Safety Evaluation of Shipping Cask for Loading 4 PWR Spent Fuel

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INTRODUCTION

The B type package development program was being carried out to transport spent fuel from temporary at-reactor(AR) storage pools short of enough storage capacities to other AR storage pools with available spaces or to away-from-reactor(AFR) interim storage facility to be built in the future.

In order to transport spent fuel assemblies, a shipping cask is inevitable. Spent fuel to be shipped in casks is dangerous due to high radioactivity and decay heat. All kinds of casks should be evaluated to determine their thermal responses, radiation and radioactve materials release, and criticality. The cask must meet the regulatory standards stipulated in domestic atomic energy law and IAEA Safety Series No. 6. The standards require that the cask prevent the loss or dispersion of radioactive material, retain shielding efficiency, assure nuclear criticality safety, and be adequate to heat dissipation under normal conditions of transportation and under hypothetical accident conditions.

The purpose of this paper is to present the safety evaluation of the KAERI designed KSC-4 shipping cask which is able to carry four spent PWR fuel assemblies.

DEVELOPMENT STATUS

The cask development procedure for compliance with regulatory standards is first approval of the package design while the second is approval of the packaging for shipment of spent fuel. The development and licensing procedure for a cask is shown in Fig.1. The conceptual design was studied with the design criteria and operation requirements. Technical standards and codes specified in transport regulations are also applied. Next, the basic design was carried out in the field of shielding, thermal, structure and criticality under normal transport and hypothetical accident conditions. Safety test with a scale model was performed to assure the structural integrity of the cask. The test consists of half an hour exposure to fire of 800 °C, a 9 m free drop onto an unyielding steel surface, 1 m puncture caused by dropping a steel bar, and a 15 m immersion in water for 8 hours.

By analysis and tests, we prepared a safety analysis report(SAR) for the design license. The SAR was submitted to a competent authority, Ministry of Science and

