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Evaluation of the KN-12 Spent Fuel Shipping Cask

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Abstract

The KN-12 shipping cask is a new design of a transport package intended for dry and wet transportation of up to 12 spent nuclear fuel assemblies from pressure water reactors. The cask has been designed basing on KEPCO-NETEC's requirements and evaluated as a transport package that complies with the requirements of IAEA Safety Standards Series No.ST-1, US 10 CFR Part 71 and Korea Atomic Energy Act for Type B(U)F package. The cask will be licensed in accordance with Korea Atomic Energy Act. The cask provides containment, radiation shielding, structural integrity, criticality control and passive heat removal for normal transport conditions and hypothetical accident conditions. The W.H 14x14, 16x16 and 17x17 fuel assemblies will be loaded and subsequently transported in the cask. The maximum allowable initial enrichment of the fuel is 5.0wt.%, the fuel assembly burnup is limited to a maximum average of 50,000MWD/MTU, and the fuel must have a minimum cooling time of 7 years. And, the KN-12 cask will be fabricated in accordance with the requirements of ASME B&PV Code Section III, Division 3.

1. Introduction

The KN-12 shipping cask is a new design of a transport package intended for dry and wet transportation of up to 12 spent nuclear fuel assemblies from pressure water reactors. The cask has been designed basing on KEPCO-NETEC's requirements and evaluated as a transport package that complies with the requirements of IAEA Safety Standards Series No.ST-1[1], US 10 CFR Part 71[2] and Korea Atomic Energy Act[3] for Type B(U)F package. The cask will be licensed in accordance with Korea Atomic Energy Act.

The cask provides containment, radiation shielding, structural integrity, criticality control and passive heat removal for normal transport conditions and hypothetical accident conditions. The W.H 14x14, 16x16 and 17x17 fuel assemblies will be loaded and subsequently transported in the cask. The maximum allowable initial enrichment of the fuel is 5.0wt.%, the fuel assembly burnup is limited to a maximum average of 50,000MWD/MTU, and the fuel must have a minimum cooling time of 7 years. The containment system of the KN-12 cask consists of a forged thick-walled carbon steel cylindrical body with an integrally-welded carbon steel bottom and is closed by a lid made of stainless steel, which is fastened to the cask body by lid bolts and sealed by elastomer O-ring. The steel thickness of the cask body wall and of the lid meet the dose rate limits of the related regulations together with neutron shielding material. Neutron shielding in radial direction is provided by polyethylene rods arranged in two concentric rows of axial bore holes and in axial direction is provided by polyethylene plates. The fuel basket to accommodate up to 12 intact PWR fuel assemblies provides support of the fuel assemblies, control of criticality and a path to dissipate heat from the fuel assemblies to the cask body. The stainless steel fuel receptacles to enclose and secure the fuel assemblies are assembled as a gridwork together with borated aluminum plates. Four trunnions are attached to the cask body for lifting and for rotation of the cask between vertical and horizontal positions. Impact limiters filled with beech and spruce woods to absorb the impact energy under 9m free drop conditions as an hypothetical accident are attached at the top and at the bottom side of the cask during transport. The loaded cask will be transported by a heavy-haul trailer.

And, The KN-12 cask will be fabricated in accordance with the requirements of ASME B&PV Code Section III, Division 3.

