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Design Study of A Spent Fuel Shipping Cask for Korea Nuclear Unit-1

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고리 1호기의 기사용 핵연료 집합체 수송용기 설계에 관한 연구

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Abstract

To transport the spent fuel assemblies of Korea Nuclear Unit 1, which is a Westinghouse type two loop pressurized water reactor, it has been found that steel is the most appropriate material for the design of a shipping cask in comparison with lead and depleted uranium. The proposed shipping cask will transport nine fuel assemblies at the same time and is well within the weight limit of transportation by unrestricted rail car. The cask requires 33cm thick steel shield and 27cm thick water region to satisfy the 3 feet apart dose rate limit set forth in 10 CFR 71, and 1.27cm thick steel boron fuel basket to hold the fuel elements inside the cask and control the effective multiplication factor. As a safety analysis, the fuel cladding and centerline temperatures were calculated under the accident condition of complete loss of water coolant, and it was found that the temperature was much lower than the limit of the melting point. k_{eff} was calculated with fresh fuel assemblies, which was found to be well lower than 0.95. For shielding computation, the multipurpose Monte Carlo code MORSE-CG and one dimensional discrete ordinates transport code ANISN were used, and the Monte Carlo codes KENO and MORSE-CG were used for criticality calculation. The radiation source terms were calculated using ORIGEN-79.

요 약

본 논문에서는 고리 1호기의 기사용 핵연료 집합체를 수송하기 위한 Cask를 설계하였다. 이를 위하여 고리 1호기의 기사용 핵연료 집합체로부터 방출되는 감마선과 중성자를 계산하여 MORSE 및 ANISN전산 코드로써 차폐 계산을 수행하였다. 그 결과, 9개의 집합체를 동시에 수송할 수 있는 Steel Cask가 가장 적합하다는 것을 밝혔다. 이 Steel Cask에 대한 안전성을 평가하기 위하여 연료봉의중심 온도와 복재온도를 계산하여 핵연료의 용융점보다 훨씬 낮음을 증명하였다. 또한 KENO와 MORSE전산 코드를 사용하여 임계도 계산을 수행하여 미임계 상태임을 증명하였다. 이로써 9개의 기사용 핵연료 집합체를 동시에 수송할 수 있는 Steel Cask를 간단히 설계 하였다.

I. Introduction

At present, the spent fuel assemblies discharged from nuclear power plants are being temporarily stored in on-site storage facilities. However, as the nuclear power industries rapidly grow, a large amount of spent fuel assemblies will be discharged and they must be eventually shipped for reprocessing or disposal. In this paper, the design of a shipping cask for spent fuel assemblies is carefully and systematically investigated to meet the shipping requirements. The design is governed not only by the physical and nuclear properties of the materials involved but also by the regulations of DOT or NRC[1], which place the specific limits on surface dose rate, internal or external temperatures, cask structural integrity, etc. Therefore the shielding problem is not an only entity in the design of the shipping cask, and can not be separated from the other problems such as dose rate, temperature, criticality, structural integrity and cost.

The purpose of this work is to design an optimized cask for transporting the spent fuel assemblies of Korea Nuclear Unit 1 (KNU-1). This study specifically covers the work as follows:

a. source term calculations,
b. shielding computation,
c. decay heat removal,
d. criticality calculation, and
e. physical design of a cask for shipping nine fuel assemblies of KNU-1

II. Source Term Calculations

The reactor parameters such as burn-up, specific power and cooling time have a major influence on the radiation source term calculation of a spent fuel assembly. In this study, a fuel assembly of KNU-1 was assumed to have the burn-up of 40,000MWD/MTU during the period of 4 cycles[2] and the cooling time of 3 years thereafter for conservatism. The radiation source term was calculated using a computer program ORIGEN-79.[3] The calculated neutron and gamma-ray source strengths per assembly are 3.43×10^{8} neutrons/sec and 8.42×10^{15} photons/sec, respectively. The Cf-252 fission spectrum as given in Table 1 was used as the neutron energy spectrum[18] and the 18-group spectra as given in Table 2 were used for gamma-ray.

