Proceedings of the Korean Nuclear Spring Meeting
Gyeong ju, Korea, May 2003

Containment Evaluation of the KN-12 Transport Cask

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Abstract

The KN-12 transport cask is designed to transport 12 PWR spent nuclear fuel assemblies and to comply with the regulatory requirements for a Type B(U)F package. W.H 14x14, 16x16 and 17x17 fuel assemblies with maximum allowable initial enrichment of 5.0 wt.%, maximum average burn-up of 50000 MWD/MTU and minimum cooling time of 7 years being used in Korea are loaded and subsequently transported under dry and wet conditions. The containment boundary of the KN-12 cask is defined by a cask body, a cask lid, lid bolts with nuts, O-ring seals and a bolted closure lid. The containment vessel for 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 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 cask must maintain a radioactivity release rate of not more than the regulatory limit for normal transport conditions and for hypothetical accident conditions, as required by the related regulations. The containment requirements of the KN-12 cask are satisfied by maintaining a maximum air reference leak rate of 2.7×10^{-4} ref cm^3/sec or a helium leak rate of 3.3×10^{-4} cm^3/sec for normal transport conditions and for hypothetical accident conditions.

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 KN-12 cask has been designed basing on NETEC's requirements and evaluated as a transport package that complies with the regulatory requirements of IAEA Safety Standards Series(SSS) No.ST-1[1], US 10 CFR Part 71[2] and Korea Atomic Energy Act for Type B(U)F package. The KN-12 cask is licensed in accordance with Korea Atomic Energy Act and fabricated in Korea in accordance with the requirements of ASME B&PV Code Section III, Division 3[3].

The KN-12 cask must maintain a radioactivity release rate of not more than the regulatory limits, 10^{-6} A_2 per hour under normal transport conditions, and 10 A_2 per week for Kr-85 and less than 1 A_2 per week for the other radioactive material under hypothetical accident conditions, as required by the related regulations. The containment boundary of the KN-12 cask is defined by a cask body, a cask lid, lid bolts with nuts, O-ring seals and a bolted closure lid. The containment vessel for 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 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 KN-12 cask uses testable O-ring seals to insure that containment requirements are met for every shipment.

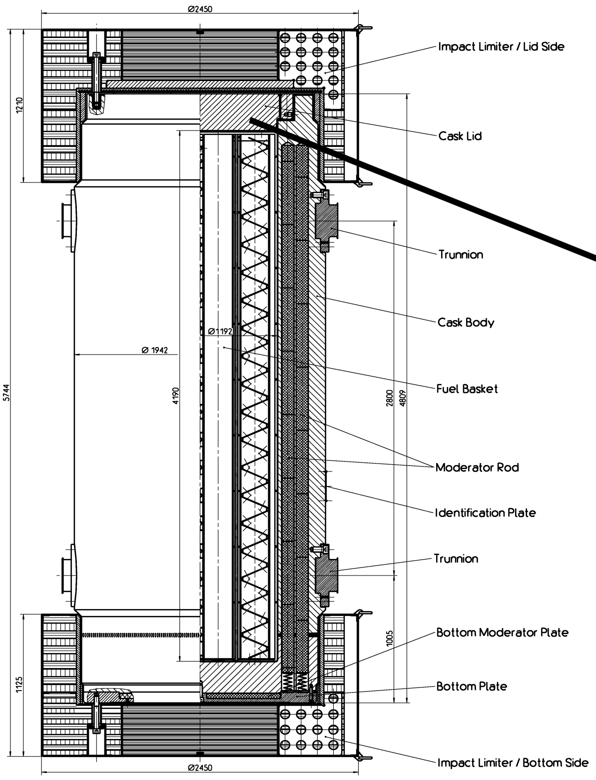
W.H 17x17 fuel assembly of all W.H fuel assemblies is the limiting assembly because of its high fuel mass and fission product inventory and is therefore used in the leakage calculations. The available gas volume employed in the pressure and release calculation is based upon the maximum fuel assembly displacement, which is for W.H 17x17 fuel assembly. The containment analysis of the KN-12 cask conservatively used a fuel rod helium pre-pressurization of 27 bar. The maximum burn-up of 50000

