Evaluation of the KN-12 Spent Fuel Transport Cask by Analysis

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Abstract

The KN-12 cask is designed to transport 12 PWR spent nuclear fuels and to comply with the requirements of Korea Atomic Energy Act, IAEA Safety Standards Series No.ST-1 and US 10 CFR Part 71 for a Type B(U)F package. It provides containment, radiation shielding, structural integrity, criticality control and heat removal for normal transport and hypothetical accident conditions. W.H 14×14, 16×16 and 17×17 fuel assemblies with maximum allowable initial enrichment of 5.0 wt.%, maximum average burn-up of 50,000 MWD/MTU and minimum cooling time of 7 years being used in Korea will be loaded and subsequently transported under dry and wet conditions. A forged cylindrical cask body which constitutes the containment vessel is closed by a cask lid. Polyethylene rods for neutron shielding are arranged in two rows of longitudinal bore holes in the cask body wall. A fuel basket to accommodate up to 12 PWR fuel assemblies provides support of the fuels, control of criticality and a path to dissipate heat. Impact limiters to absorb the impact energy under the hypothetical accident conditions are attached at the top and at the bottom side of the cask during transport. Handling weight loaded with water is 74.8 tons and transport weight loaded with water with the impact limiters is 84.3 tons. The cask will be licensed in accordance with Korea Atomic Energy Act and fabricated in Korea in accordance with ASME B&PV Code Section III, Division 3.

1. Introduction

The KN-12 spent fuel transport cask is a new design of a transport package intended for dry and wet transportation of up to 12 spent nuclear fuels from pressure water reactors. The cask has been designed basing on 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 and will be fabricated in Korea in accordance with the requirements of ASME B&PV Code Section III, Division 3[4]. The cask provides containment, radiation shielding, structural integrity, criticality control and passive heat removal for normal transport and hypothetical accident conditions. The W.H 14×14, 16×16 and 17×17 fuels will be loaded and subsequently transported in the cask. The maximum allowable initial enrichment of the fuel is 5.0 wt.%, the fuel burnup is limited to a maximum average of 50,000 MWD/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 double elastomer O-rings. The steel thickness of the cask body wall and of the lid meet the dose rate limits of the 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 PWR fuels provides support of the fuels, control of criticality and a path to dissipate heat from the fuels to the cask body. The stainless steel fuel receptacles to enclose and secure the fuels are assembled as a gridwork together with boronated 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 the beech and spruce woods to absorb the impact energy under 9 m free drop conditions as a hypothetical accident are attached at the top and at the bottom side of the cask during transport.
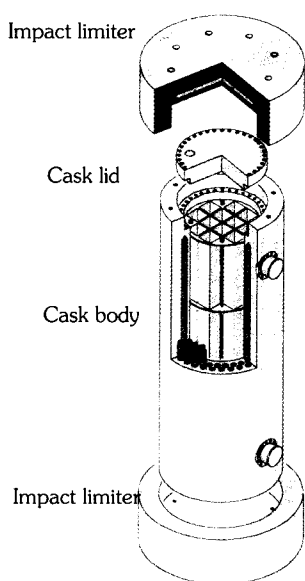
Package type: B(U)F

Transport capacity: 12 PWR spent nuclear fuels

Design basis fuel
- Fuel type   : W.H 14x14, 16x16, 17x17
- Max. burn-up   : 50,000 MWD/MTU
- Max. enrichment   : 5.0 wt.%
- Min. cooling time   : 7 years

Fig. 1. Overview of the KN-12 Cask

2. Cask Description

2.1. Package

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.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 by 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. 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 12.6 kW is dissipated from the outer cask body surface by radiation and by natural convection to the surrounding air. 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 9m 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 as shown in the Fig.2 is 4,809 mm with a wall thickness of 375 mm. The cylindrical cask cavity has an internal diameter of 1,192 mm and an internal length of 4,190 mm. The lid is 290 mm thick. Each impact limiter is 2,450 mm in diameter and extends 700 mm along the side of the cask in axial direction. The open dimension of the fuel basket is 220 mm x 220 mm, and the free length of the basket between basket inside bottom surface up to lower lid surface is 4170mm. Weights of the KN-12 cask are as the followings; cask body of 51.5 tons, cask lid of 3.3 tons, basket of 7 tons, impact limiters of 11.7 tons, fuels of 7.9 tons, water filing of 2.2 tons, and cask lifting device of 2.3 tons. 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 84.3 tons.

