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# Containment Evaluation of the KN-12 Transport Cask

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**Abstract** - The KN-12 transport cask has been designed to transport 12 PWR spent nuclear fuel assemblies and to comply with the regulatory requirements for a Type B(U) package. The containment boundary of the 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 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 cask are satisfied by maintaining a maximum air reference leak rate of $2.7 \times 10^{-4}$ ref.$cm^3 s^{-1}$ or a helium leak rate of $3.3 \times 10^{-4} cm^3 s^{-1}$ for normal transport conditions and for hypothetical accident conditions.

*Key words : spent nuclear fuel, transport cask, containment boundary, radionuclide, radioactivity release, leak rate, elastomer O-ring, normal transport conditions, hypothetical accident conditions*

## Introduction

The KN-12 spent nuclear 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 and evaluated as a transport package that complies with the regulatory requirements of IAEA Safety Standards Series No.TS-R-1[1], US 10 CFR Part 71[2] and Korea Atomic Energy Act for Type B(U) package. The cask was licensed in compliance 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 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 $^{85}$Kr and less than 1 $A_2$ per week for the other radioactive material under hypothetical accident conditions, as required by the related regulations.

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. The containment analysis of the cask conservatively used a fuel rod helium pre-pressurization of 27bar. The maximum burn-up of 50,000MWD/MTU, maximum enrichment of 5.0wt.% $^{235}$U 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 fuels. Radionuclide inventories for W.H 17x17 fuels were determined by detailed ORIGEN2 isotopic depletion calculations. These results demonstrate that the caskmeets the containment requirements of the related regulations for normal conditions and for accident conditions.

The regulatory requirements for the cask were satisfied by maintaining a maximum air reference leak rate of $2.7\text{x}10^{-4}$ref.cm$^3$s$^{1}$ or a helium leak rate of $3.3\text{x}10^{-4}$cm$^3$s$^{-1}$ for normal conditions and accident conditions. The allowable leak rate calculated for accident conditions are numerically much larger, and hence less restrictive, than those for normal conditions. The allowable leak rate for normal 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

The containment boundary of the transport cask, as shown in Fig.1 is defined as a forged cylindrical cask body and a welded forged bottom, a cask lid, lid bolts with nutsand 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 cask during transport operation through inner Oof the cask lid and through O-ring of the closure lid. The 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.

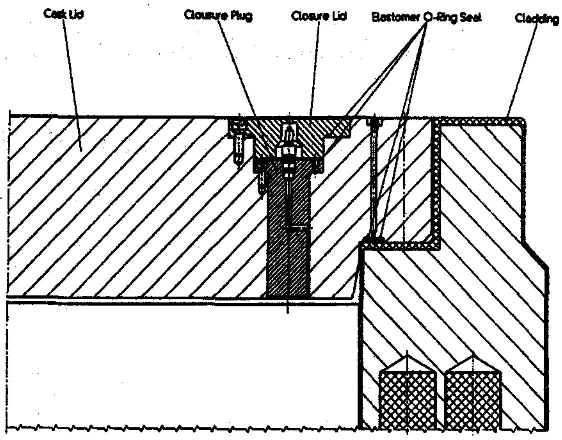

Fig. 1. Enlarged cask lid assembly of the KN-12 cask

The containment vessel for the 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 cask will be tested using a helium leak test or a pressure rise test after fabrication, annual verification and prior to each shipment. A circumferential weld wasused 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 boun-dary 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 was recessed into the cask lid fixed with the cap screws and sealed by an O-ring. The cask lid was recessed and bolted into the top of the cask body. The bottom surface of the lid was sealed to the top of the cask body by a testable O-ring. The O-rings were made from Viton, or Fluorocarbon rubber, which could accommodate temperatures up to 204℃. The temperatures of the cask lid and the closure lid seals during accident (fire) were 130℃ for dry (helium-filled) shipments and 124℃ for wet (water-filled) shipments. These temperatures were within the allowable upper temperature limit for Viton; hence, the Viton O-rings were capable of providing containment under accident conditions.