III. Shielding Calculation

Each fuel assembly measures 19.718cm square

Table 1. Neutron Group Structure, Source Spectrum, and Flux-To-Dose Conversion Factors

Neutron Group	Upper Energy (eV)	Source Spectrum (neutron/sec.)	Flux-To-Dose Conversion Factor[18] [(mrem/hr)/neut/cm²/sec.)]
1	1.492×10^{7}	0.4653×10^{-3}	2.088×10^{-1}
2	1.220×10^{7}	0.1883×10^{-2}	1.656×10^{-1}
3	1.000×10^{7}	0.5756×10^{-2}	1.476×10^{-1}
4	8.180×10^{6}	0.1924×10^{-1}	1.476×10^{-1}
5	6.360×10^{6}	0.4000×10^{-1}	1.404×10^{-1}
6	4.960×10^{6}	0.5174×10^{-1}	1.332×10^{-1}
7	4.060×10^{6}	0.1094×10^{0}	1.296×10^{-1}
8	3.010×16^{6}	0.8804×10^{-1}	1.260×10^{-1}
9	2.460×10^{6}	0.2088×10^{-1}	1.260×10^{-1}
10	2.350×10^{6}	0.1156×10^{0}	1.296×10^{-1}
11	1.830×10^{6}	0.2089×10^{0}	1.332×10^{-1}
12	1.110×10^{6}	0.1920×10^{0}	1.188×10^{-1}
13	5.500×10^{5}	0.1327×10^{0}	5.400×10^{-2}
14	1.100×10^{5}	0.1345×10^{-1}	6.480×10^{-3}
15	3.350×10^{3}		4.320×10^{-3}
16	5.830×10^{2}		4.680×10^{-3}
17	1.010×10^{2}		4.680×10^{-3}
18	2.900×10^{1}		4.500×10^{-3}
19	1.010×10^{1}		4.320×10^{-3}
20	3.060×10^{0}		4.140×10^{-3}
21	1.120×10^{0}		3.960×10^{-3}
22	4.140×10^{-1}		3.780×10^{-3}
	1.000×10^{-2}		

Table 2. Gamma-ray Group Structure, Source Spectrum, And Flux-To-Dose Conversion Factors.

Gamma Group	Upper Energy (eV)	Source Spectrum (gamma-ray/sec)	Flux-To-Dose Conversion Factors[18] [(mR/hr/phot/cm²)/sec]
1	1.000×10^{7}	0.0	9.792×10^{-3}
2	8.000×10^{6}	0.0	8.280×10^{-3}
3	6.500×10^{6}	0.0	6.840×10^{-3}
4	5.000×10^{6}	0.0	5.760×10^{-3}
5	4.000×10^{6}	0.0	4.752×10^{-3}
6	3.000×10^{6}	8.09609×10^{-5}	3.960×10^{-3}
7	2.500×10^{6}	8.86858×10^{-4}	3.492×10^{-3}
8	2.000×10^{6}	3.29789×10^{-3}	2.988×10^{-3}
9	1.660×10^{6}	1.17200×10^{-2}	2.412×10^{-3}
10	1.330×10^{6}	9.85158×10^{-2}	1.908×10^{-3}
11	1.000×10^{6}	1.89400×10^{-1}	1.602×10^{-3}
12	8.000×10^{5}	3.19099×10^{-1}	1.260×10^{-3}
13	6.000×10^{5}	3.19099×10^{-1}	9.216×10^{-4}
14	4.000×10^{5}	2.89499×10^{-2}	6.372×10^{-4}
15	3.000×10^{5}	2.89499×10^{-2}	4.392×10^{-4}
16	2.000×10^{5}	0.0	2.376×10^{-4}
17	1.000×10^{5}	0.0	1.404×10^{-4}
18	5.000×10^{4}	0.0	3.024×10^{-4}
	1.000×10^{4}		