MWD/MTU, maximum enrichment of 5.0wt% U-235 and the minimum cooling time of 7 years were used to generate the containment analysis source term. The containment analysis used the payload of 12 design basis W.H 17x17 fuel assemblies. Radionuclide inventories for W.H 17x17 fuel assemblies are determined by detailed ORIGEN2 isotopic depletion calculations. These results demonstrate that the KN-12 cask meets the containment requirements of the related regulations for normal transport conditions and for hypothetical accident conditions.

The regulatory requirements for the KN-12 cask are satisfied by maintaining a maximum air reference leak rate of 2.7×10^{-4} ref cm^3/sec or a helium leak rate of 3.3×10^{-4} cm^3/sec for normal transport conditions and hypothetical accident conditions. The allowable leak rate calculated for hypothetical accident conditions are numerically much larger, and hence less restrictive, than those for normal transport conditions. The allowable leak rate for normal transport conditions is significantly more limiting and is therefore used for the helium test leak rate of the cask fabrication performance tests and verification leak tests.

Containment Boundary of the KN-12 cask

The containment boundary of the KN-12 transport cask, as shown in Fig.1 and Fig.2, is defined as a forged cylindrical cask body and a welded forged bottom, a cask lid, lid bolts with nuts and an inner elastomer O-ring seal, and a closure lid in the cask lid, cap screws and an elastomer O-ring seal. There are two possible paths for the escape of radioactive material from the KN-12 cask during transport operation; through inner O-ring of the cask lid and through O-ring of the closure lid. The KN-12 cask containment is verified by leak testing prior to all transport operations. A helium leak test or a pressure rise test are used to verify the assembly of the cask lid and of the closure lid.



