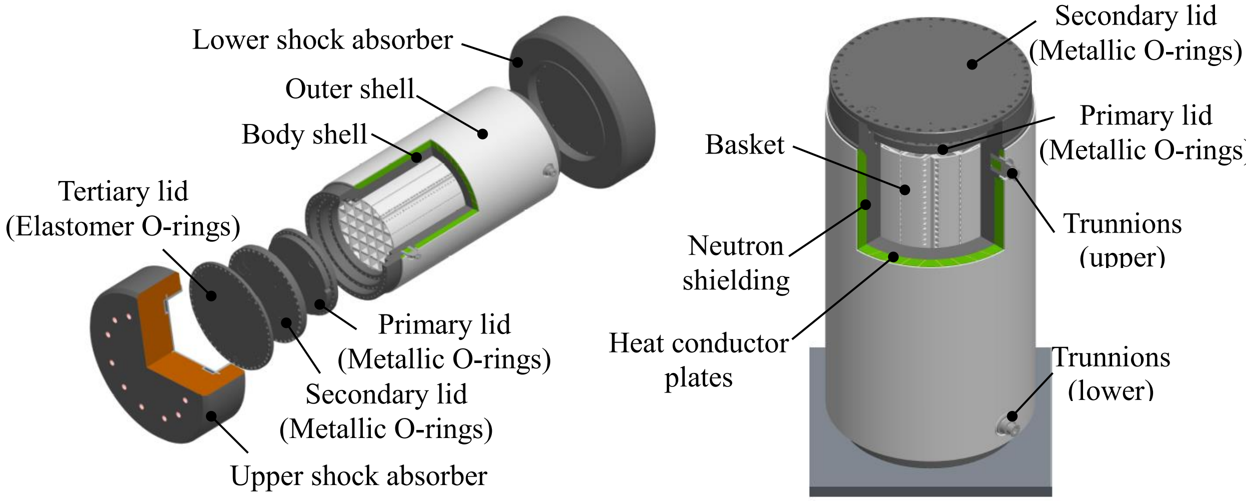
In order to establish severe accident scenarios in storage facilities, we preliminary evaluated the safety of the MSF-24P cask against the following severe accidents; aircraft crash impact, fire accident after an aircraft crash, and burial in debris due to air craft crash, earthquake or tsunami.

2. Features of MSF-24P cask

(1) Specifications of MSF-24P cask

The MSF-24P cask was developed as a high-integrity dual-purpose cask which can accommodate 24 PWR spent fuel assemblies. Schematic views of the transport and storage configurations of the MSF-24P cask are shown in Figure 1.

Typical specifications of the MSF-24P cask are shown in Table 1.



a. Transport configuration **b. Storage configuration**

Figure 1 Configurations of MSF-24P cask

Table 1 Specifications of MSF-24P cask (design sample)

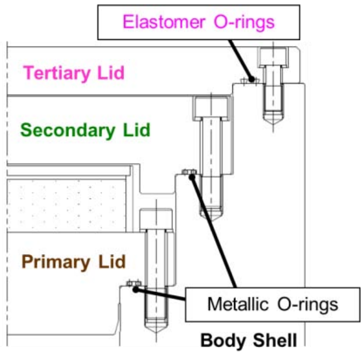
Items		Specifications
Contents	Fuel type	PWR
	Number of fuels	24
	Burnup (GWd/MTU)	48 (Max.)
	U-235 initial enrichment (%)	4.1
	Cooling period (years)	15
Cask	Thermal power (kW)	15.1
	Dimensions (m)	Φ2.6 x 5.2 (Storage configuration) Φ3.6 x 6.8 (Transport configuration)
	Total weight (tons)	119 (Storage configuration) 133 (Transport configuration)

(2) Design of closure system

Outline of the MSF-24P cask closure system is shown in Figure 2.

During storage, the primary lid and the secondary lid are bolted to the body flange with metallic O-rings. The primary lid and the cask body form a containment boundary. Leakage of the lids can be detected by continuous monitoring of pressure variation in the space between the lids during storage. Sealing performance for long-term services has been ensured by metallic O-rings attached on the lids.