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 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 cask 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
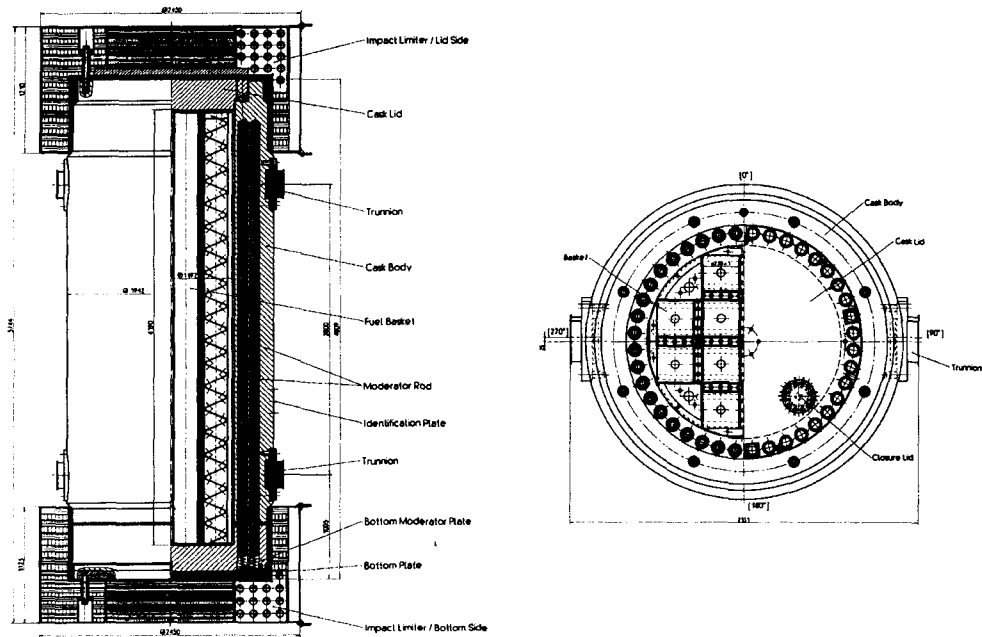
Fig. 2. General Arrangement of the KN-12 Cask

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 fuels, control of criticality, and a path to dissipate the heat from the fuel assembly to the cask body, and is designed to accommodate up to 12 PWR spent fuels. The fuel receptacles are manufactured by the welding of stainless steel plates to form a square tube to enclose and secure the fuels. The receptacles are assembled as a gridwork together with boronated aluminum plates. Each stainless steel fuel receptacle is fully surrounded by the boronated 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 boronated aluminum plates of this basket gridwork provide the sufficient heat removal. The boron content of these plates assures nuclear criticality safety under normal transport and 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[5]. 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 9 m free drop as a hypothetical accident. The impact limiters are manufactured from an inner carbon steel structure and an outer stainless steel shell filled with the beech and spruce woods. 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.

2.2. Operational Features

The cask is designed for dry and wet transportation of up to 12 PWR fuels. The typical fuel of W.H 17×17 might be transported in the cask. Known or suspected failed fuel assemblies with cladding defects are not to be transported in the cask. The maximum allowable initial UO_2 enrichment is 5.0 wt.%. The fuel burnup is limited to a maximum average of 50,000 MWD/MTU. Prior to load in the cask, the fuel must have a minimum cooling time of 7 years. W.H 14×14, 16×16 or 17×17 fuels may be loaded and subsequently transported in the cask provided that the fuels meet the requirements. Each fuel is

assumed to have a maximum decay heat load of 1.05kW, and the cask has a total heat dissipation capability of 12.6kW. The heat rejection dissipation capability of the cask maintains the maximum fuel rod cladding temperature below 398 ℃ under normal operating conditions with a 12.6kW decay heat load, 38℃ ambient air and insolation. The fuels can be transported alternatively in an inert helium gas atmosphere or in a water filling inside the cask cavity. Criticality safety is achieved by utilizing neutron absorption materials, i.e., boronated aluminum plates, in the basket structure. For the basket arrangement, k_{eff} is limited to 0.95 even with unboronated 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 and hypothetical accident conditions. The shielding features of the cask including impact limiters are designed to maintain the maximum combined gamma and neutron dose rate to less than 2 mSv/hr at the surface and to less than 0.1 mSv/hr in 2 m distance under normal transportation conditions. The loaded cask will be transported by a heavy-haul trailer.