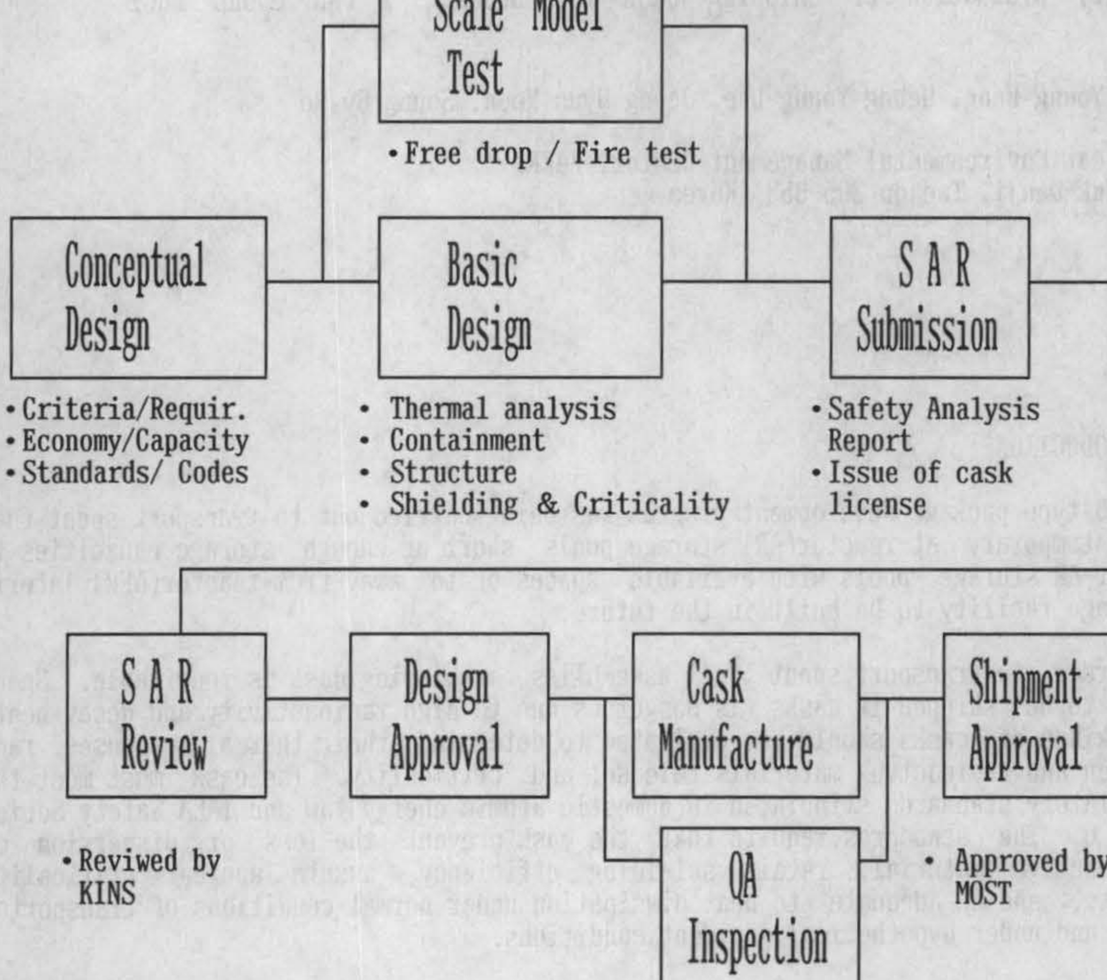

Fig. 1 Cask Development & Licensing Procedure

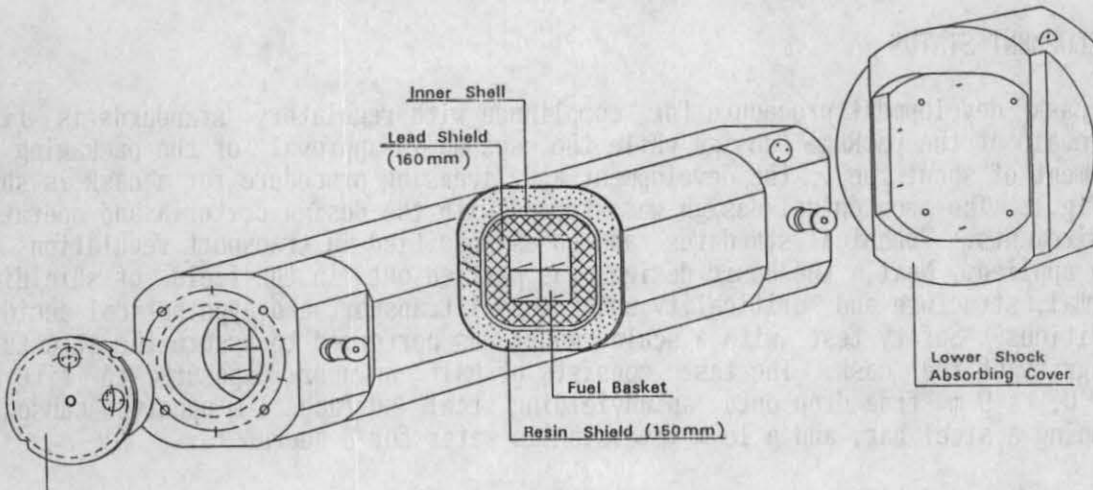

Fig. 2 KSC-4 Shipping Cask Overview

Technology (MOST), and reviewed by Korea Institute of Nuclear Safety(KINS). During the cask manufacturing, the KINS inspected the manufacture procedure in order to conform the cask design related to the quality assurance program. Finally, we obtained a certificate from MOST to approve shipment and transportation of spent nuclear fuel.

CASK DESCRIPTION

The KSC-4 cask consists of a cask body, a lid, and shock absorbers bolted to each end of the cask body. The cask body is composed of fuel baskets, an inner shell and an outer shell made of stainless steel. Gamma-ray shielding between the fuel basket and inner shell is made by lead casting. Neutron shielding between the inner and outer shell is provided by solid resin. The internal cavity which forms the containment vessel is divided into 4 compartments. Each compartment is large enough to contain one PWR fuel assembly. Each fuel basket which surrounds each cavity is constructed of stainless steel. The poisoned plate between the fuel baskets consists of boral(Boron + Aluminium) or borated stainless steel to control criticality due to 4 PWR fuel assemblies. The lead gamma shield is cast at the cask bottom and around the basket shell. 24 copper plates between the inner shell and outer shell are fixed to help the heat transfer of resin with low thermal conductivity.

The lid consists of stainless steel shell, lead and solid resin. The lid flange is secured by 16 cap screws. The shock absorbers on both ends of the cask body are

Table 1. The Summary of KSC-4 Shipping Cask

Items	Description
1. Package Name	• KSC-4 (KAERI Shipping Cask - 4)
2. Type of Package	• B(U) Type, Fissile Class III
3. Cavity Cooling Type	• Wet (water) or Dry (hellium)
4. Loaded Cask Weight	37 Ton
5. Size	• Outside Diameter : 1.35 m • Height : 4.82 m
6. Materials	• Inner, Outer shell: SA 240 Type 304 • Poison plate : Boral/ Borated S.S • Gamma shield : Lead • Neutron shield : Solid resin • Shock absorbing cover : Balsa /red wood
7. Fuel specification	• Type of Fuel : PWR Assembly (17x17) • Max. Burnup : 38,000 MWD/MTU • Cooling Time : 3 years • Decay Heat : 7.0 kW

filled with balsa wood to protect the cask from external impact due to transport accidents. Fig. 2 shows the KSC-4 shipping cask which contains a cask body, a lid, and shock absorbers. And the design basis, size and materials of the cask are summarized in Table 1.