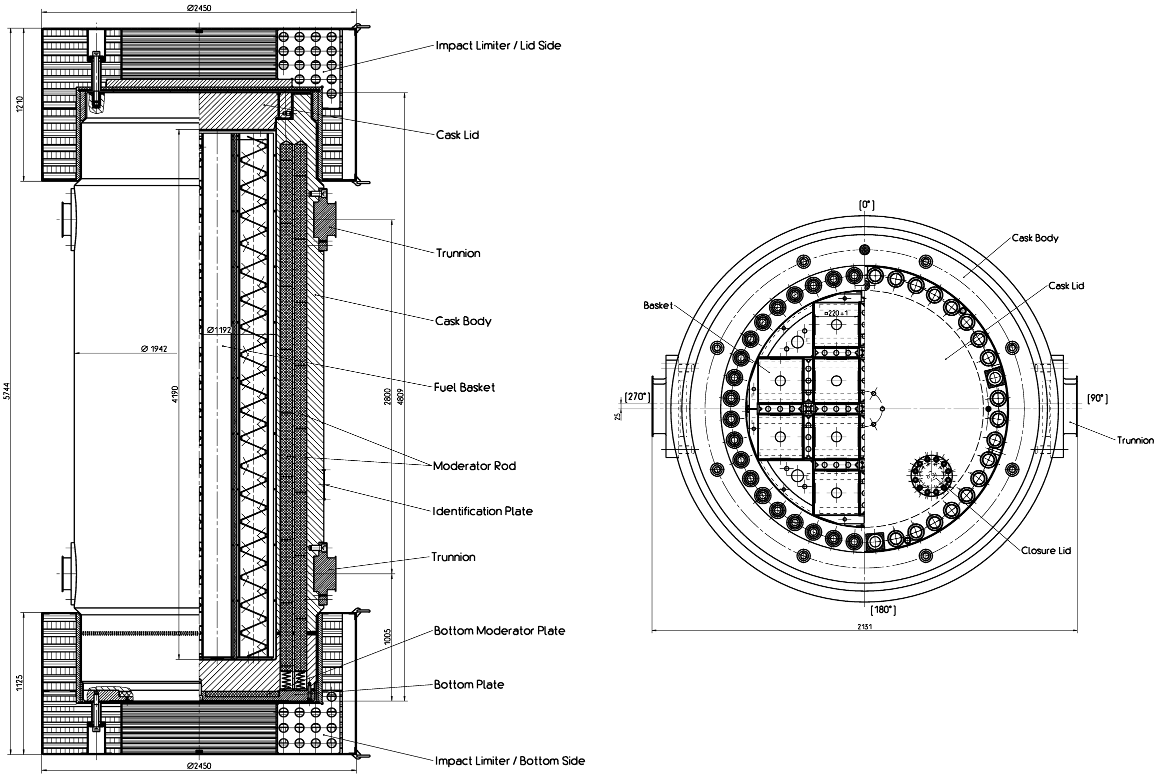
2. Cask Description

2.1 Packaging

The KN-12 cask is a cylindrical vessel that is placed in the horizontal position on a tie-down structure during transportation. The cask as shown in the Fig. 2.1 consists of a cask body, a cask lid, polyethylene rods, a fuel basket, trunnions and impact limiters. A cylindrical thick-walled cask body which constitutes the containment vessel made of forged carbon steel. The cask is closed be the bolted cask lid made of forged stainless steel. It provides radioactive material containment within a cavity loaded by the spent fuel assemblies inserted in the basket and filled with helium or water. Polyethylene rods for neutron shielding are arranged in two rows of longitudinal bore-holes in the cask body wall. A polyethylene plate for neutron shielding is arranged at the bottom side of the cask covered by steel-made bottom plate. A fuel basket that locates and supports the spent fuel assemblies in fixed positions, provides boron for neutron absorption to satisfy nuclear criticality safety requirements and to transfer the heat to the cask body wall. Upper and lower pairs of trunnions to provide support for lifting and for rotation of the cask between the vertical and horizontal position. The bottom trunnions also serve as attachment points for securing the cask during transportation. A set of impact limiters manufactured from wood encased in stainless steel sheeting. The impact limiters are bolted at the lid side and at the bottom side of the cask during transportation. They provide the sufficient impact energy absorption to meet the stress limits during the hypothetical accident conditions such as the 9 m free drop. During transportation, the cask will be supported by a specially designed tie-down structure. The tie-down structure including a hood will provide the support, the weather protection respectively for the cask and a personnel barrier.

The overall cask length is 4,809mm with a wall thickness of 375mm. The cylindrical cask cavity has an internal diameter of 1,192mm and an internal length of 4,190mm. The lid is 290mm thick. Each impact limiter is 2,450mm in diameter and extends 700mm along the side of the cask in axial direction. The open dimension of the fuel basket is 220mmx220mm, and the free length of the basket between basket inside bottom surface up to lower lid surface is 4,170mm. Dimensions of the cask is shown in the Fig. 2.1.

Weights of the KN-12 cask are as the followings; cask body of 51.5tons, cask lid of 3.3tons, basket of 7tons, impact limiters of 11.7tons, fuel assemblies of 7.9tons, water filing of 2.2tons, and cask lifting device of 2.3tons. The handling weight loaded with water with the cask lifting device is 74.8tons and the transportation weight loaded with water with the impact limiters is 84.3tons.



(a) Vertical section

(b) Cross section

Fig. 2.1 General arrangement of the KN-12 shipping cask

The containment vessel for the cask consists of a forged thick-walled carbon steel cylindrical body with an integrally-welded carbon steel bottom and is closed by a lid made of stainless steel, which is fastened to the cask body by lid bolts with nuts and sealed by double elastomer O-rings. In the cask lid an opening is integrated closed by a plug with an O-ring seal and covered by the bolted closure lid sealed with an O-ring. The containment system of the is defined by the cask body, the cask lid, lid bolts/nuts, O-ring seals and the bolted closure lid. The steel thickness of the cask body wall and of the cask lid are designed to meet the dose rate limits together with the neutron shielding material.

The neutron shielding is provided in both radial and axial direction. Neutron shielding in the radial direction is provided by polyethylene rods arranged in two concentric rows of axial bore holes in the wall of the cask. Each concentric row contains 36 bore holes for a total of 72 bore holes. The bore holes in the two concentric rows are offset to provide an unbroken line of neutron shielding for radiation from the cask cavity. The polyethylene rods are firmly secured in the long direction by springs located in the bottom of the bore holes fixed by the bolted bottom plate. The neutron shielding in the axial direction is provided by polyethylene plates. A polyethylene plate at the lid side is integrated in the referring top impact limiter. To provide neutron shielding at the bottom of the cask, a polyethylene plate is inserted into a cavity at the outside of the cask bottom. This plate is secured in place by the steel made bottom plate fixed by cap screws.

The fuel basket provides support of the fuel assemblies, control of criticality, and a path to dissipate the heat from the fuel assembly to the cask body. The fuel basket is designed to accommodate up to 12 intact PWR fuel assemblies. The fuel receptacles are manufactured by the welding of stainless steel plates to form a square tube to enclose and secure the fuel assemblies. The receptacles are assembled as a gridwork together with borated aluminum plates. Each stainless steel fuel receptacle is fully surrounded by the borated aluminum plates of the basket gridwork. This arrangement is fixed on the bottom side by a welded plate and on the lid side connected by screwing. The borated aluminum plates of this basket gridwork provide the sufficient heat removal. The boron content of these plates assures nuclear criticality safety under normal transportation and under hypothetical accident conditions.

Four trunnions are attached to the cask body for lifting and for rotation of the cask between the vertical and the horizontal position. Two of the trunnions are mounted near the top of the cask body and two of the trunnions are mounted near the bottom of the cask. The top trunnions are used as attachment points for lifting the cask in the vertical direction and for rotating the cask between the horizontal and the vertical positions. The bottom trunnions are utilized as support points when rotating the cask between the vertical and the horizontal positions**.** The two bottom side trunnions are used as tie-down points during transportation of the cask on the transport frame. The top and bottom trunnions are designed, fabricated and tested in accordance with ANSI N14.6.