## Normal Transport Conditions

The regulatory limit for the release of radioactive material under normal conditions 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 Safety Standards Series No.TS-R-1. The release fractions for the various radionuclides transported in the 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/CR6487 conservatively estimates the maximum $^{60}$Co concentrations on fuel assemblies to be less than $5.18\text{x}10^{-6}$TBqcm$^{-2}$ for PWR assemblies at initial discharge. The surface area of W.H 17x17 fuels is calculated to be 30,500cm$^2$. The total assembly crud activity, calculated by the conservative surface area and maximum activity, is 1.591TBq per assembly at discharge of the spent fuel, or 0.629TBq 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;

$$R_N = L_N\, C_N \leq A^2 \text{ x } 1\text{x } 10^{-6}\ \text{hr}^{-1} \quad \text{or}$$

$$R_N = L_N\, C_N \leq A^2 \text{ x } 2.78\text{x}10^{-10}\ \text{s}^{-1}$$

where, $L_N$ is volumetric gas leakage rate (cm$^3$s$^{-1}$), $C_N$ is curies per unit volume, termed activity density, of the radioactive material that passes through the leak path (Bqcm$^{-3}$), and $R_N$ is release rate for normal conditions (Bqs$^{-1}$).

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.

$$C_N = C_{crud} + C_{vol} + C_{gas} + C_{fine}$$

where $C_{crud}$ is activity density inside containment vessel resulting from crud spallation (Bqcm$^{-3}$), ($C_{vol}$+$C_{gas}$) is releasable activity concentration inside the containment vessel resulting from gases and volatiles released from cladding breaches (Bqcm$^{-3}$) and $C_{fine}$ is activity concentration inside containment vessel resulting from fines released from cladding breaches (Bqcm$^{-3}$).

$$C_{crud} = f_c M_T \,/\, V = f_c S_c N_A S_{AR} \,/\, V$$

where $f_c$ is crud spallation factor, $M_T$ is total crud activity inventory (Bq), V is available gas volume inside containment vessel (cm$^3$), $S_c$ is crud surface activity (Bqcm$^{-2}$), $N_A$ is number of assemblies and $S_{AR}$ is surface area per rod (cm$^2$).

$$C_{vol} + C_{gas} = N_R N_A f_B W_R\ (A_V f_V + A_g f_G)\ /\ V$$

where $N_R$ is number of fuel rods per assembly, $f_B$ is fraction of fuel rods that develop cladding breach, $W_R$ is mass of the fuel in fuel rod (g), $A_V$ is specific activity of volatiles in fuel rod ($Bqg^{-1}$), $f_V$ is fraction of volatiles in fuel rod released if rod develops cladding breach, $A_G$ is specific activity of gas in fuel rod ($Bqg^{-1}$) and $f_G$ is fraction of gas that would escape from fuel rod that develops cladding breach.

$$C_{fines} = N_A N_R f_B W_R A_F f_F\ /\ V$$

where $A_F$ is specific activity of fines released from cladding breach in fuel rod ($Bqg^{-1}$) and $f_F$ is fraction of fuel rod's mass released as fines resulting from cladding breach.

$A_2$ value for the mixture of radioisotopes are calculated for all radionuclides produced by ORIGEN2 code calculation (plus $^{60}$Co) in accordance with IAEA Safety Standards Series No.TS-R-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 $^{85}$Kr in determining mixture $A_2$ is 10 times the non-mixture $A_2$ value for $^{85}$Kr. Table 1 provides the source term and $A_2$ values per group for W.H 17x17 fuels. The calculated mixture $A_2$ value for normal conditions is 3.182TBq. The release limit is $10^{-6}$ $A_2$ per hour, or $3.182 \times 10^{-6}$TBqhr$^{-1}$. The allowable leak rate for the cask containing 12 W.H 17x17 fuels under normal conditions was calculated to be $1.2 \times 10^{-4}$ cm$^3$s$^{-1}$.

