Drop Impact Analysis for Basket Design Selection in Spent Fuel Shipping Cask for Korean Standard Nuclear Power Plant

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ABSTRACT

This paper describes a structural evaluation process for optimal basket structure design of the spent nuclear fuel shipping cask for Korean standard nuclear power plant. The cask is assumed to store 18 PWR fuel assemblies with water for transport. Code and standard requires the cask should remain safe with no release of radioactive material to public in both normal transport and hypothetical accident condition. Depending upon how the basket structure is supported in the cask, there could be a couple of options like an insertion round plate type and a weld plate type, and the final basket design should be picked up thru engineering evaluation. Therefore, preliminary impact analyses for a typical case of the 9m drop accident for the two options are executed with review of fabrication efficiency. As a result, the cell insertion type design turns out to be the better in viewpoint of structural integrity and fabrication.

1. INTRODUCTION

The structural safety of spent fuel shipping cask is considered very stringent because serious effect can be brought to both mankind and environment in case of radioactive material leakage by the accident occurred during transportation. According to the applicable codes and standards, the spent fuel shipping cask must be able to withstand 9m free drop impact onto an unyielding surface and 1m drop impact onto a mild steel bar in a position causing maximum damage. A cylindrical thick-walled steel cask, which provides radioactive material containment within a cavity loaded by fuel assembly inserted in the basket and filled with water, is to be designed for Korean standard pressurized water reactor nuclear power plant, YGN units 5&6. Inside the cask cavity, a fuel basket that locates and supports the fuel assemblies in fixed positions, provides function of neutron absorption to satisfy nuclear criticality requirement and heat transfer out thru the cask body wall. There are a couple of options for the basket design depending on how the fuel storage cells are fixed by the supporting structures on the cask wall.

This paper describes how the design of fuel storage basket in the cask cavity has been structurally determined from the options of supporting type in the preliminary design process of the spent fuel shipping cask. The basic design methodology references the CASTOR KN-12 which has been designed most recently in Korea. At initial stage of cask basket design, tentative sizing of each cell should be done through discussion and evaluation among physics, thermal, radiation, and structural groups to solve the design interfaces. That includes basically the cell to cell or the center to center pitch, and the wall, gap, and neutron absorber material thickness of each cell. Next, the basket frame, which locates and supports the cells within the cask cavity, should be fixed. By the way, some options are possible for the design of supporting structures according to the review of reference designs and previous experiences. The less stress and deformation it has in the most severe condition, and the more easily it can be fabricated, the better the design would be. The nonlinear drop analysis in a typical accident condition and engineering judgement about fabrication difficulties are discussed in the following chapters.

2. DESIGN REQUIREMENT

From the review of the contract and code requirement, followings are set up as the basic top tier requirements for the preliminary basket design inside the cask.

- The basket should take 18 PWR fuel assemblies of the Korean standard nuclear plant.
- Basket is designed in 4-5-5-4 array type with Borated Aluminum attached to the cell wall which is made of stainless steel.
- The maximum total weight of the cask should not exceed 110 ton.

3.1 Shipping Cask

The structural dimension of designed cask was obtained from criticality and shielding analyses. The cask is capable of loading 18 PWR CE-type spent fuel assemblies with a burn-up of 55,000 MWD/MTU and a cooling time of 7 years. The loaded cask weighs about 110 ton maximum. The whole cask system consists of cask body, cask lid, basket, neutron shielding, outer shell and impact limiters. The cask dimension and conceptual drawing are shown in Fig. 1.

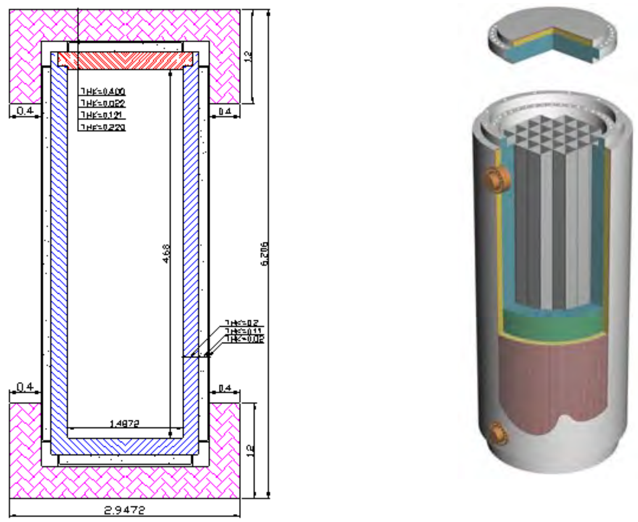


Fig. 1 Cask Dimension and Conceptual Drawing

3.2 Basket Structures

The fuel basket is to be designed to accommodate 18 PWR fuel assemblies, and the fuel receptacles ("cell" in other words) are manufactured by the welding of stainless steel plates to form a square tube to enclose and secure the fuel assemblies. The cells are assembled as a gridwork together with borated aluminum plates. To minimize the inside diameter of the cask vessel, 4-5-5-4 array is picked up as a preliminary basket arrangement as shown in the Fig.2, in spite of some worries about possible excessive deformation or stress near the T-type cross section in accidental condition.