Impact limiters are attached at the top and at the bottom side of the cask during transport. The impact limiters are designed to absorb the impact energy during the 9m free drop as an hypothetical accident. The impact limiters are manufactured from an inner carbon steel structure and an outer stainless steel shell filled with woods (beech and spruce). The outer steel shell is welded water tight to protect the wood against humidity. The steel shell is specially designed to enhance the shock absorbing properties of the materials of construction of the impact limiter.

The cask is designed to dissipate the decay heat from the fuel to the basket and from the basket to the outer cask body surface. No active systems are required for the removal and dissipation of the decay heat from the fuel that is loaded within the cask. The design heat-load of 12.6kW is dissipated from the outer cask body surface by radiation and by natural convection to the surrounding air.

2.2 Operational Features

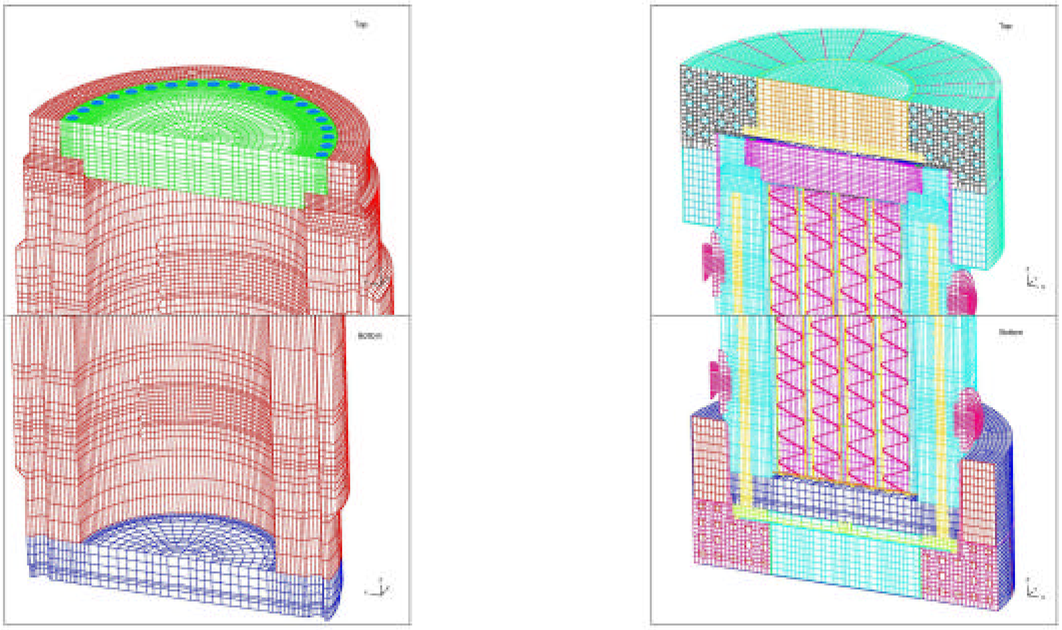
The cask is designed for the dry and wet transportation of 12 intact PWR fuel assemblies. The loaded cask will be transported by a heavy-haul trailer.

Criticality safety is achieved by utilizing neutron absorption materials (borated aluminum plates) in the basket structure. For the basket arrangement, k_{eff} is limited to < 0.95 even with unborated water in the cask cavity. During transport, with the cavity dry and sealed, criticality control measures within the installation are not necessary because of the boron poison in the fuel basket assembly. The criticality control features of the cask are designed to maintain the neutron multiplication factor k_{eff} (including uncertainties and calculational bias) at less than 0.95 under normal transport conditions and hypothetical accident conditions.

The cask is designed for dry and wet transportation of up to 12 intact PWR fuel assemblies. The typical fuel assembly W.H. 17x17 might be transported in the cask. Known or suspected failed fuel assemblies (rods) with cladding defects are not to be transported in the cask. A PWR fuel assembly typically consists of Zircaloy fuel rods containing uranium dioxide(UO_2) fuel pellets. The fuel rods are spaced and supported laterally by grid structures in a square

RG 7.8 also states, “the water

. Therefore, these four conditions were not be discussed. Structural behaviour of the cask under the heat, cold, reduced external pressure and increased external pressure were analysed by LS-DYNA3D finite element code. The model is shown in Fig. 3.1(a) and it consists only of the cask's containment structure. One basic model was used for analysing all four conditions, by application of different loading. Analysis results and stress comparison with stress limits are shown in Table 3.1.



(a) Normal transport condition (b) Hypothetical accident condition

Fig. 3.1 Structural analysis model

Table 3.1 Structural analysis results under normal transport conditions

Anlysis	Component	Stress limit, Mpa	Max. shear stress, MPa	Max. stress Intensity, MPa
Hot	Body Lid	155 264	36 58	72 116
Cold	Body Lid	160 264	27 58	54 116
Increased External pressure	Body Lid	160 264	27 58	54 116
Reduced External pressure	Body Lid	160 264	36 58	72 116