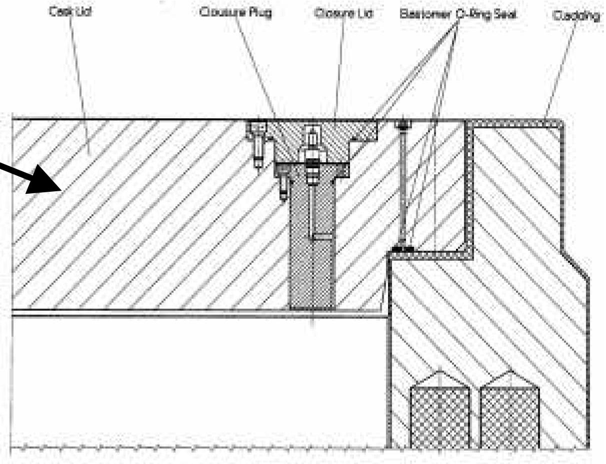


Fig.2 Enlarged cask lid assembly

Fig.1 General arrangement - vertical section

The containment vessel for the KN-12 cask consists of the forged steel cylindrical cask body, the welded forged steel bottom, the cask lid and the closure lid. The containment vessel components are fabricated from SA-350 Grade LF3 carbon steel (cask body and bottom) and SA-182 Grade F6NM stainless steel (cask lid and closure lid) according to ASME B&PV code. The containment vessel and basket do not have any significant chemical, galvanic, or any other reaction with the fuel as with inert gas or with water under any of the normal of hypothetical conditions for transport. The penetrations in the cask primary containment vessel are the cask lid, and the closure lid. The penetrations are designed to seal the boundary and to ensure that leakage from the cavity does not exceed the regulatory limits. The inner O-ring of the cask lid and the O-ring of the closure lid are the seals that provide containment boundary. The KN-12 cask was tested using a helium leak test or a pressure rise test after fabrication, annual verification and prior to each shipment. A circumferential weld was used to join the forged cylindrical shell to the bottom forging. The containment vessel weld was full penetration to ensure structural integrity. After completion, the weld was 100% ultrasonic volumetric examined in accordance with ASME code requirements. Upon completion of containment vessel fabrication, the cask containment boundary was hydrostatically tested in accordance with ASME B&PV code requirements to ensure the integrity of the welds and containment components. Following hydrostatic testing, all containment vessel welds were visually inspected by the dye penetrant examination method and evaluated in accordance with ASME Code requirements. The closure assembly for the cask consists of the cask lid, the lid bolts with nuts, the inner O-ring and the closure lid which is recessed into the cask lid fixed with the cap screws and sealed by an O-ring. The cask lid is recessed and bolted into the top of the cask body. The bottom surface of the lid is sealed to the top of the cask body by a testable O-ring. The O-rings are made from Viton, or Fluorocarbon rubber, which can accommodate temperatures up to 204 °C. The temperatures of the cask lid and the closure lid seals during hypothetical accident (fire) are 130 °C for dry (helium-filled) shipments and 124 °C for wet (water-filled) shipments. These temperatures are within the allowable upper temperature limit for Viton; hence, the Viton O-rings are capable of providing containment under hypothetical accident conditions.

Containment Evaluation for Normal Transport Conditions

The regulatory limit for the release of radioactive material under normal transport is 10^{-6} A_2 per hour. A_2 values for the gas mixture is determined by using the method described in US 10 CFR Part 71 and A_2 values for each radionuclide are obtained from IAEA SSS No.ST-1. The release fractions for the various radionuclides transported in the KN-12 cask are obtained from NUREG/CR-6487[4] and summarized in Table 1. In addition to the radionuclides produced by the fuel material, fuel assemblies develop a coating, which is known as crud, of impurities deposited by cooling water during power generation. Crud contains mostly non-radioactive elements but also contains a significant amount of ^{60}Co. NUREG/CR-6487 conservatively estimates the maximum ^{60}Co concentrations on spent fuel assemblies to be less than 140 μCi/cm^2 for PWR assemblies at initial discharge. The surface area of W.H 17x17 fuel assemblies is calculated to be 30500 cm^2. The total assembly crud activity, calculated by the conservative surface area and maximum activity, is 43 Ci per assembly at discharge of the spent fuel, or 17 Ci per assembly at 7 years cooling time.

The allowable leak rate from the cask under normal transport conditions is determined from the regulatory limit of 10^{-6} A_2 per hour;

$$R_N = L_N C_N \le A_2 \text{ x } 1\text{x}10^{-6}\,\text{hr}^{-1} \quad \text{or} \quad R_N = L_N C_N \le A_2 \text{ x } 2.78\text{x}10^{-10}\,\text{sec}^{-1}$$

where L_N = volumetric gas leakage rate (cm^3/s)
C_N = curies per unit volume (termed “activity density”) of the radioactive material that passes through the leak path (Ci/cm^3)
R_N = release rate for normal transport conditions (Ci/sec)

The total inventory of fission product gases, volatiles, and fuel fines (also called particulates) and crud are calculated by using the source terms produced by ORIGEN2 code and the release fractions and ^{60}Co content from NUREG/CR-6487. A_2 value for the mixture of radioisotopes are calculated for all radionuclides produced by ORIGEN2 code calculation (plus ^{60}Co) in accordance with IAEA SSS No.ST-1 and summarized in Table 1. Mixture A_2 values are determined including gas, volatile, fine, and crud contributions to the mixture. As per 10 CFR 71 A_2 value used for Kr-85 in determining mixture A_2 is 10 times the non-mixture A_2 value for Kr-85. Table 1 provides the source term and A_2 values per group for W.H 17x17 fuel assemblies. The calculated mixture A_2 value for normal transport conditions is 86 Ci. The release limit is 10^{-6} A_2 per hour, or $8.6\text{x}10^{-5}$ Ci per hour.