During transport before and after storage, the tertiary lid is bolted to the top of body flange with elastomer O-rings. The tertiary lid and the secondary lid have a function as multiple containment boundaries during transport. In case of leakage of the primary lid during storage, the MSF-24P cask can be transported safely.



a. Transport configuration **b. Storage configuration**

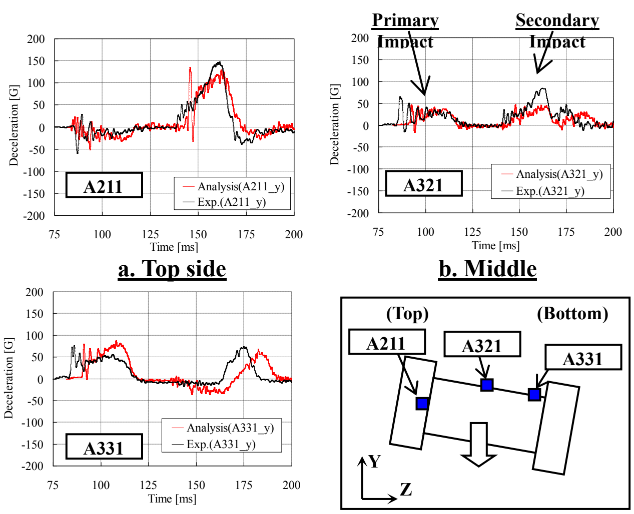
Figure 2 Closure system of MSF-24P cask

(3) Development of closure system

The closure system of the MSF-24P cask has been developed and designed based on the full-scale drop test results of the MSF prototype cask [2] [3].

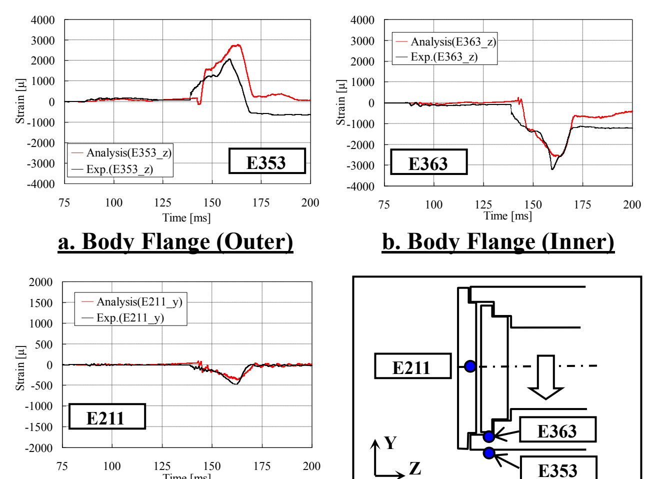
First of all, MHI conducted five drop tests using the full-scale MSF prototype cask with the cooperation of BAM (Bundesanstalt für Materialforschung und -prüfung) for demonstration of containment performance in transportation, and then demonstrated compliance of containment integrity for the closure system.

Next, a dynamic FE analysis model was established and verified especially in terms of impact behaviors of the closure system and shock absorbers. Analyses results for the 9.3m slap down drop test are shown in Figure 3 and 4 as an example. These figures show good agreement between the analysis results and the drop test results.



a. Top side **b. Middle** **c. Bottom side**

Figure 3 Comparison of Decelerations (9.3m Slap down)



a. Body Flange (Outer) **b. Body Flange (Inner)** **c. Secondary Lid**

Figure 4 Comparison of Strains (9.3m Slap down)

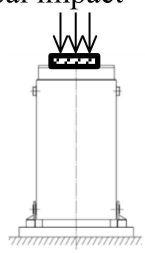
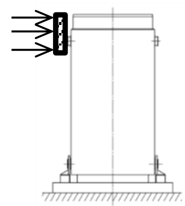
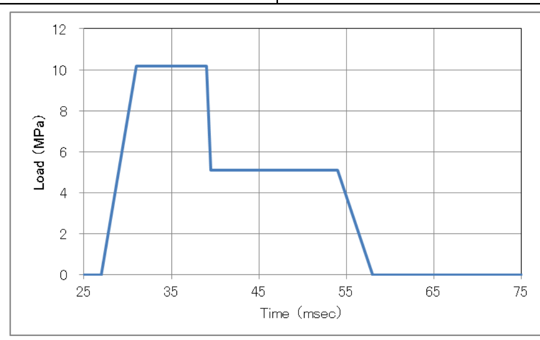
Containment integrity of the MSF-24P cask under the accident conditions of transport was demonstrated by using MSF-24P cask analysis model established on the basis of the verified drop test analysis model.