and 365.76cm active length.[4] The inactive portion of the fuel assembly extends through water regions to the top and bottom of the cask cavity. For shield analysis, the fuel assemblies of KNU-1 were assumed to contain 3.19w/o enriched uranium oxide, and the properties of pure iron were used in place of stainless steel or cast iron for simplicity. For ANISN[5] calculations, the fuel assemies were homogenized and modified to a cylindrical shape with the same cross sectional area and infinite length. The determination of shielding thickness was based upon the dose rate at 3 ft from the external surface rather than the contact dose rate of 200 mrem/hr at the external surface. Hence, the casks were evaluated under the former guideline of the dose rate of 10 mrem/hr at 3ft from any accessible external surface of the cask. With the homogenized model of the 1-assembly steel shipping cask, the comparison of MORSE and ANISN codes was made in shielding calculations. For these shielding calculations, 22 neutron group and 18 gamma-ray group DLC-23/CASK[6] library

Table 3. Results of Shielding Calculations for One-Assembly PWR Steel Shipping Cask

Shielding	ANISN		MORSE			
			HOMOGENIZED MODEL		ACTUAL MODEL	
	With Water in Cask Cavity	Without Water in Cask Cavity	With Water in Cask Cavity	Without Water in Cask Cavity	With Water in Cask Cavity	Without Water in Cask Cavite
Gamma (mR/hr) 3ft apart from cask surace	6.5	13.7	6.1	15.7	6.0	15.4
Neutron (mrem/hr) 3ft apart from cask surface	0.6	9.1	0.4	6.1	0.3	5.1

Table 4. Comparison of Steel-, Lead-, Depleted Uranium Cask for Nine Assemblies

Shielding Material (Thickness. Cm)	Inner Shell* Thickness, Cm	Outer Shell* Thickness, Cm	Gamma(mR/hr) 3′ from cask surface		Neutron(mrem/hr) 3′ from cask surface		The Weight with Water and Assemblies (ton)
			With Water in Cavity	Without Water in Cavity	With Water in Cavity	Without Water in Cavity	
Iron(33.0)	—	—	5.0	18.5	0.3	18.6	76.22
Lead(17.0)	1.27	3.81	6.7	15.6	0.8	68.2	62.65
Depleted Uranium(9.5)	1.27	3.81	5.0	17.9	0.6	36.1	55.90

* Stainless steel shells are provided for lead and depleted uranium for encapsulation.

was used. Table 3 summarizes the resultant dose rates calculated by both MORSE[7] and ANISN. In MORSE calculation, it was found that the dose rates with the actual geometry were slightly lower than those with the homogenized cask model.

Using ANISN, the casks for shipping four and nine fuel assemblies are analyzed. The results showed that even though the source intensities of four and nine assemblies are exactly four and nine times as high as a single fuel assembly, the required steel shield are only 1cm thicker than that of one assembly due to increased water region shields.

The results of shielding calculations for the nine-assembly shipping cask are summarized in Table 4, which show that the cask weight is lower than the transportation limit of 100 tons by rail-car, but heavier than the limit of 35 tons by unrestricted truck-trailer. Therefore, the nine-assembly shipping cask can be transported by rail-cars.

In spite of larger weight, steel is the most proper material for such a shipping cask, since steel eliminates the problem of high differential thermal expansion found in the lead cask, and does not melt under a postulated accidental fire. The structural integrity is also excellent compared to the other shield materials[8]. Under an accident condition, such as the loss of water coolant, the neutron dose rate will increase as shown in Table 4. However, since steel is relatively good for slowing down fast neutrons by inelastic scattering, and is also a good absorber of thermal neutrons, the neutron dose rate at 3 feet from the steel cask is lower than the dose rates from the other types of casks. The result shows that the steel cask is more efficient for neutron shielding than the other casks under the accident condition.