3. Evaluation by Analysis

3.1. Structural

The structural design of the cask incorporates criteria based on the following codes and standards; IAEA SSS No.ST-1, US 10 CFR 71, Korea Atomic Energy Act, ASME Sec.III, Div.3, and US NRC RGs 7.6[6] and 7.8[7]. Structural performance of the cask has been evaluated for
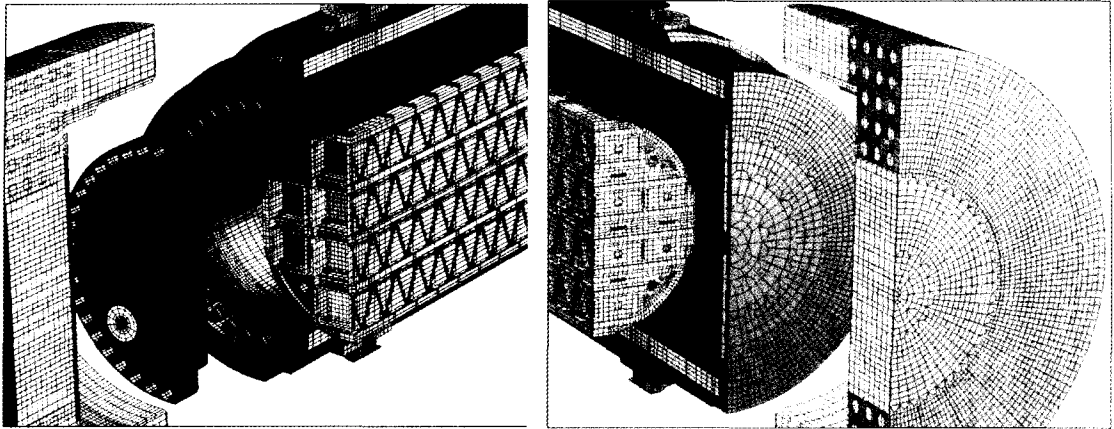
Fig. 3. Finite Element Analysis Model

the load conditions that need to be considered are defined in 10 CFR 71 and RG 7.8. Stress limits for containment structure and bolts of the structure are stated in ASME Sec.III, Div.3, and are consistent with those stated in RG 7.6. The non-containment structural members are shown to satisfy essentially the same structural criteria as the containment structure, even though RG 7.6 applies only to containment structures. Non-containment structures include all structural members other than the containment boundary components, but exclude the trunnions and impact limiters. The impact limiters, including their cladding structure, are not stress-limited. While performing their intended function during the free-drop impact, the impact limiters crush and thereby absorb the energy of the impact. The crushing of the spruce and beech woods contained in the impact limiter absorbs the kinetic energy of the cask while limiting the deceleration forces applied to the cask.

Analyses were performed to evaluate the performance of the cask under both normal transport and hypothetical accident conditions specified in the regulations using DYNA3D explicit transient finite element analysis code. One basic finite element model as shown in the Fig. 3, which

consists of 360,000 elements with different initial conditions and boundary condition was used for each analysis. All the components of the cask were modeled, and interaction between all contacting components were modeled. 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 modeled 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 9 m 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.

Analysis results and stress comparison with stress limits are shown in Tables 1 and 2. The regulations require the cask to be evaluated for the following normal transport conditions; heat, cold, reduced external pressure, increased external pressure, vibration, water spray, free drop of 0.3m, corner drop, compression and penetration.

Table 1. Structural Analysis Results Under Normal Transport Conditions

Analysis	Component	Stress limit, MPa	Max. shear stress, MPa	Max. stress intensity, MPa
Hot	Body	155	36	72
	Lid	264	58	116
Cold	Body	160	27	54
	Lid	264	58	116
Increased external pressure	Body	160	27	54
	Lid	264	58	116
Reduced external pressure	Body	160	36	72
	Lid	264	58	116

Table 2. Structural Analysis Results Under Accidental Conditions

Analysis	Component	Stress limits, MPa				Max. shear stress, MPa	Max. stress intensity, MPa
		Hot		Cold			
		2.4 Sm	0.7 Su	2.4 Sm	0.7 Su		
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

However, because of its dimensions and weight, structural behaviour of the cask under the heat, cold, reduced external pressure and increased external pressure were analysed. The regulations require the cask to be evaluated for the following hypothetical accident conditions; free drop from 9m and 1m puncture. Additionally, the cask is subjected to water immersion condition under an external water pressure of 2 MPa. The regulations require the structural adequacy be demonstrated for a free drop through a height of 9m onto a flat unyielding 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 15 degrees to the horizontal. The regulations require the cask be assessed for a free drop of 1 m 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.

3.2. Thermal

The backfill medium in the cask cavity can be helium or water for dry and wet transport conditions, respectively. 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 fuels 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 ℃ for normal and accidental conditions. To avoid failure of the fuel cladding from accelerated oxidation, the maximum temperature of the fuel rod cladding should be limited below 398 ℃ for normal operating conditions and 426 ℃ for accidental conditions. These are the same as the design criteria for the fuels in the reactor core.