The regulations require the cask to be evaluated for the following hypothetical accident conditions; free drop from 9m, crush and 1m puncture. Crush condition is not applicable to the cask because its weight exceeds 500kg. Additionally, the cask is subjected to water immersion condition under an external water pressure of 2MPa. The regulations require the structural adequacy be demonstrated for a free drop through a height of 9m onto a flat, unyielding, horizontal surface, striking the surface in a position for which maximum damage is expected. The cask was evaluated for the following CG over initial point of impact orientations; corner - lid edge drop, axis vertical - top down drop, and axis horizontal - side drop. Additionally, it had also been analysed for oblique impact with the cask at 30 degrees to the horizontal. Evaluation was carried out using LS-DYNA3D explicit transient finite element analysis code. One basic finite element model, with different initial conditions and boundary condition was used for the analysis of all the CG over point of impact and oblique drop events. The model consists of 350,000 elements and is shown in Fig. 3.1(b). All the components of the cask were modelled, and interaction between all contacting components were modelled. For all the impact analyses, the model was a half model, assuming symmetry about the plane which dissects both sets of trunnions in half. This is true for the body and the basket, but not for the lid – due to the asymmetric location of the hexagonal socket head cap screws and the closure plug and closure lid. The half of the cask modelled was the half which encompassed the closure lid. At the start of the impact analyses of the CG over point of impact scenarios, the whole cask model was given an initial velocity of 13.3m/sec perpendicular to the target, representing the initial impact velocity in a 9m free drop. For the oblique drop, the analysis model was given the velocity distribution at second impact due to an initial drop angle of 15 degrees. The regulations require the cask be assessed for a free drop of 1m onto a stationary and vertical mild steel bar of 0.15m in diameter, after a 9m free drop on the same cask, and to suffer no loss of containment. The bar is required to hit the cask at a position that is expected to inflict maximum damage on the cask. The maximum damage will result from impact where the pin is directly located below the centre of gravity, so as to maximise the energy that needs to be absorbed in the deformation of the cask or the pin, i.e. without the cask rotating off the pin due to the presence of moment arm between the pin and the CG. The worst combination of drop orientation and pin location will be the side drop onto the pin such that the pin is vertically below the CG and the top down drop onto the pin with the pin vertically below the CG, i.e. with the pin co-linear with the cask axis. The side pin drop is the worst possible pin drop onto a side to cause maximum damage. The top pin drop is the worst possible drop onto the cask ends. Since the lid port is located off-centre, and is protected by the plate on the underside of the impact limiter, pin drop onto the lid ports location will not cause any significant damage to the cask. Analyses were carried out on the same model by LS-DYNA3D code. And, performance of the cask under 2Mpa external pressure was also analyzed by LS-DYNA3D code. Analysis results and stress comparison with stress limits are shown in Table 3.2.

Table 3.2   Structural analysis results under the hypothetical accident conditions

Analysis	Component	Stress limits, Mpa				Max. shear stress, MPa	Max. stress Intensity, Mpa
		Hot		Cold			
		2.4Sm	0.7Su	2.4Sm	0.7Su		
Side drop	Body	372	337	385	337	168	336
	Lid	633	555	633	555	170	340
Lid down drop	Body	372	337	385	337	140	280
	Lid	633	555	633	555	170	340
Lid edge drop	Body	372	337	385	337	154	308
	Lid	633	555	633	555	162	324
Oblique drop	Body	372	337	385	337	168	336
	Lid	633	555	633	555	235	470
Side pin drop	Body	372	337	385	337	150	300
	Lid	633	555	633	555	65	130
Top pin drop	Body	372	337	385	337	57	114
	Lid	633	555	633	555	159	318
Water immersion	Body	372	337	385	337	32	64
	Lid	633	555	633	555	64	128

3.2 Thermal

The cask has been designed for carrying up to twelve PWR fuel assemblies in a basket structure. The fuel assemblies can be W.H. 17x17, 16x16 or 14x14. And, the backfill medium can be helium or water. Heat is transferred between the cask and the environment by passive means only. It does not rely on any forced cooling. In transport, the cask is fitted with two shock absorbers, one at each end. It is transported horizontally under a transport hood.

The main mode of heat transfer between the fuel assemblies and the basket is via conduction and radiation. Where gaps between basket components exist, heat is transferred across the gaps via conduction through the backfill medium and radiation. Heat is transferred through the gaps between the basket and the inner surface of the cask body and the gap between the basket and the underside of the lid by radiation and conduction. Heat is transferred through the cask wall by conduction. Since the cask cavity within the basket is highly compartmentalised and the cask is transported horizontally, the effect of convection within the cask is not significant. During normal transport conditions, the cask is covered by a transport hood, which is intended as a insolation shield. The hood is exposed to the ambient temperature and insolation. On its outer surface, heat transfer between the surface and the environment takes place by convection and radiation while insolation heats up the outer surface of the hood. The cask exchanges heat with the surrounding by convection and radiation. During transport, the cask is fitted with two shock absorbers, one at each end. The shock absorbers consist of layered wood encased within a stainless steel cladding, and they act like insulators in terms of transfer of heat into and out of the cask. Under the normal transport conditions, the cask must lose the heat generated by the fuel to the environment without exceeding the operational temperature limits of the cask components important to safety. In order to avoid melting of the fuel pellet, the temperature of the pellet centreline must not exceed 2,593°C for normal operating conditions and hypothetical accident conditions. To avoid failure of the fuel cladding from accelerated oxidation, the maximum temperature of the fuel rod cladding should be limited below 398°C for normal operating conditions and 426°C for hypothetical accident conditions. These are the same as the design criteria for the fuel assemblies in the reactor core.