IV. Heat Removal

In compliance with Appendices *A* and *B* to 10 CFR part 71, all shipping casks are subject to be evaluated against the thermal exposure under normal and accident conditions. The fuel maximum temperature in the steel shipping cask was calculated to prove that it was well lower than the melting temperature of the fuel under accident cases. In the calculation, it was assumed that the coolant water would be completely lost and absent since it might be difficult to guarantee the retention of coolant under accident condition.

Two heat sources were considered: radioactive decay heat and solar heat. The radioactive decay heat of KNU-1 spent fuel was caculaced to be 2.93KW/ASSEMBLY using ORIGEN-79. The solar heat was calculated by assuming that the cask would be transported at a latitude of 36 degree during the summer solstice. With the conservative hourly solar energy (0.072W/cm^2)[9] on clear summer days on horizontal surface, the calculated solar heat generation was 6.59KW/cask. Assuming an unfinned surface, the heat removed from the surface of the cask is given by

$$Q_T=h_cA_c(T_s-T_a)+\sigma A_r\varepsilon(T_s^4-T_a^4) \qquad (1)$$

where Q_T=total heat transferred, Watt,

h_c=convective heat transfer coefficient, W/cm^2°K,

A_c=effective convective surface area, cm^2,

A_r=effective radiative surface area, cm^2,

T_s=cask surface temperature, °K,

T_a=ambient temperature, °K,

σ=Stefan-Boltzman coefficient, 5.669×10^{12}W/cm^2°K^4, and

ε=emissivity.

The exterior surface temperature of the shipping cask, T_s was calculated with conservative parameters like the worst ambient temperature of 55°C (130°F). The surface temperature of 150°C (302°F) was found using the trial and error method to dissipate the requisite amount of heat.

With this cask external surface temperature known, the inner shell surface temperature was calculated to be 200°C (392°F) by using the conduction equation.

With the given inner shell surface temperature, the temperature distributions of spent fuels in the shipping cask were computed by assuming that water was completely lost and air was the only heat transfer medium in the cavity. For conservatism and simplicity, only radiation was considered in predicting temperature distributions in the fuel. The net heat radiated, Q_i, from rod i is:

$$Q_i = A_i \sigma \sum_{j=1}^{N} Z_{ij}(T_i^4 - T_j^4). \tag{2}$$

The grey-body radiation factor (Z_{ij}) can be calculatd from following equation

$$Z_{ij} \cong \frac{1}{1/F_{ij} + 2(1/\varepsilon - 1)} \tag{3}$$

where F_{ij}=configuration factor between i and j,

ε=emissivity.

Except the peripheral rods, N is considered sixteen since a given rod can radiate its heat to four unshadowed adjacent rods, four diagonally spaced rods that are shadowed by the adjacent rods, and eight more-distant rods adjacent to the diagonal rods. In case of peripheral rods, N is 10 for side rods because these rods see nine other rods and the inner shell of the cask, six for corner rods because these see five other rods and the inner shell of the cask, and 15 for the next to the side rods which radiate to fourteen rods and to the inner shell. The trial and error procedure is adopted for predicting temperature distributions of 42×42 fuel rods (3×3 assemblies) in the cask. The value of the configuration factors and the computer program, which had been developed by Watson,[11] were used for this calculation. With the rod pitch to diameter ratio of 2.635, the configuration factors (F_{ij}) are as follows:

F_{12}=configuration factor from adjacent rods (0.12824),

F_{13}=configuration factor from diagonally located rods (0.08602), and

F_{14}=configuration factor from more-distant rods (0.01787).