The temperatures of the cask and components were determined by using finite element methods.

Table 3. Maximum Component Temperatures for Normal Hot Conditions of Transport

Cask component	Safe operating temperatures, °C	Temperature, °C	
		Helium	Water
Cask outer/inner surface	-	98 / 115	98 / 113
Lid	O-ring seals: -40 to 250	103	104
Moderator rod inner/outer row	Max. 120	110 / 103	110 / 104
Basket wall	-	189	167
Boronated aluminium plates	Max. 400	191	168
Backfill medium	-	162	140

Table 4. Maximum Component Temperatures for Accidental Conditions

Cask component	Safe operating temperatures, °C	Temperature, °C	
		Helium	Water
Cask outer/inner surface	-	350 / 197	350 / 189
Lid	O-ring seals: -40 to 250	141	134
Moderator rod inner/outer row	Max. 120	217 / 281	190 / 282
Basket wall	-	241	202
Boronated aluminium plates	Max. 400	243	202
Backfill medium	-	207	173

Only the cask with the W.H 17 × 17 fuels was analysed, as this represent the worst case, in terms of temperatures in the cask and in the fuels 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 fuels and to calculate the temperatures in the fuels was carried out using MSC/NASTRAN code, and a steady state analysis was performed using DYNA3D code. The worst normal condition as far as temperature in the cask components and fuels are concerned is the hot condition with W.H 17 × 17 fuels. Hence, only the hot condition with W.H 17 × 17 fuels was analysed, firstly with helium as the backfill and then with water backfill. Comparison between the temperatures of the safety related components during normal hot conditions of transport and their safe operating temperatures in Table 3 shows that the temperatures of safety related components are maintained below safe operating temperatures. 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 4. Table 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 and hypothetical accident conditions.

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 mSv/h (10,000 μSv/h) on the external surface of the package, 2 mSv/h (2,000 μSv/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 0.1 mSv/h (100 μSv/h) at any point 2 m from the outer lateral surface 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 0.02 mSv/h (20 μSv/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 mSv/h at 1 m from the external surface of the cask should be reached. And, the additional NETEC's requirements are: the cask shall be so designed that under normal transport conditions the radiation level does not exceed 2 mSv/h at any point on, and 0.1 mSv/h at 2 m from, the
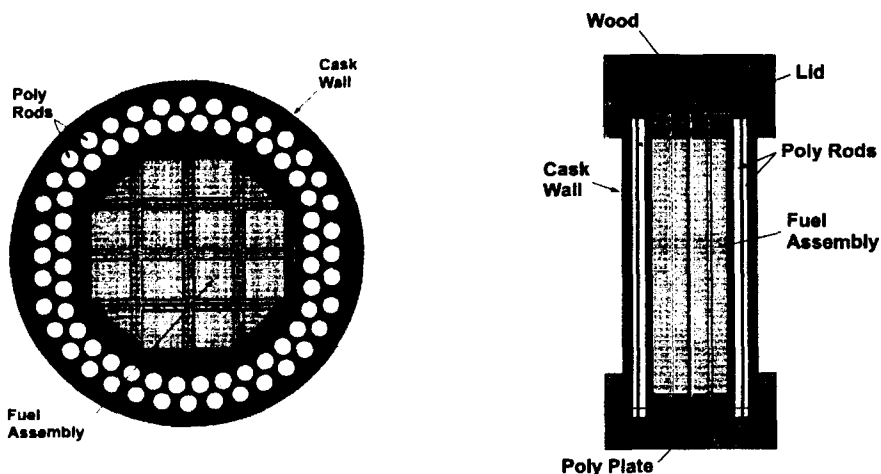

Fig. 4. Radiation Shielding Analysis Model

Table 5. Dose Rates on the Cask Surface for Normal Conditions

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

Table 6. Dose rates at 2 m from the Cask Surface for Normal Conditions

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

Table 7. Dose Rates at 1 m from the Cask Surface for Accidental Conditions

Dose point location	Gamma, µSv/h	Neutron, µSv/h	Total, µSv/h
Lid impact limiter center	209	212	421
Side top/middle/bottom	784 /287 / 682	1132 / 2509 / 1517	1916 / 2796 / 2199
Bottom impact limiter center	281	431	713
Regulatory limit	-	-	10,000

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 1 m from the surface of the cask would not exceed 10 mSv/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 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. For distant locations geometric attenuation enhanced by air and ground, provides additional shielding.