3. Structural analysis in aircraft crash

3.1. Analysis conditions

The mechanical behavior of the MSF-24P cask closure system was evaluated assuming an aircraft crash in a storage facility. A dynamic FE analysis code of LS-DYNA [4] was used. The analysis conditions and load time function derived from the reference [5] shown in Table 2 were applied in the impact analysis.

Table 2 Analysis conditions and load time function [5]

Items	Conditions	
Impact direction	a. Vertical impact 	b. Lateral impact 
Impact load (Load time function)		

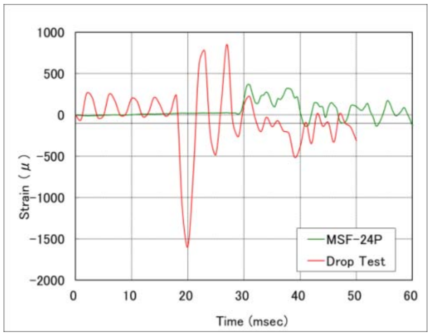
3.2. Analysis results

(1) Vertical impact

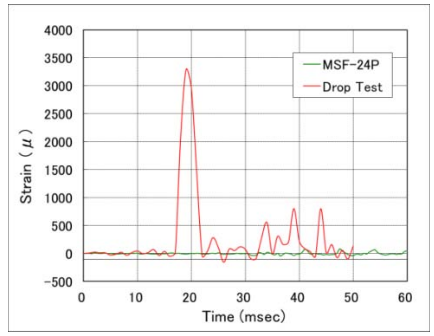
Relative displacements of the lids for the MSF-24P cask under vertical impact due to an aircraft crash are shown in Table 3. In addition, strains of the lids and bolts between the analyses results of the MSF-24P cask under vertical impact and 9.3m vertical drop analysis results of the full-scale model are compared in Figure 5. The analysis results indicate that the displacement of the primary lid and the strains of the lid and bolts for the MSF-24P cask are smaller than that for the full scale drop test model which satisfied the requirements of leak-tightness of the lids, so that the containment integrity of the primary lid is maintained. The analysis results also indicate that the structural integrity of the secondary lid for MSF-24P cask is maintained because the strains of the secondary lid and bolts are considerably smaller than breaking strain.

Table 3 Relative displacement of lids (Vertical impact)

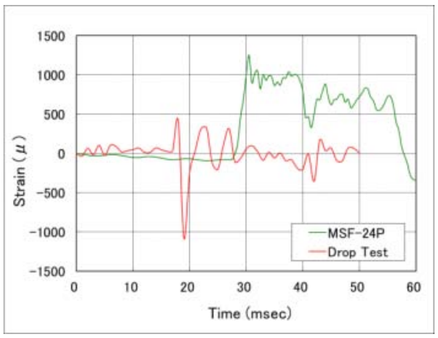
No.	Components	Direction of displacement	Calculated displacement at O-rings	
			MSF-24P Cask	Drop test model
1	Primary lid (Containment boundary)	Lateral	0.06 mm	2.85 mm
		Axial (Opening)	0.07 mm	0.86 mm
2	Secondary lid (For reference)	Lateral	0.49 mm	2.85 mm
		Axial (Opening)	0.46 mm	0.86 mm



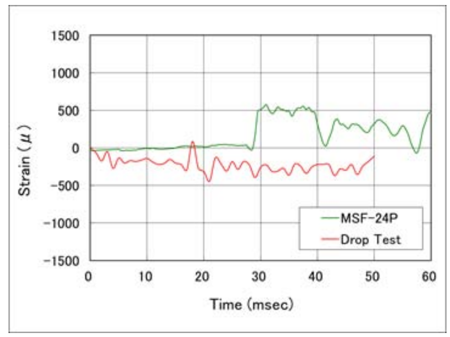
a. Primary lid (center)



b. Primary lid bolts



c. Secondary lid (center)