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].

$$L = (F_c + F_m)\ (P_U\ \ P_d)$$

$$F_c = 2.49 \times 10^6 \times D^4\ /\ a$$

$$F_m = 3.81 \times 10^3 \times D^3\ (T\ /\ M)^{1/2}\ /\ (a\ Pa)$$

where $F_c$ is coefficient of continuum flow conductance per unit press[cm$^3$(atm-s)$^{-1}$], $F_m$ is coefficient of free molecular flow conductance per unit press[cm$^3$(atm-s)$^{-1}$], $P_U$ is upstream pressure (atm), $P_d$ is downstream pressure (1atm), D is leakage hole diameter(cm), a is leakage hole length, that is, O-ring diameter (cm)  is fluid viscosity at operating temperature (cP), T is fluid absolute temperature, normal transport conditions ($^o$K), M is molecular weight of helium and Pa is average pressure (atm).

The calculated value for the reference air leak rate for normal conditions is $2.7 \times 10^{-4}$ ref.cm$^3$s$^{-1}$. This is equivalent to a helium test leak rate of $3.3 \times 10^{-4}$cm$^3$s$^{-1}$. The reference air leak rate of $2.7 \times 10^{-4}$ref.cm$^3$s$^{-1}$ (or equivalently a helium leak rate of $3.3 \times 10^{-4}$cm$^3$s$^{-1}$) 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 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 $3.3 \times 10^{-4}$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.

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

$$L = F_c\ (P_U - P_d) = (2.49 \times 10^6 \times D^4\ /a\mu)\ (P_U - P_d)$$

where, $F_c$ is coefficient of continuum flow conductance per unit pressure [cm$^3$(atm-s)$^{-1}$], $P_U$ is upstream pressure (atm), $P_d$ is downstream pressure (1atm), D is leakage hole

Table 1. Release rate source and $A_2$ value for normal conditions

| | Crud | Fission gas | Volatiles | Fuel fines | Total |
|---|---|---|---|---|---|
| Total activity per assembly (GBq) | 629 | 166,870 | 5,217,000 | 2,049,800 | 7,434,299 |
| Releasable activity per cask (GBq) | 1,147 | 18,019 | 370 | 37 | 19,573 |
| | Cask total | | | | |
| Cask volumetric activity (GBqcm$^{-3}$) | 7.4x10$^{-3}$ | | | | |
| $A_2$ value (GBq) | 3,182 | | | | |

Table 2. Leak rates for normal conditions

| Release limit (GBqhr$^{1}$) | Leak rates (cm$^{3}$s$^{-1}$) | | |
|---|---|---|---|
| | Allowable | Reference air | Helium |
| 3.182x10$^{-3}$ | 1.2x10$^{-4}$ | 2.7x10$^{-4}$ | 3.3x10$^{-4}$ |

Table 3. Cask available volumes and pressures for normal conditions

| | |
|---|---|
| Available (backfill) volume (cm$^{3}$) | 2,681,000 |
| Pre-pressurization helium free volume (cm$^{3}$) | 60,700 |
| Fission gas free volume (cm$^{3}$) | 73,600 |
| Residual water vapor volume (cm$^{3}$) | 6,700 |
| Total free gas volume (cm$^{3}$) | 2,822,000 |
| Maximum average gas temperature(°K) | 441 |
| Pressure (atm) | 1.55 |

diameter (cm), a is leakage hole length, that is, O-ring diameter (cm), and is 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 (heliumfilled) 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 5.9x10$^{-7}$ $A_2$ per hour which is less than the 1x10$^{-6}$ $A_2$ 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 7.0x10$^{-7}$ $A_2$ 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 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 3.6x10$^{-3}$cms$^{-1}$. This corresponds to a radioactivity release rate for the gas phase of 0.027 $A_2$ per week, 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 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 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 conditions is backfilled to 1bar 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 conditions gas temperature to the original helium backfill temperature (25°C). These factors raise 1atm of the backfill helium to 1.55atm (22.8psia) for the mixture.

## Hypothetical Accident Conditions

The cask is designed to maintain a release rate of less than 10 $A_2$ per week for $^{85}$Kr and less than 1 $A_2$ per week for the other radioactive material for 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 accident conditions is met by ensuring that a reference air leak rate limit of $2.3\times10^{-2}$ref.cm$^3$ s$^{-1}$ is not exceeded. The regulatory requirement for the release of radioactive material under accident conditions is met by ensuring that a reference air leak rate limit of $2.3\times10^{-2}$ref..cm$^3$ sec$^{-1}$ is not exceeded.