By the way, the receptacle system of basket could be designed by two optional types of support to locate and fix the cell structures inside the cask body. Those are insertion plate type and weld plate type. As shown in Fig. 2, the insertion plate type is such a structure that is assembled and fabricated by insertion of each fuel receptacle through each hole among 18 rectangular holes of a number of round supporting plates located at constant intervals in axial direction. The round supporting plates are connected by 12 penetrating rods equally located in circumferential direction. Previous work for the assembly of cell structures is not necessary in this design. However, it should have very strict tolerances for the assembly of all the cells into the hundreds of slots with no problem. On the contrary, the weld plate type is such a structure whose receptacles are assembled and fabricated by welding in advance. The whole fuel receptacle structures, then, are assembled to each supporting plates in circumferential direction located at constant intervals in axial direction as shown in Fig.3.

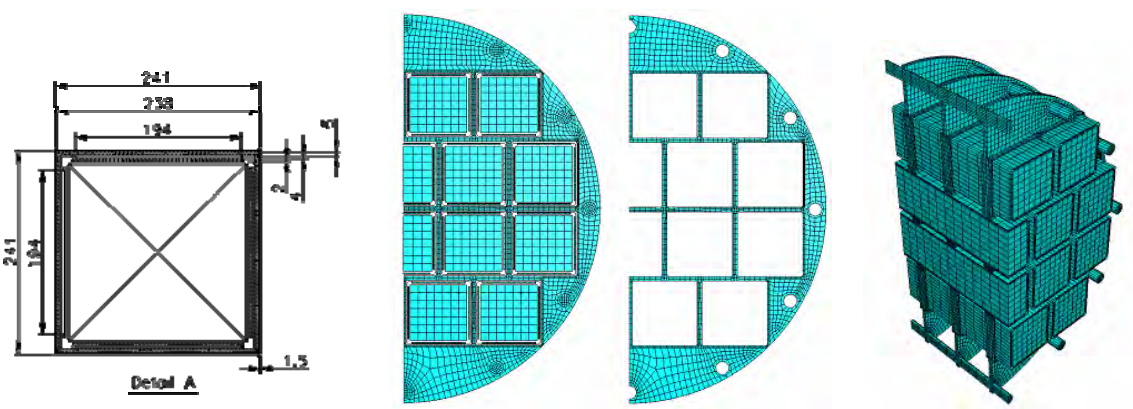


Fig.2 Insertion plate type basket design

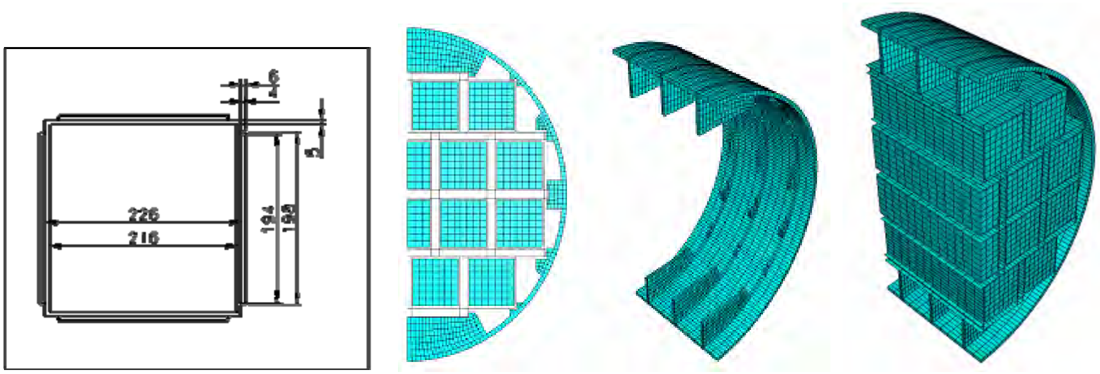


Fig.3 Weld plate type basket design

The weld plate type has less pitch size than the insertion plate type, however, it needs more frame structures to keep the minimum required gaps between the cells, so to speak, it is more difficult and expensive to make the cell structures before assembly to the supporting plates. In addition, there is not enough space given for welding between the cell system and the plates as far as it sticks to close cylinder style in the weld plate type design.

3.3 Material Property

In accordance with ASME section Ⅲ, Division 3, elastic material properties were used for all the cask components. However, since the claddings of the impact limiters rely on large plasticity to absorb the energy and mitigate impact, elastic-perfectly plastic properties were applied. The material properties of major cask component used for the analysis are shown in Table 1.