Table 1 Release rate source and A_2 value for normal transport conditions

	Crud	Fission gas	Volatiles	Fuel fines	Total
Total activity per assembly (Ci)	17	4510	141000	55400	200927
Releasable activity per cask (Ci)	31	487	10	1	529
	Cask total				
Cask volumetric activity (Ci/cm^3)	$2.0\text{x}10^{-4}$				
A_2 value (Ci)	86				

The allowable volumetric gas leak rate is independent of cask pressure and temperature, and must be converted to a reference air or helium test leak rate, which depends on gas temperatures, pressures, and the leakage path. This conversion requires calculation of the theoretical hole diameter through which the leakage occurs. A combination of continuum and molecular flow occurs, depending on the pressure and viscosity of the flow. The postulated leak hole diameter can be calculated in accordance with Equations B-2, B-3, and B-4 of ANSI N14.5[5]. The solution for the hole diameter is found using an iterative process. A value for leakage hole diameter is assumed and the resultant leakage rate is calculated. The assumed value of hole diameter is refined until the calculated leakage rate equals the maximum allowable leakage rate. Once the hole diameter is known, the leak rate for reference air or helium is computed. The allowable leak rate for the cask containing 12 W.H 17x17 fuel assemblies under normal transport conditions is calculated to be 1.2×10^{-4} cm^3/sec. The calculated value for the reference air leak rate for normal transport conditions is 2.7 $\text{x}10^{-4}$ ref. cm^3/sec. This is equivalent to a helium test leak rate of $3.3\text{x}10^{-4}$ cm^3/sec. The reference air leak rate of $2.7\text{x}10^{-4}$ ref. cm^3/sec (or equivalently a helium leak rate of $3.3\text{x}10^{-4}$ cm^3/sec) is the maximum leak rate allowed if the seals are to be tested at 1 atmosphere and 25 °C. The difference between two leak rates is due to a difference in viscosity. Containment of the KN-12 cask must be verified prior to each shipment of the cask by means of the helium leakage test. The helium leak rate must be less than $3.3\text{x}10^{-4}$ cm^3/sec. This is also the allowable leak rate for the cask fabrication and verification leak tests. The calculated leak rates are provided in Table 2.

Table 2 Leak Rates for normal transport conditions

Release limit (Ci/hr)	Leak rates (cm^3/sec)		
	Allowable	Reference air	Helium
$8.6\text{x}10^{-5}$	$1.2\text{x}10^{-4}$	$2.7\text{x}10^{-4}$	$3.3\text{x}10^{-4}$

The equivalent leakage for the water phase of a wet shipment may be obtained using Equations B-9 and B-3 of ANSI N-14.5;

$$L = F_C\ (P_U - P_d) = (2.49\text{x}10^6 D^4/a\mathit{m})\ (P_U - P_d)$$

where F_C = coefficient of continuum flow conductance per unit press (cm^3/atm-s)
P_U = upstream pressure (atm)
P_d = downstream pressure = 1 atmosphere
D = leakage hole diameter (cm)

a leakage hole length, that is, O-ring diameter (cm)
μ = fluid viscosity at operating temperature (cP)

These equations provide the equivalent leak rate for water using the leakage hole diameter determined for the dry shipment (helium–filled) conditions. Only the pressure and viscosity affect the equivalent leak rate for water. Water is more viscous than helium and for similar cask internal pressures, water will have a lower leak rate than helium. Using the hole diameter determined from the dry shipment conditions and assuming 80% of the cask is water filled, the radioactivity release would be $5.9\text{x}10^{-7}$ A_2 per hour which is less than the $1\text{x}10^{-6}$ A_2 regulatory limit. The leakage of the gas bubble phase of a wet shipment is obtained from the gas leakage equations. The radioactivity release rate for the gas bubble phase would be 7.0x 10^{-7} A_2 per hour using the same size hole as determined for the dry cask. Since the leakage rate for both the gas and liquid phases are less than the regulatory limit wet shipments satisfy the regulatory release limit for normal transport conditions. Due to a much higher allowable release rate (1 A_2 per week) normal transport conditions are significantly more limiting. Using the hole size determined from the release limits for a dry cask the gas bubble release rate is $3.6\text{x}10^{-3}$ cm^3/sec. This corresponds to a radioactivity release rate for the gas phase of 0.027 A2 per wee, which is significantly less than the regulatory limit of 1 A_2 per week. The liquid phase leak rate is only 0.020 A_2 per week.