Since the lower the emissivity is, the higher the fuel cladding temperatures are, the emissivity of 0.325[12,13] which is the lowest value by assumidg that the oxidation layer is zero (in the case of fresh fuel), was used. Using Equation 3 and these values, the grey-body radiation factor was calculated and the maximum cladding temperature was calcuated 708°C (1306°F) from Equation 2. The fuel centerline temperature was also calculated to be 714°C (1317°F) using heat conduction equations, and is well below than the fuel melting temperature of 2627°C (4849°F)[4].

V. Criticality

The shipping cask is required to remain subcritical at all times. Therefore, the criticality evaluation of the nine-assembly steel shipping cask was carried out under normal condition with MORSE and KENO. Since a criticality analysis should be made for the case where the fuel is in the most reactive condition, the criti cality was evaluated by assuming:

a. The cask contains the fresh fuel assemblies, which are enriched 3.19 weight percent, and all fission products are neglected,

b. The fuel is at room temperature.

These assumptions are all conservative. Hence, the actual k_{eff} is expected to be lower than the calculated value in this paper. The 16 group

Table 5. Results of Criticality Calculation

	KENO	MORSE
K_{eff} of nine assembly steel shipping cask	0.870±0.004	0.877±0.006

Hansen-Roach cross section set[16] was used for MORSE and KENO[17] calculation. Table 5 summarizes the criticality calcuations for the nine-assembly steel shipping cask. Even the maximum calculated value of k_{eff} at 95% confidence level by KENO or MORSE is lower than the designed limit of 0.95. (This is not a firm limit, but is widely used for safety.)

VI. Cask Design

Through this study it has been found that the nine-assembly steel shipping cask is the most proper container to transport the spent fuel assemblies of KNU-1. Figure 1 provides an artistic view of the caks and illustrates the major components. The cask is mounted on the skid by lifting trunnion and trunnion block cap and it is mounted on a railcar by using the skid. Figure 2 shows a plan and front view of the cask. To transport nine spent fuel assemblies of KNU-1 in a cask, 1.27cm thick steel boron plates, which are bonded to themselves as well as to the 0.2cm thick stainless steel fuel basket, are used in 9.859cm space to control the effective multiplication factor. Although the steel boron plate is expensive and has relatively low thermal conductivity, it is used to sustain the adequate structure integrity even above the thermal test limit of 802°C(1475°F) during postulated accident conditions.

10cm long and 0.6cm thick steel fins are attached to the outer shell effectively to dissipate the decay heat. In addition, they are welded to protect the cask against the impact during the accident by acting as a shock absorber. The cask, exclusive of the skid, weighs about 76 tons, and has an external diametric envelope of 204cm (as established by the heat rejection fins), and an overall length of 503cm. The inner cavity has an internal diameter of 118cm