The temperatures of the cask and components were determined by using finite element methods. Only the cask with the W.H. 17x17 PWR fuel assemblies was analysed, as this represent the worst case, in terms of temperatures in the cask and in the fuel assemblies and also in terms of pressure. And among the normal transport conditions, only the hot condition was analysed for the same reasoning. Analyses considered both water and helium as backfill mediums. One basic three dimensional finite element model was used to simulate the normal hot condition of transport and the hypothetical accident condition of both the dry and the wet cask, by applying different sets of boundary conditions and material properties. The half model of the cask taking advantage of symmetry consists of all significant components of the whole package. For the evaluation of the cask for the normal hot condition of transport, two dimensional anlaysis to simulate the traverse heat transfer characteristic through the fuel assemblies and to calculate the temperatures in the fuel assemblies was carried out using MSC/NASTRAN code, and a steady state analysis was performed using LS-DYNA3D code. The worst normal condition as far as temperature in the cask components and fuel assemblies are concerned is the hot condition with W.H. 17x17 fuel assemblies. Hence, only the hot condition with W.H. 17x 7 fuel assemblies was analysed, firstly with helium as the backfill and then with water backfill. Figure 3.2 show the temperatures over the cask for the helium filled case. Comparison between the temperatures of the safety related components during normal hot conditions of transport and their safe operating temperatures in Table 3.3 shows that the temperatures of safety related components are maintained below safe operating temperatures. The maximum temperature of the cask exterior surface exceeds 85°C. The transient thermal analysis was carried out for the 30 minute fire phase and another transient thermal analysis was carried out for post-fire cool down phase. The cool down phase of these analyses were allowed to run for 30 hours or more to ensure that all the components have reached their maximum temperature. The maximum component temperatures during the fire and cool down phases can be found in Table 3.4. Table 3.4 shows that all the safety related cask components do not exceed their maximum safe operating temperatures under hypothetical accident conditions except for the moderator rods and the moderator plate below the cask. From the analyses carried out, the maximum fuel pellet centreline temperature and the maximum fuel rod cladding temperature did not exceed their limiting temperatures for normal transport conditions and hypothetical accident conditions.

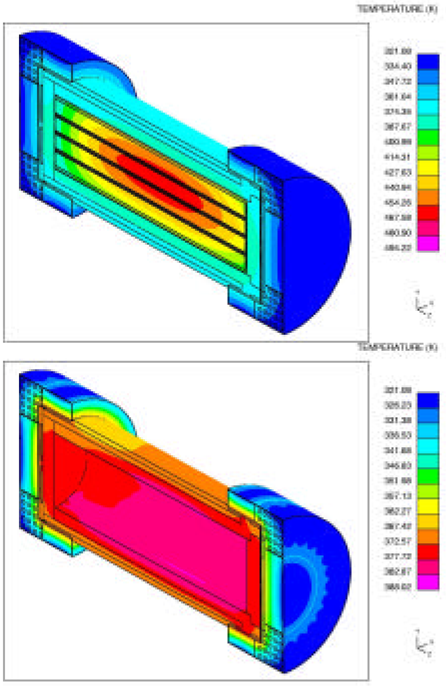


Fig. 3.2 Temperatures Over the Cask for the He Filled Case

Table 3.3 Maximum component temperatures for normal hot conditions of transport

Cask component	Safe operating temperatures,°C	Temperature, °C	
		Helium	Water
Cask outer surface	-	98	98
Cask inner surface	-	115	113
Lid	O-ring seals: -40 to 250	103	104
Moderator rod inner row	Max. 120	110	110
Moderators rod outer row	Max. 120	103	104
Outer basket wall	-	189	167
Boron Aluminium Plates	Max. 400	191	168
Receptacle walls	-	191	168
Fuel cladding / Fuel pellet	Max. 398 / Max. 2593	221	180
Backfill medium	-	162	140

Table 3.4 Maximum component temperatures and time of occurrence for hypothetical accident conditions

Cask component	Safe operating temperatures,°C	Temperature, °C	
		Helium	Water
Cask outer surface	-	350 (0hr)	350 (0hr)
Cask inner surface	-	197 (2.9hr)	189 (2.4hr)
Lid	O-ring seals: -40 to 250	141 (30hr)	134 (30hr)
Moderator rod inner row	Max. 120	217 (0.4hr)	190 (2.3hr)
Moderators rod outer row	Max. 120	281 (0hr)	282 (0hr)
Outer basket wall	-	241 (12.6hr)	202 (23.9hr)
Boron Aluminium Plates	Max. 400	243 (12.6hr)	202 (23.9hr)
Receptacle walls	-	243 (12.6hr)	202 (23.9hr)
Fuel cladding / Fuel pellet	Max. 398 / Max. 2593	270 (14.7hr)	215 (23.9hr)
Backfill medium	-	207 (12.6hr)	173 (23.9hr)