The maximum pressure in the KN-12 cask during normal transport conditions is calculated from the total number of moles of gas and from the gas temperature. Assumptions underlying this calculation are that during normal transport conditions, 3 % of the fuel rods may fail. The free volumes of the helium backfill gas, the fuel pre-pressurization helium gas, and the releasable fission gas (30 % release fraction), are included in the calculation. Due to a large volume of non-radioactive Krypton and Xenon produced the free volume contributions of volatiles and fuel fines are negligible. See Table 3. The cask cavity under normal transport conditions is backfilled to 1 bar with 99.9% pure helium gas. The initial cavity pressure of 1 bar is raised by the ratio of the free volume of the gas mixture to the initial free volume of the helium backfill, and is further increased by the ratio of the normal transport conditions gas temperature to the original helium backfill temperature (25^{o} C). These factors raise 1 atmosphere of the backfill helium to 1.55 atmospheres (22.8 psia) for the mixture.

Table 3 Cask available volumes and pressures for normal transport conditions

Available (backfill) volume (cm^3)	2681000
Pre-pressurization helium free volume (cm^3)	60700
Fission gas free volume (cm^3)	73600
Residual water vapor volume (cm^3)	6700
Total free gas volume (cm^3)	2822000
Maximum average gas temperature (°K)	441
Pressure (atm) (psia)	1.55 22.,8

The KN-12 cask containment is structurally intact for normal transport conditions and is tested to demonstrate compliance with the regulatory release limits, and the KN-12 cask satisfies the regulatory requirements for the cask containment.

Containment Evaluation for Hypothetical Accident Conditions

The KN-12 cask is designed to maintain a release rate of less than 10 A_2 per week for Kr-85 and less than 1 A_2 per week for the other radioactive material for hypothetical accident conditions, as required by the related regulations. A_2 for a mixed gas is determined by using the method described in

10 CFR 71. The 10 CFR 71 requirement for the release of radioactive material under hypothetical accident conditions is met by ensuring that a reference air leak rate limit of $2.3\text{x}10^{-2}$ ref·cm^3/sec is not exceeded. The regulatory requirement for the release of radioactive material under hypothetical accident conditions is met by ensuring that a reference air leak rate limit of $2.3\text{x}10^{-2}$ ref cm^3/sec is not exceeded.

The allowed leak rate under hypothetical accident conditions is calculated by using the same method for normal transport conditions. Total inventory of fission product gases, volatiles, fines, and crud are calculated by using the source terms generated by ORIGEN2 code and release fractions specified by NUREG/CR-6487. Using the A_2 values IAEA SSS No.ST-1, the mixture A_2 values are determined for the mixture of fission gases, volatiles, fuel fines, and crud. Then the allowable release rate is calculated by using hypothetical accident conditions release limit;

$$R_A = L_A C_A \le A_2 \,\text{week}^{-1} \quad \text{or} \quad R_A = L_A C_A \le A_2 \,\text{x}\, 1.65 \,\text{x}\, 10^{-6} \sec^{-1}$$

where L_A = volumetric gas leakage rate (cm^3/s)
C_A = curies per unit volume of the radioactive material that passes through the leak path (Ci/cm^3)
R_A = release rate for normal transport conditions (Ci/sec)

The assumptions for the calculations of hypothetical accident conditions are that 100% of the fuel rods fail and 100% of the crud is released (compared with the assumptions that 3 % of the fuel rods fail and 15% of the crud is released for normal conditions of transport). The hypothetical accident conditions assumes a simultaneous occurrence of a fire accident. For a gas temperature of 465 °K, the pressure within the cask cavity is 3.98 atmospheres or 58.5 psia. The calculated allowable release rate is tabulated in Table 4.