The allowed leak rate under accident conditions is calculated by using the same method for normal 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.TS-R-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 accident conditions release limit of $A^2$ per week

$$R_A = L_A C_A \le A^2 \text{ week}^{-1} \quad \text{or}$$

$$R_A = L_A C_A \le A^2 \times 1.65\times10^{-6} \text{ s}^{-1}$$

where $L_A$ is volumetric gas leakage rate (cm$^3$s$^{-1}$), $C_A$ is curies per unit volume of the radioactive material that passes through the leak path (Bq cm$^{-3}$) and $R_A$ is release rate for accident conditions (Bqs$^{-1}$).

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). The accident conditions assume a simultaneous occurrence of a fire accident. For a gas temperature of 465°K, the pressure within the cask cavity is 3.98atm or 58.5psia. The calculated allowable release rate is tabulated in Table 4.

The allowable leak rate was conservatively calculated including $^{85}$Kr in the mix of isotopes and comparing. However, since the safety criteria are actually based on $^{85}$Kr only and all isotopes except $^{85}$Kr. 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 $^{85}$Kr.

The allowable leak rate calculated previously for accident conditions are numerically much larger, and hence less restrictive, than those for the normal conditions. The allowable leak rate for normal conditions is significantly more

Table 4. Release rate source and $A_2$ value for accident conditions

| | Crud | Fission gas | Volatiles | Fuel fines | Total |
|---|---|---|---|---|---|
| Total activity per assembly (GBq) | 629 | 166,870 | 5,217,000 | 2,049,800 | 7,434,299 |
| Releasable activity per cask (GBq) | 7,400 | 599,400 | 12,506 | 740 | 613,386 |
| | Cask total | | | | |
| Cask volumetric activity incl. $^{85}$Kr (GBqcm$^{-3}$) | 2.2x10$^{-1}$ | | | | |
| Mixture $A_2$ value incl. $^{85}$Kr (GBq) | 4,810 | | | | |
| Cask volumetric activity excl. $^{85}$Kr (GBqcm$^{-3}$) | 6.3x10$^{-1}$ | | | | |
| Mixture $A_2$ Value excl. $^{85}$Kr (GBq) | 518 | | | | |

Table 5. Leak rates for accident conditions

| | Release limit (GBqweek$^{-1}$) | Leak rates (cm$^3$s$^{-1}$) | | |
|---|---|---|---|---|
| | | Allowable | Reference air | Helium |
| All isotopes | 4,810 | 3.5x10$^{-2}$ | 1.7x10$^{-2}$ | 1.8x10$^{-2}$ |
| Excluding $^{85}$Kr | 518 | 3.6x10$^{-2}$ | 1.8x10$^{-2}$ | 1.8x10$^{-2}$ |
| $^{85}$Kr only | 99,900 | 8.1x10$^{-1}$ | 0.39 | 0.39 |

Table 6. Cask available volumes and pressures for normal conditions

| | |
|---|---|
| Available (backfill) volume (cm$^3$) | 2,740,000 |
| Pre-pressurization helium free volume (cm$^3$) | 2,030,000 |
| Fission gas free volume (cm$^3$) | 2,450,000 |
| Residual water vapor volume (cm$^3$) | 6,850 |
| Total free gas volume (cm$^3$) | 7,226,850 |
| Maximum average gas temperature(°K) | 465 |
| Pressure (atm) | 3.98 |

limiting and is therefore used for the helium test leak rate for the containment system fabrication and annual verification leak tests.

## Conclusion

The allowable leak rate for the cask containing 12 W.H 17x17 fuels under normal conditions is calculated to be 1.2x10$^{-4}$cm$^3$s$^{-1}$. The calculated value for the reference air leak rate for normal conditions is 2.7x10$^{-4}$ref.cm$^3$s$^{-1}$. This is equivalent to a helium leak rate of 3.3x10$^{-4}$cm$^3$s$^{-1}$. The allowable leak rate calculated for accident conditions are numerically much larger, and hence less restrictive, than those for the normal conditions. The allowable leak rate for normal conditions is significantly more limiting and will be used for the helium leak rate for the cask fabrication and verification leak tests.

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

## Reference

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