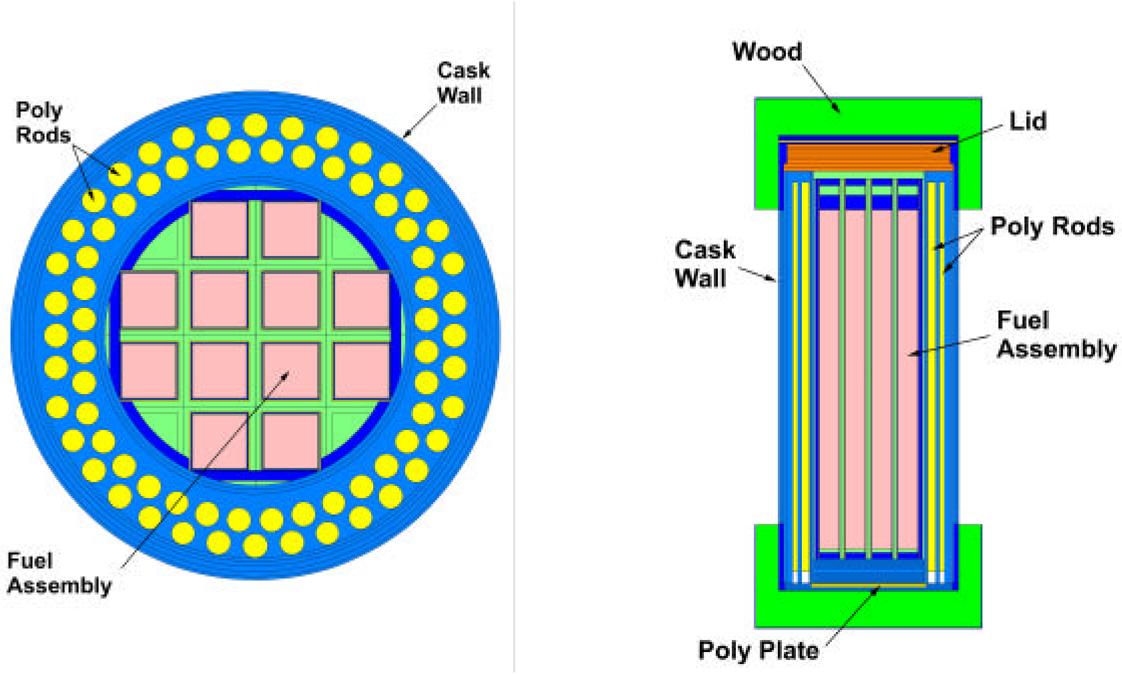
3.3 Radiation Shielding

The radiation shielding features for the cask are sufficient to meet the radiation dose requirements in the related regulations. The cask must be transported by exclusive use shipment only. The dose rate limits are 10,000µSv/h on the external surface of the package, 2,000µSv/h at any point on the outer surface of the vehicle, including top and underside of the vehicle; or in the case of a flat-bed style vehicle, at any point on the vertical planes projected from the outer edges of the vehicle, on the upper surface of the load or enclosure if used, and on the lower external surface of the vehicle; and 100µSv/h at any point 2m from the outer lateral surface of the vehicle (excluding the top and underside of the vehicle); or in the case of a flat-bed style vehicle, at any point 2m from the vertical planes projected by the outer edges of the vehicle (excluding the top and underside of the vehicle); and 20µSv/h in any normally occupied space, except that this provision does not apply to private carriers, if exposed personnel under their control wear radiation dosimetry devices. In case of a hypothetical accident codition no external radiation dose rate exceeding 10,000µSv/h at 1m from the external surface of the cask should be reached. And, the additional KEPCO-NETEC’s requirements are: the cask shall be so designed that under normal transport conditions the radiation level does not exceed 2,000µSv/h at any point on, and 100µSv/h at 2m from, the external surface of the cask, and the cask shall be so designed that, if it were subjected to hypothetical accident conditions, it would retain sufficient shielding to ensure that the radiation level at 1m from the surface of the cask would not exceed 10,000µSv/h with the maximum radioactive contents which the cask is designed to carry.

Shielding for the cask is provided by the thick-walled cask body and the lid. For neutron shielding, polyethylene rods are arranged in longitudinal boreholes in the vessel wall and polyethylene plates are inserted between the cask lid and lid side shock absorber and between the cask bottom and bottom steel plate. Additional shielding is provided by the basket structure. For transport, shock absorbers are installed at the top and bottom of the cask end areas. The package will be transported with a vehicle using a transport hood. For distant locations geometric attenuation enhanced by air and ground, provides additional shielding. The source terms for the design spent PWR fuel were determined using ORIGEN-2.1 code. The shielding analyses were performed with MCNP-4B, which is a Monte Carlo transport code that offers a three-dimensional combinatorial geometry modelling capability including complex surfaces The W.H. fuel type 17x17 with intact zircaloy cladding has been determined to be the design basis for shielding calculations. For source term calculations the design basis spent fuel is characterized by the following parameters: burnup of 50,000 MGWD/ MTU, initial enrichment of 5wt.% and cooling time of 7 years.

Normal transport conditions are modelled with the cask with shock absorbers and transport hood. Hypothetical accident conditions assume the absence of the transport hood, the shock absorbers and the neutron moderator. The dose analysis covers the hypothetical accident conditions in the related regulation in a conservative manner, because the shock absorbers remain on the cask and the complete loss of neutron moderator is not possible. Moderator regions in the shielding model are replaced by air. The expected maximum dose rates from the cask for normal transport conditions of transport and hypothetical accident conditions are provided. The radial and axial views of the analysis model are shown in Fig. 3.3(a) and 3.3(b). Tables 3.5 through 3.7 show the results of the shielding calculations. The tables give maximum dose rates in their respective region. The maximum dose rate at 1 meter distance from the cask surface is 170µSv/h. No additional shielding from the transport hood was considered. As the length of the vehicle may vary, the dose rates at 2m from the transport frame surface (lid and bottom side) are conservatively assumed to be the same as the dose rates at 2m from the cask surface (lid and bottom side), which is less than 20µSv/hr, the limit for any normally occupied space.

The source term calculations were performed using the program ORIGEN2 with the extended burnup library, PWRU50. The calculations were based on the following assumptions: (a) design basis fuel assembly with 464.0 kg of U-metal, (b) the fuel has an enrichment of 5.0wt.% of U-235, (c) the burnup is 50,000MWD/MTU, (d) the cooling time after the last burn cycle is 7 years, (e) the fuel is burned during 3 cycles with 396.825 days each at an average specific power of 42 MW/MTU (50.4 the first cycle, 42.0 the second cycle, and 33.6 the third cycle), and (f) between the burn cycles, a 60 day shut down period was assumed.