The source terms for the design 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 17 · 17 with intact zircaloy cladding has been determined to be the design basis for shielding calculations. The radial and

axial views of the radiation shielding analysis model are shown in Fig. 4.

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. Tables 5 through 7 show the results of the shielding calculations. The tables give maximum dose rates in their respective region. The maximum dose rate at 1m distance from the cask surface is $170\,\mu$Sv/h. No additional shielding from the transport hood was considered. As the length of the vehicle may vary, the dose rates at 2 m from the transport frame surface are conservatively assumed to be the same as the dose rates at 2m from the cask surface, which is less than $20\,\mu$Sv/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) basis fuel with 464.0kg of U-metal, (b) the fuel has an enrichment of 5.0 wt.% of U-235, (c) the burnup is 50,000 MWD/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.

3.4. Criticality

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

The criticality analysis was performed for each fuel 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 with a smaller pin diameter such as the W.H OFA fuel actually produces a higher initial keff. 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 fuels are weighed. The error in this weight is very low. The maximum possible fuel 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 ℃) is considered in performing the criticality analyses. Non-uniform flooding of the fuel basket and the fuels is not assumed because all free spaces in the cavity, the fuel basket structures and the fuels 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 fuels 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 ℃ is assumed for the fuel and 4 ℃ 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 transport conditions. The fuel basket with its 12 fuel 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.

The method for performing the criticality analysis is the three-dimensional Monte Carlo Code KENO-Va. 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

Table 8. Criticality Analysis Results

W.H fuel type	Enrichment, wt.%	Unadjusted k_{eff}	Deviation (2σ)	Bias	Max. k_{eff}
14 × 14 STD	5.00	0.9085	0.0004	0.0087	0.9176
14 × 14 KNFC	5.00	0.9199	0.0004	0.0087	0.9290
14 × 14 JDFA	5.00	0.9034	0.0004	0.0087	0.9125
16 × 16 STD	5.00	0.9006	0.0004	0.0087	0.9097
16 × 16 JDFA	5.00	0.8978	0.0004	0.0087	0.9069
17 × 17 STD	5.00	0.9338	0.0004	0.0087	0.9429
17 × 17 JDFA	5.00	0.9313	0.0004	0.0087	0.9404
17 × 17 OFA	5.00	0.9394	0.0004	0.0087	0.9485
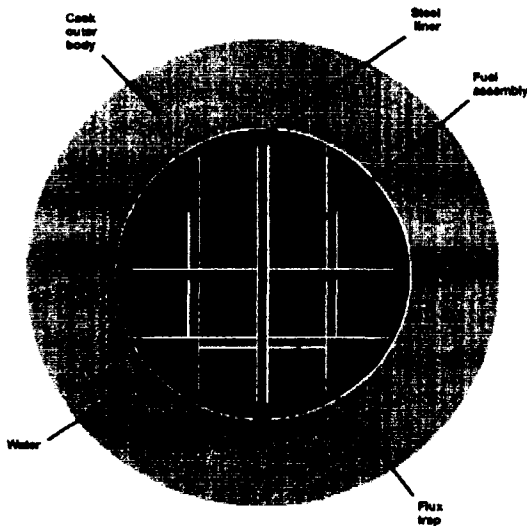
Fig. 5. Criticality Analysis Model

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. The criticality analysis model is shown in Fig. 4.

Maximum values of the keff resulting from the criticality analysis considering the condition of optimum partial flooding with fresh water are presented in Table 8. The criticality analyses were performed for fresh fuels for each of the fuel designs being used in Korea. The data confirm that for each of the candidate fuel designs, the effective multiplication factor, k_{eff}, including all biases and uncertainties at a 95% confidence level, do not exceed 0.95.

4. Conclusions

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

Structural and thermal performances of the cask have been evaluated to maintain the integrity for the load conditions defined in US 10 CFR 71 and US NRC RG 7.8 under normal transport and accidental conditions. The radiation shielding features of the cask including impact limiters are evaluated to maintain the maximum combined gamma and neutron does rate to less than 2

mSv/h at the surface and to less than 0.1 mSv/h at 2m from the external surface of the cask under normal transport conditions, and to less than 10 mSv/h at 1 m from the external surface of the cask. The effective multiplication factor, k_{eff}, including all biases and uncertainties at a 95 % confidence level, do not exceed 0.95 for each of all W.H 14×14, 16×16 and 17×17 fuel assemblies. Therefore, the cask provides containment, radiation shielding, structural integrity, criticality control and passive heat removal for both normal transport and hypothetical accident conditions.

5. Reference

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