SAFETY EVALUATION

Safety analysis under the normal transport and hypothetical accident conditions has been performed by the analytical methods for the structure, shielding, thermal and criticality. And a scale model test was carried out to conform the cask integrity under free drop impact and fire condition. The normal transport and hypothetical accident conditions specified in regulatory standards of domestic nuclear law, IAEA safety series No.6 are described as below.

< Normal transport conditions >
- Heat & Cold; an ambient temperature of 38 °C & - 40 °C for 1 week
- Vibration ; vibration normally incident to transport
- Penetration ; impact of steel bar on the cask surface from 1 m height
- Free drop ; free drop through a height of 0.3 m
- Water spray ; rainfall of 50 mm/hr for at least one hour

< Accident conditions >
- Free drop ; free drop through a height of 9 m
- Puncture ; free drop onto a vertical mild steel bar at 1 m height(6" dia.)
- Fire ; fire condition at 800 °C ambient temperature for 0.5 hrs.
- Immersion ; immersion under a head of water at least 15 m (8 hrs)

Structural analysis for evaluating the integrity of cask structure materials was carried out by using the ANSYS code. The cask body with shock absorbers was dropped onto an unyielding surface in vertical position at the height of 9 m. The simulated results for the 9 m drop condition are given in Table 2. The results show that all drop energy is absorbed by the deformation of the shock absorbers. The maximum stress intensity of the cask is 3314 kg/cm², and the value is lower than the criteria specified as ASME Sec.III code. The 9 m drop gives no significant damage to the cask body.

Drop tests of a 1/3 scale model at 9m height were performed in vertical, horizontal, corner position. The peak acceleration values after 9 m vertical drop was measured to be 290 g value at 3.3 msec during the acceleration time histories.

Thermal analysis on the cask was performed by the HEATING-5 computer code. The cask was exposed to a thermal environment of 800 °C for 30 minutes. The simulated thermal analysis showed that during fire state, the temperature on the cask surface was increased up to 700 °C and the temperature of fuel rod in dry cavity was increased up to approximately 280 °C. The results of thermal analysis in dry cavity condition during the fire accident for 0.5 hrs are shown in Fig. 3. As shown in the transient temperature profile, no melting of the lead occured below the melting point of 327 °C. Based on the simulated thermal analysis, we performed a real fire test at an ambient temperature of 800 °C for 30 minutes. At this time the temperature on the cask surface was increased up to 600 °C and the temperature at the lead shield was about 230 °C. From the two analyses, it was found that the simulated analysis gave more conservative values than the real case. In both cases, the temperature of lead was lower than the melting point, 327 °C.

Table 2. Results of Maximum Calculated Stress Intensities for 9 m Drop Condition (unit : Kg/cm²)

Description	Calculated Stress		Allowable Stress	
	Location	Value	Value	Type
9 m Free drop [top-end on]	Inner shell	805	4219	Pm < 2.4 Sm
		1573	6329	Pm+Pb<3.6 Sm
	Outer shell	96	4219	Pm < 2.4 Sm
		55	6329	Pm+Pb<3.6 Sm
	Lid	313	4219	Pm < 2.4 Sm
		133	6329	Pm+Pb<3.6 Sm
	Top plate	1467	4219	Pm < 2.4 Sm
		3314	6329	Pm+Pb<3.6 Sm

* Pm : Primary membrane stress, Pb: Primary bending stress
Sm : Design stress intensity