Table 4 Release rate source and A_2 value for hypothetical accident conditions

	Crud	Fission gas	Volatiles	Fuel fines	Total
Total activity per assembly (Ci)	17	4510	141000	55400	200927
Releasable activity per cask (Ci)	200	16200	338	20	16578

	Cask total
Cask volumetric activity including Kr-85 (Ci/cm^3)	$6.1\text{x}10^{-3}$
Mixture A_2 value including Kr-85 (Ci)	130
Cask volumetric activity excluding Kr-85 (Ci/cm^3)	$6.4\text{x}10^{-4}$
Mixture A_2 Value excluding Kr-85 (Ci)	14

The allowable leak rate was conservatively calculated including Kr-85 in the mix of isotopes and comparing. However, since the safety criteria are actually based on Kr-85 only and all isotopes except Kr-85. These calculations were also performed. The allowable leak rate for hypothetical accident conditions using the simplified lumping of all isotopes is converted to a reference air leak rate and a helium test rate by using the same methodology for normal transport conditions. The results are tabulated in Table 5, which shows that the minimum allowable leak rate is calculated by the simplified method which lumped all isotopes including Kr-85.

The allowable leak rate calculated previously for hypothetical accident conditions are numerically much larger, and hence less restrictive, than those for the normal transport conditions The allowable leak rate for normal transport conditions is significantly more limiting and is therefore used for the helium test leak rate for the containment system fabrication and annual verification leak tests.

Table 5 Leak Rates for Hypothetical Accident Conditions

	Release limit (Ci per week)	Leak Rates (cm^3/sec)		
		Allowable	Reference Air	Helium
All isotopes	130	$3.5x10^{-2}$	$1.7x10^{-2}$	$1.8x10^{-2}$
Excluding Kr-85	14	$3.6x10^{-2}$	$1.8x10^{-2}$	$1.8x10^{-2}$
Kr-85 only	2700	$8.1x10^{-1}$	0.39	0.39

Table 6 Cask available volumes and pressures for hypothetical accident conditions

Available (backfill) volume (cm^3)	2740000
Pre-pressurization helium free volume (cm^3)	2030000
Fission gas free volume (cm^3)	2450000
Residual Water Vapor Volume (cm^3)	6850
Total free gas volume (cm^3)	7226850
Maximum average gas temperature (°K)	465
Pressure (atm) (psia)	3.98 58.5

Conclusion

The allowable leak rate for the cask containing 12 W.H 17x17 fuel assemblies under normal transport conditions is calculated to be 1.2×10^{-4} cm^3/sec. The calculated value for the reference air leak rate for normal transport conditions is $2.7\ x10^{-4}$ ref. cm^3/sec. This is equivalent to a helium leak rate of $3.3x10^{-4}$ cm^3/sec. The allowable leak rate calculated for hypothetical accident conditions are numerically much larger, and hence less restrictive, than those for the normal transport conditions. The allowable leak rate for normal transport conditions is significantly more limiting and is used for the helium leak rate for the cask fabrication and verification leak tests.

The containment of the KN-12 transport cask is structurally intact through the structural and thermal evaluations for normal transport conditions and hypothetical accident conditions, and is tested to demonstrate compliance with the regulatory release limits. Therefore, these results demonstrate that the KN-12 transport cask meets the containment requirements of the related regulations for normal transport conditions and for hypothetical accident conditions.

Reference

[1] IAEA Safety Standards Series No.ST-1 “Regulation for the Safe Transport of Radioactive Material”, 1996
[2] US NRC 10 CFR Part 71, “Packaging and Transportation of Radioactive Materials”, 1996
[3] ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers, 1995
[4] US NRC NUREG/CR-6487, Anderson, B.L., Carlson, R.W., and Fisher, L.E., “Containment Analysis for Type B Packages Used to Transport Various Contents,” LLNL, 1996
[5] ANSI N14.5-1997, “American National Standard for Radioactive Materials - Leakage Tests on Packages for Shipment,” American National Standards Institute, 1997