d. Secondary lid bolts

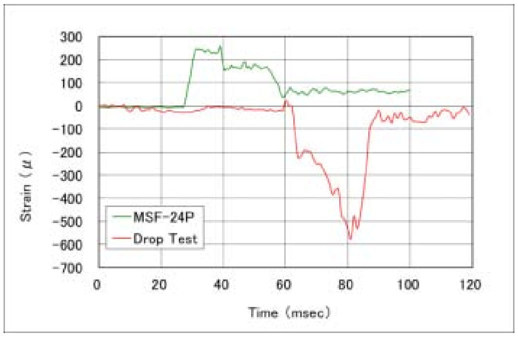
Figure 5 Comparison between calculated strains of MSF-24P cask under aircraft impact (vertical direction) and those of drop test model under 9.3m vertical drop

(2) Lateral impact

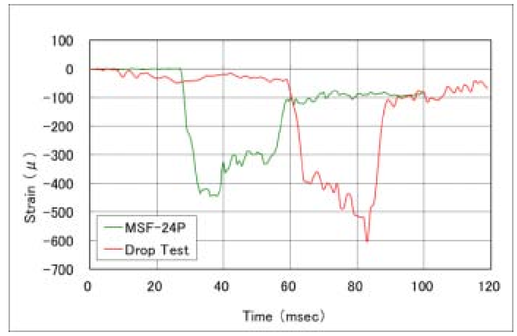
Relative displacements of the lids for the MSF-24P cask under lateral impact due to an aircraft crash are shown in Table 4. In addition, strains of the lids and bolts between the analyses results of the MSF-24P cask under lateral impact and 9.3m slap down analysis results of the full-scale model are compared in Figure 6. The primary lid and secondary lid are displaced to lateral direction due to load at the impact onto the body shell. Analysis results indicate that the displacement of the primary lid and the strain of the primary lid periphery of the MSF-24P cask are smaller than those for the full scale model which satisfied the requirements of leak-tightness of the lids, so that the containment integrity of the primary lid is maintained. The analysis results also indicate that the structural integrity of the secondary lid for MSF-24P cask is maintained because the strain of the secondary lid is considerably smaller than breaking strain.

Table 4 Relative displacement of lids (Lateral impact)

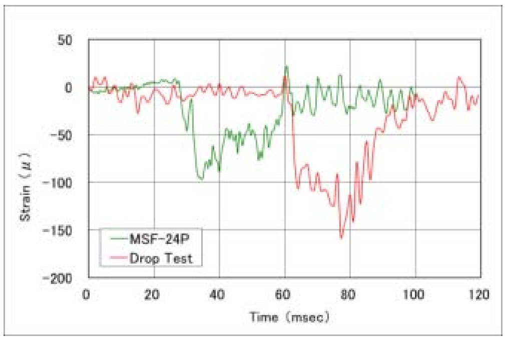
No.	Components	Direction of displacement	Calculated displacement at O-rings	
			MSF-24P cask	Drop test model
1	Primary lid (Containment boundary)	Lateral	1.10 mm	2.85 mm
		Axial (Opening)	0.03 mm	0.86 mm
2	Secondary lid (for reference)	Lateral	1.10 mm	2.85 mm
		Axial (Opening)	0.15 mm	0.86 mm



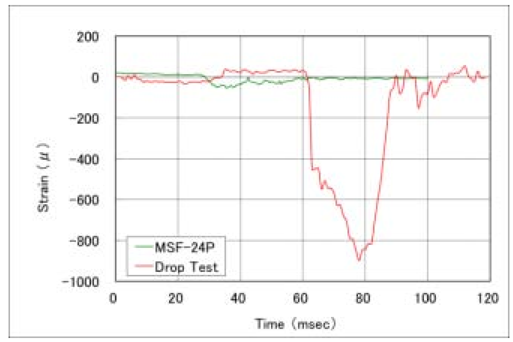
a. Body flange (inner)



b. Body flange (outer)



c. Primary lid (periphery)



d. Secondary lid (periphery)

Figure 6 Comparison between calculated strains of MSF-24P cask under aircraft impact (lateral direction) and those of drop test model under 9.3m slap down

4. Thermal analysis in fire accident due to jet fuel

4.1. Analysis conditions

We evaluate the safety system of the MSF-24P cask in storage assuming a fire accident “at 1200°C for 1 hour” (which is severer than those at 800°C for 0.5 hours specified in the IAEA Safety Standards) caused by jet fuel leakage due to an aircraft crash onto a storage facility. Unsteady thermal analysis was conducted using ABAQUS code[6]. Normal storage condition was applied to the initial thermal conditions before fire loading.