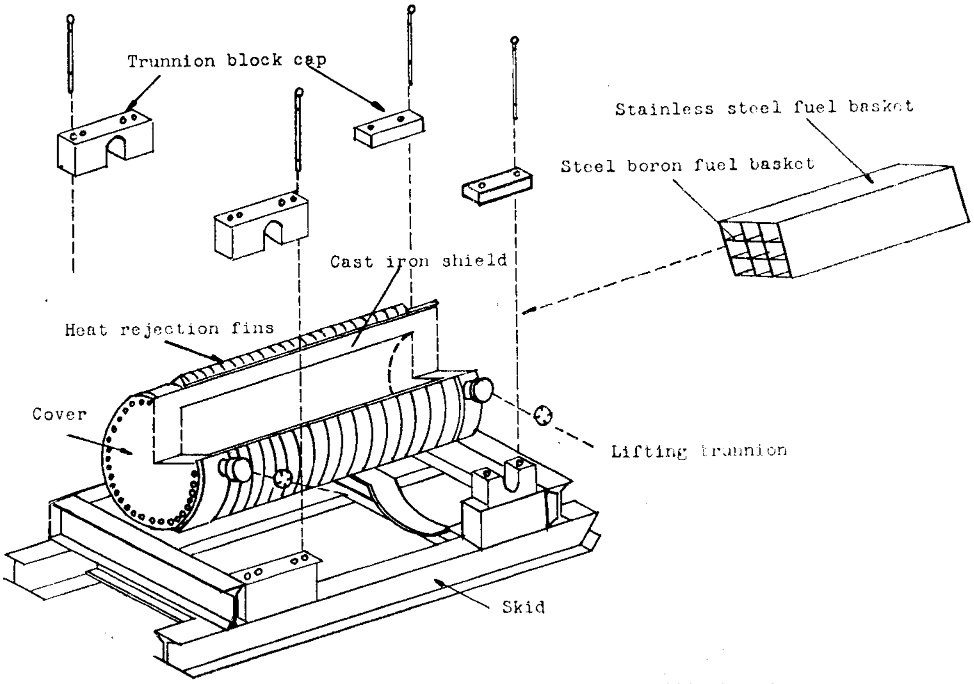

Fig. 1 Exploded View of Nine Assembly Steel Shipping Cask

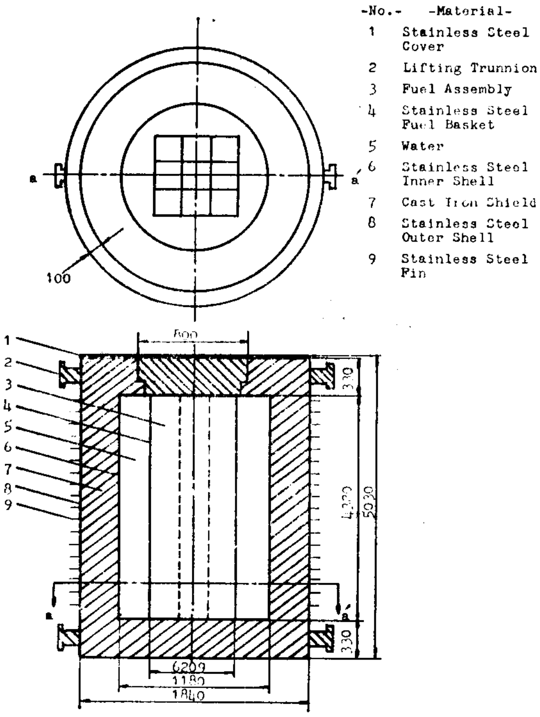

Fig. 2 Nine Assembly Steel Shipping Cask

and length of 431cm.

VII. Conclusions

Based upon the results of study, a 76 ton steel shipping cask, which has 204cm external diameter, 118cm inner diameter and 503cm overall length, is recommended for transporting the spent fuel assemblies of KNU-1. This cask is designed to transport nine assemblies at one time by unrestricted railcar. Steel is used for the shield material due to its excellent structural integrity and the other advantages.

For shielding calculation the source terms were calculated by ORIGEN-79, and the neutron and gamma-ray sources of a KNU-1 spent fuel assembly are 3.43×10^8 neutrons/sec and 8.42×10^{15} photons/sec, respectively. ANISN and MORSE were used for shielding calculation and the nine-assembly steel shipping cask is required to have 33cm thick steel shield including the inner and outer stainless steel shell, and 27cm thick water region to satisfy the limit of the dose rate (10 mrem/hr) at 3ft from any accessible external surface of the cask. With this configuration, the heat removal and criticality were also evaluated for the nine-assembly steel shipping cask. The heat removal capacity was studied under a postulated accident condition of no water in the cavity. The result indicates that the fuel centerline temperature of the fuel is much lower than the limit of the melting temperature of the fuel. The k_{eff} of the cask was computed with the fresh fuel assemblies by using MORSE and KENO. It is calculated to be lower than the safety limit of 0.95.

In practice, a detailed design should be performed for realization of the shipping cask. First of all, the safety of the cask must be verified by various experiments under a postulated accident condition. In addition, elaborate studies are also recommended specifically in the areas of structural analysis and heat removal.

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