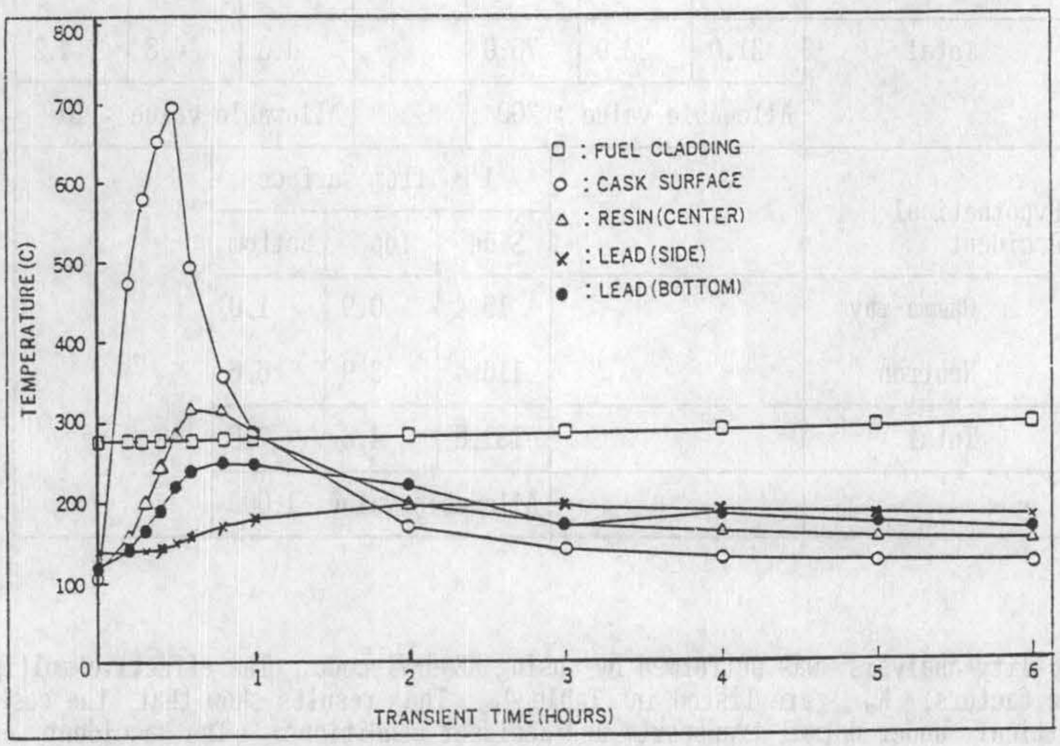

Fig. 3 Transient Temperature Profile of Dry Cask under Fire Condition

Shielding analysis for the KSC-4 cask was performed by using 1-D ANISN code for both gamma-ray and neutron, QAD-CG code for gamma-ray, and DOT4.2 code for calculating 2-D geometry model. The dose rates on the surface and at 2 m from the cask surface under normal transport are tabulated in Table 3. The calculated dose rates under the hypothetical accident condition at 1 m from the cask surface are also given in Table 3. The dose rates at cask surface are less than 200 mrem/hr specified as the allowable limit for the normal transportation. In the accident condition, the dose rates at 1 m from the cask surface are also less than 1,000 mrem/hr.

Table 3. Summary of the Calulated Dose Rates under Normal Transport and Hypothetical Accident Conditions

Condition	Dose rates (mrem/hr)						
	On the surface				2 m from surface		
	Side	Top	Bottom		Side	Top	Bottom
Normal Transport							
Gamma-ray	17.6	2.3	6.0		3.7	0.5	0.6
Neutron	3.4	20.6	70.0		0.6	2.1	3.6
Total	21.0	22.9	76.0		4.3	4.8	4.2
	Allowable value : 200				Allowable value : 10		

Hypothetical Accident		1 m from surface		
		Side	Top	Bottom
Gamma-ray		15.4	0.9	1.0
Neutron		116.4	3.9	6.6
Total		131.8	4.8	7.6
		Allowable value: 1,000		

Criticality analysis was performed by using KENO-VI code. The effective multiplication factors, K_{eff}, are listed in Table 4. The results show that the cask is subcritical under normal transport and accident conditions. The accident conditions on criticality analysis mean damaged single cask and infinite array of casks without neutron resin shield under optimum interspersed hydrogenous moderation.

Table 4 Results of Criticality Analysis

Conditions	Keff $\pm\ \sigma$
1. Normal Transport Condition	
• Undamaged single cask	0.89734 ± 0.01464
• Infinite array of undamaged cask	0.90280 ± 0.01284
2. Hypothetical Accident Condition	
• Damaged single cask	0.94572 ± 0.01230
• Infinite array of damaged casks	0.95124 ± 0.01322

CONCLUSION

The KSC-4 cask had complied with several stringent requirements and standards imposed by transport regulation and shipment inspection. Having successfully completed the scale model test and safety analysis, it was concluded that the cask maintained its integrity under the normal transport and hypothetical accident conditions. After having submission of safety reports and review by competent authority, the design approval of the cask was obtained and it was manufactured by heavy industries.

It is revealed that the KSC-4 cask is practically useful, e.g., the cask was used to carry out safely transshipment of 156 spent PWR fuel assemblies from the Kori unit-1 to Kori unit-3 without any problems during a period of 1990 to late 1991.

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