4.2. Analysis results

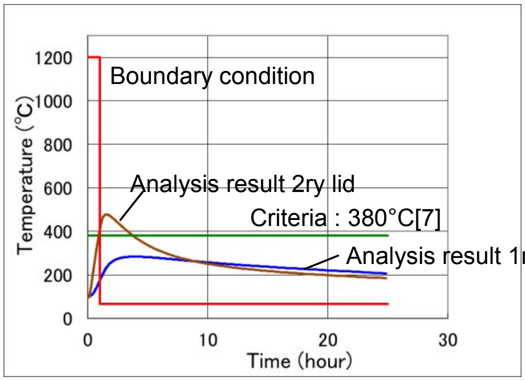
Temperature-time histories at main components of the MSF-24P cask are shown in Figure 7.

The cask closure system maintains its containment integrity at the primary lid, because the maximum temperature at O-rings of the primary lid is below the allowable temperature of 380°C[7]. However, it could fail to maintain the containment integrity at the secondary lid, because the maximum temperature at O-rings of the secondary lid exceeds the allowable temperature.

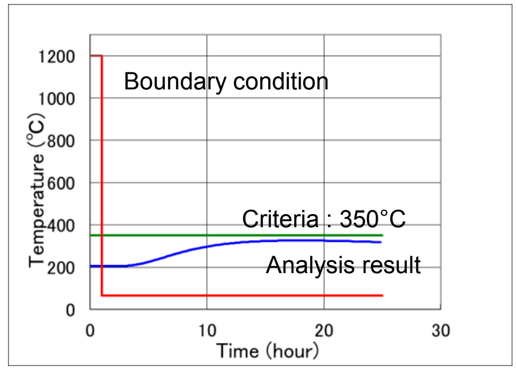
The maximum temperature at the basket satisfies the evaluation criterion which defines material characteristics of the basket, so that sub-criticality would be maintained,

In addition, neutron shielding would be lost because its maximum temperatures exceed the operable temperature. In this case, a dose equivalent rate at 1m from the cask surface is sure not to exceed 10mSv/h because of compliance with the Japanese transport regulation

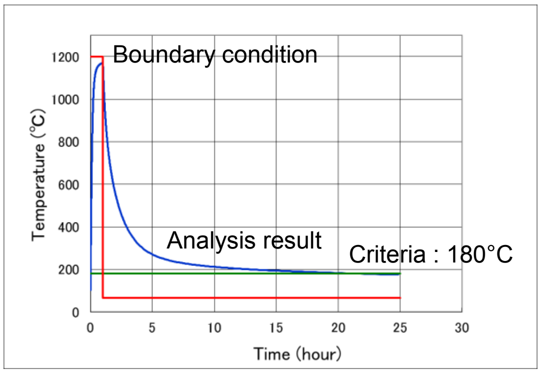
The maximum temperature at fuel cladding satisfies the allowable temperature of 570°C[8] and so would maintain its integrity.



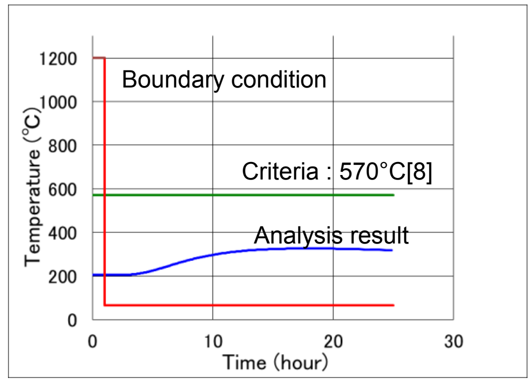
a. O-rings



b. Basket



c. Neutron shielding



d. Fuel cladding

Figure 7 Temperature-time histories

5. Thermal analysis with cask buried in debris

5.1. Analysis conditions

We evaluated the safety system of the MSF-24P cask in storage assuming the cask will be buried in debris due to an air craft crash, earthquake or tsunami. ABAQUS code was used for the unsteady thermal analysis. The evaluation cases are shown in Table 5. The case 1 is 50% heat insulation, 50% heat-transfer coefficient of boundary condition of cask surface. The case 2 is 100% heat insulation, adiabatic boundary on cask surface.