(a) Radial cross section (b) axial section

Fig. 3.3 Shielding analysis model

Table 3.5 Dose rates at the cask surface for normal transport conditions

Dose point location	Gamma dose rate (μSv/h)	Neutron dose rate (μSv/h)	Total dose rate (μSv/h)
Lid impact limiter center	6	5	11
Side top	419	26	445
Side middle	302	119	421
Side bottom	267	58	325
Bottom impact limiter center	91	14	105
KEPCO-NETEC’ s limit	-	-	2,000

Table 3.6 Dose rates at 2m from the cask surface for normal transport conditions

Dose point location	Gamma dose rate (μSv/h)	Neutron dose rate (μSv/h)	Total dose rate (μSv/h)
Lid impact limiter center	1	1	2
Side top	38	14	52
Side middle	67	24	91
Side bottom	39	15	54
Bottom impact limiter center	12	2	14
KEPCO-NETEC’ s limit	-	-	100

Table 3.7 Dose rates at 1m from the cask surface for hypothetical accident conditions

Dose point location	Gamma dose rate (μSv/h)	Neutron dose rate (μSv/h)	Total dose rate (μSv/h)
Lid impact limiter center	209	212	421
Side top	784	1,132	1,916
Side middle	287	2509	2,796
Side bottom	682	1,517	2,199
Bottom impact limiter center	281	431	713
KEPCO-NETEC’ s limit	-	-	10,000

3.4 Criticality

The cask is designed to transport 12 zirconium clad PWR fuel assemblies without any criticalities under normal transport conditions and hypothetical accident conditions. This is accomplished by controlling the neutron multiplication with plates of borated aluminum between the basket cells. These borated plates are sandwiched between a flux trap and the fuel assembly. The flux trap forces a physical separation between the fuel assemblies and, when filled with water, slows down the neutrons so that they can be captured in the borated aluminum (see Fig. 3.4). The basket assembly within the cask cavity maintains the relative position of the fuel assemblies under normal transport conditions and hypothetical accident conditions. Fuel for the cask can be loaded with fuel from three plant types, W.H. 14x14, 16x16 and 17x17 fueled plants. All of the different fuel designs being used in Korea for these three plant types were analyzed in the criticality analysis.

The cask is designed to transport all of the W.H. PWR zircaloy-clad fuel being used in Korea. The criticality analysis was performed for each fuel assembly design being used in Korea. Prior to analyzing each fuel type, some general properties of fuel in the cask were identified. First, the worth of the fresh water in the fuel receptacles is positive. Replacing clad volume with water volume increases k_{eff}. This means that in comparing fuel designs, the design with the thinnest clad (all else being equal) produces the highest k_{eff}. The second important observation was that replacing fuel with water also has a positive worth. This observation is also generally true in power reactors where a fuel assembly with a smaller pin diameter such as the W.H. OFA fuel actually produces a higher initial k_{eff}. In the flux trap design of the cask, the importance of water inside the fuel receptacles is such that even replacing fuel with water increases the reactivity. Both the clad/water effect and the fuel/water effect are in the same direction for all fuel designs. This determines which fuel properties are most limiting. However, analysis of each individual fuel type was performed to confirm this observation. The uncertainty in the individual fuel pin dimensions is not significant to k_{eff}. The tolerance on the cladding thickness and cladding outside diameter are insignificant to k_{eff} since both the worth of exchanging clad with water and the tolerance are very small. Any reduction in pitch between any two pins would be compensated by an increase in the pitch on the other side of the pin. Uniform reduction of the pitch lowers k_{eff}. Tolerances for enlarging the pitch are small due to space considerations in loading the PWR. A uniform increase in pitch following an accident is not credible. The tolerance on the pellet dimensions is small since the fuel assemblies are weighed. The error in this weight is very low. The maximum possible fuel assembly weight is used to assure conservative analysis.

The cask is designed for both dry and wet transport. For wet transport, 80% of the volume of the cavity is filled with water. However, the cask for loading and unloading operations is totally flooded. The flooded state is more limiting in terms of reactivity than the dry state. Optimum moderation (unborated fresh water at 4°C) is considered in performing the criticality analyses. Non-uniform flooding of the fuel basket and the fuel assemblies is not assumed because all free spaces in the cavity, the fuel basket structures and the fuel assemblies are interconnected, and therefore a non-uniform flooding state is not a credible condition. The condition that results in the highest reactivity is not the fully flooded condition - instead it is a condition in which the cask is laying on its side and the water level is exactly between the second row of assemblies (counting from the top) and the flux trap between the first and second row of assemblies. This condition is more reactive than the fully flooded case because the flux traps are very important in keeping the reactivity down. By uncovering the flux traps above the second top row of assemblies, the reactivity loss from the top two fuel assemblies is more than offset by the reactivity gain in not flooding the flux traps. The fuel rod pellet-to-clad air gaps are also assumed to be flooded with 100% fresh water. Higher temperatures of both the fuel and the moderating water - resulting from decay heat - are neglected, and a temperature of 20°C is assumed for the fuel and 4°C is assumed for the water. With regard to the fresh fuel, no credit is taken for small amounts of U-236 that may be present. The fuel stack density is assumed to be 95% of theoretical for all criticality analyses. No credit is taken for fuel pellet dishing or chamfering. The hypothetical accident conditions have no effect on the cask design parameters important to criticality safety. Therefore, these conditions are identical to those for the normal conditions. The fuel basket with its 12 fuel assembly positions is designed such that the neutron-absorbing material is fixed and will remain effective for storage periods greater than 20 years. There are no credible conditions that will displace the neutron-absorbing material. Therefore, there is no need to provide a surveillance or monitoring program to verify the continued efficacy of the neutron absorber. A list of the cask modeling assumptions are given in the followings: 1) The cask is assumed to be completely surrounded on all sides by identical casks in a conservative arrangement having the maximum reactivity effect. This is modeled by a reflective boundary condition. 2) All of the flux traps are assumed to be flooded when the fuel assemblies are flooded because there is no credible mechanism to flood the fuel without flooding the flux traps. The exception to this is a partially flooded condition in which the water level is exactly between the second row of assemblies (counting from the top) and the flux trap between the first and second row of assemblies. This is the worst case condition and is used for the criticality analysis. 3) The steel inside the flux traps is approximated by two thin sheets of steel having the same volume as the steel in the design. Calculations showed that neglecting the steel inside the flux traps would decrease the reactivity due to the water displacement of the steel. The water inside the flux traps has a negative worth in that less water causes the borated plates to be less effective as neutron absorbers. Therefore, including the steel inside the flux traps is conservative. 4) The steel profile pieces in the four corners of the cask were conservatively approximated by small cuboids. Including these pieces in the model is conservative for the same reasons as given above (water outside of the fuel receptacles has a negative worth. 5) The minimum B-10 content of the borated aluminum will be manufactured to be 0.1100 g/cc. This amount of B-10 was then conservatively reduced in the model by 20%. This 20% reduction is slightly less than the 25% reduction. This reduction is to account for self-shielding, grain size, and as-built boron content. Critical experiments with borated aluminum, however, show that this 25% penalty is unreasonable. These critical experiments were modeled with 0% penalty and no significant trend or bias was observed. Therefore, a 20% penalty is sufficiently conservative to account for self-shielding, grain size, and as-built boron content. The remaining material of the borated aluminum was modeled to be pure aluminum. 6) To account for manufacturing tolerances of the cask structure, the nominal dimensions are either increased or decreased by the manufacturing tolerance. Calculations show that this results in the largest reactivity for the loaded cask. 7) The material compositions and dimensions of the borated plates, steel basket, steel supports, and outer shell of the cask are assumed to be those.