Table 5 Evaluation cases

No.	Conditions
1	50% heat insulation
2	100% heat insulation

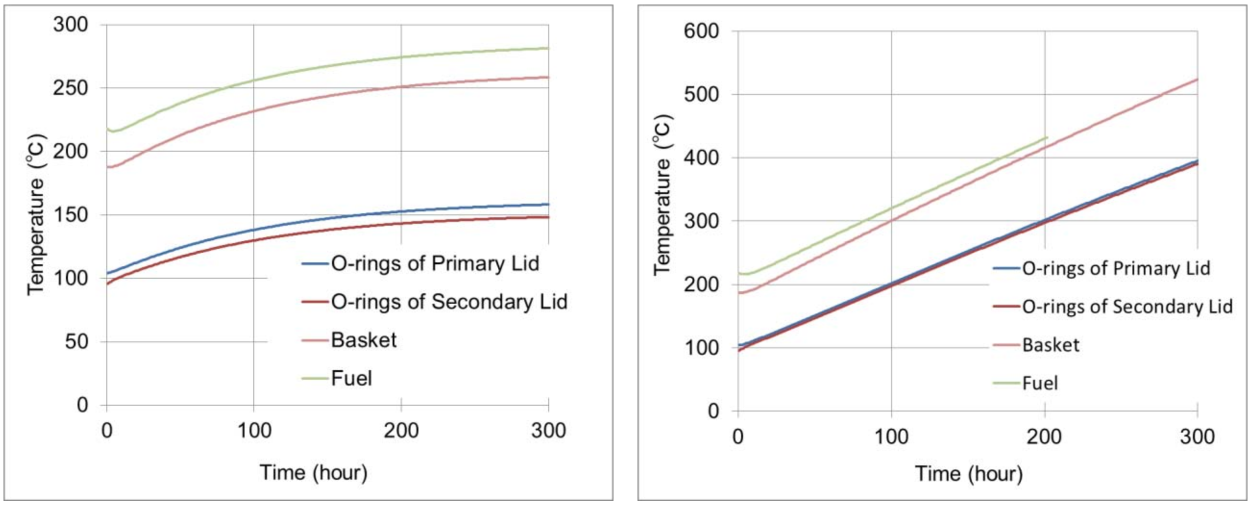
5.2. Analysis results

Time to reach the allowable temperature of O-ring of the primary lid, O-ring of the secondary lid, basket and fuel cladding is shown in Table 6. Temperature-time histories at components of the MSF-24P cask are shown in Figure 8. In case 1, the maximum temperature of each main component does not reach each allowable temperature. In case 2, the temperatures of O-rings which are related to containment integrity reach allowable temperature around 280 hour. The temperature of basket which is related to sub-criticality reaches allowable temperature around 99 hours.

Table 6 Time to reach allowable temperature

Components	Allowable temperature	Case1 (Maximum temperature)	Case2
O-rings of primary lid	380 °C[7]	- (170°C)	283 hours
O-rings of secondary lid	380 °C[7]	- (160°C)	289 hours
Basket	300 °C	- (290°C)	99 hours
Fuel cladding	570 °C[8]	- (290°C)	330 hours*

(Note) *: Extrapolated value



a. Case 1(50% heat insulation) b. Case 2(100% heat insulation)

Figure 8 Temperature-time histories

6. Conclusions

MHI performed preliminary evaluations for the safety of the MSF-24P cask against the severe accident conditions of aircraft crash and burial in debris. In the impact analysis for aircraft crash, mechanical behaviors of the closure system were analyzed by applying the dynamic FE analysis model established and verified based on the MSF prototype full scale drop test results, and it was confirmed that its containment integrity can be maintained. In the thermal analyses for fire accident after aircraft crash, it is also confirmed that its containment integrity and sub-criticality can be maintained. The temperature increasing tendency and time for maintaining safety of the MSF-24P cask under burial in debris were obtained. Based on these safe evaluations, MHI will continue to develop the dry storage facilities with the MSF-type dual purpose cask.

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