The method for performing the criticality analysis is the three-dimensional Monte Carlo Code KENO-Va. KENO-Va was selected because it has been extensively used and validated by others and has all the necessary features for this analysis. The criticality calculations were performed with SCALE 4.4a program system. For criticality calculations, this program can use several different cross-section libraries. The 44 Group library based on the ENDF/B-V evaluation was selected for the analysis. The program system also has routines for dealing with self-shielding according to the Bondarenko method or according to the Nordheim method for these cross-section sets. These programs are called up according to the resonance data available. The self-shielded cross-sections are used by KENO-Va to calculate the multiplication factor. In addition, the program system has several auxiliary routines, e.g., for the calculation of the Dancoff factor, calculation of nuclide densities, or for the automated transfer of the cross-sections. A minimum of 8,000 histories were simulated per generation, and a minimum of 2,020 generations were accumulated. The number of generations skipped before averaging was found by selecting the number that results in the smallest statistical error. The neutrons are started with a cosine distribution within the cuboid spanned by the fuel assembly receptacles.

Maximum values of the k_{eff} resulting from the criticality analysis considering the condition of optimum partial flooding with fresh water are presented in Table 3.8. The criticality analyses were performed for fresh fuel assemblies for each of the fuel designs being used in Korea. The most limiting design within a particular plant type is shown in bold. The data confirm that for each of the candidate fuel assembly designs, the effective multiplication factor(k_{eff}), including all biases and uncertainties at a 95% confidence level, do not exceed 0.95.

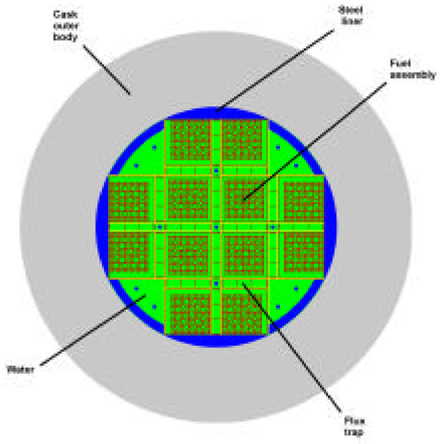


Fig. 3.4 Criticality analysis model

Table 3.8 Criticality analysis results

W.H. fuel type	Enrichment, wt.%	Unadjusted k_{eff}	Deviation (2σ)	Bias	Maximum k_{eff}
14x14 – STD	5.00	0.9085	0.0004	0.0087	0.9176
14x14 – KNFC	5.00	0.9199	0.0004	0.0087	0.9290
14x14 – JDFA	5.00	0.9034	0.0004	0.0087	0.9125
16x16 – STD	5.00	0.9006	0.0004	0.0087	0.9097
16x16 – JDFA	5.00	0.8978	0.0004	0.0087	0.9069
17x17 – STD	5.00	0.9338	0.0004	0.0087	0.9429
17x17 – JDFA	5.00	0.9313	0.0004	0.0087	0.9404
17x17 – OFA	5.00	0.9394	0.0004	0.0087	0.9485

4. Conclusion

The KN-12 shipping cask is a new design of a transport package intended for dry and wet transportation of up to 12 spent nuclear fuel assemblies from pressure water reactors. The cask has been designed basing on KEPCO-NETEC's requirements and evaluated as a transport package that complies with the requirements of IAEA Safety Standards Series No.ST-1, US 10 CFR Part 71 and Korea Atomic Energy Act for Type B(U)F package. The cask provides containment, radiation shielding, structural integrity, criticality control and passive heat removal for normal transport conditions and hypothetical accident conditions.

5. Reference

[1] IAEA, IAEA Safety Standards Series No.ST-1, “Regulations for the Safe Transport of Radioactive Material”, 1996
[2] U.S NRC, 10 CFR Part 71, “Packaging and Transportation of Radioactive Material”, 1997
[3] Korea MOST, Korea Atomic Energy Act, 1999