Table 1. Material Property

	Material	σ_y (MPa)	σ_u (MPa)	Limit (MPa)	Temp.
Cask Body	C/S SA350	258.6	482.6	337.8 *	Room Temp.
Basket Cell	SS SA-240/321	166.9	458.1	448.9 **	167°C
Impact Limiter	Beech wood	Refer to KN-12	Refer to KN-12	N/A	Room Temp.
Fuel Assembly	Dummy	Steel	Steel	N/A	N/A

* ASME Sec.III, Div.3 (Pm < lesser of 2.4Sm or 0.7Su)

** ASME Sec.III, Div.1, App.F (Pm < larger of 0.7Su or Sy+1/3(Su-Sy))

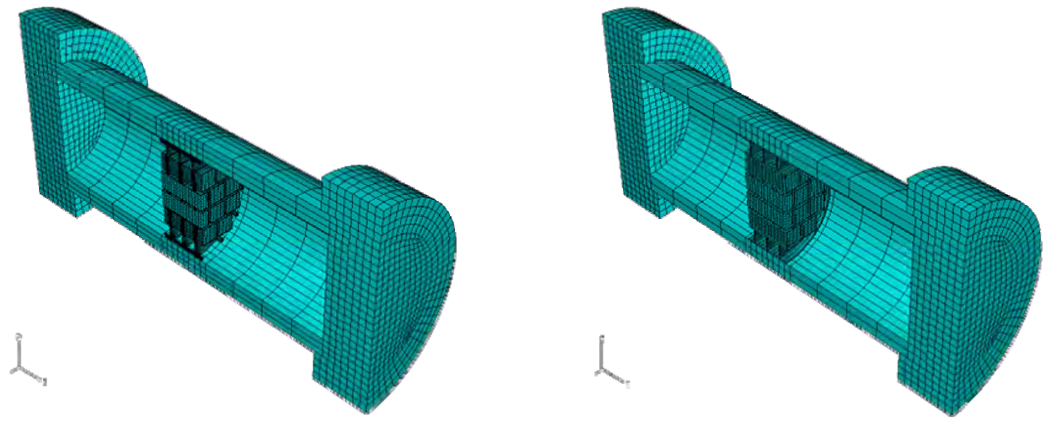
P_m : Primary membrane stress, P_b : Primary bending stress

S_m : Design stress intensity, S_u : Ultimate tensile strength

3. OUTLINE OF ANALYSIS

The structural analysis is conducted for hypothetical accident conditions according to the requirements specified in domestic atomic laws, IAEA Safety Series, US 10CFR 71 and Reg. Guide 7.8. It is to evaluate the structural integrity of the basket system and the criticality safety by checking the stress and the deformation of the cell and support structures in accident condition. As the most governing case among the postulated accidents, horizontal drop is chosen to be analyzed on the preliminary design purpose. The computer program ABAQUS Explicit V6.5 is used for this analysis. The assumptions and methods of analysis are as follows;

- The cask body is simply modeled while the basket system is done in detail because the basket design is of major concern.
- The 3-D half model is used for the analysis of the whole structure and the basket is modeled only for the 3 span portion near the axial center.
- To compensate the weight effect of the other component, the specific weight of the cask body is adjusted.
- The cask is assumed to drop onto a rigid horizontal surface with the initial velocity of 13.3 m/s perpendicular to the target.



a) Model for insertion plate type b) Model for weld plate type

Fig.4 Analysis models for the two basket design options

Fig. 4 shows the models for nonlinear drop impact analysis both for the insertion plate type and weld plate type. And each model includes 3 spans of basket filled with fuel assemblies and water, surrounded by cask body and impact limiter at top and bottom. Modeling of cask body and impact limiters are relatively simplified for the preliminary analysis purpose. For example, the steel cladding structure of the impact limiter, the neutron shielding and stainless steel shell in cask body are not modeled, and the effects of bolt prestress, temperature distribution, and internal pressure are not considered in this preliminary analysis. After the analysis is checked in viewpoint of reliability and correctness, the analysis results were evaluated according to the procedures and code requirements prescribed in Table 1 about stress limits for hypothetical accident conditions.

4. Summary of Results

As a result, stress distribution of the support plates, the receptacles, and deformed shape of basket sectional view are given to explain how much they can actually be deformed in accidental case with the fuel assembly inserted for both of the insertion plate type and weld plate type as shown in Fig. 5 and Fig. 6. As the analysis is performed for the horizontal drop case, the stress of the receptacles and plates get higher near the bottom portion of the basket because of the accumulated weight effect above the lower set. And the deformation increase rapidly near the cross section of the cell wall plate.

The maximum stress intensity of the major components, receptacles, support plates and neutron absorbers in basket structure is tabulated in Table 2 and Table 3 from the analysis result, whose limit is calculated according to the ASME code. As a result of stress evaluation for the insertion plate type as shown in Table 2, the stresses of the major components turns out to be within the code limit, though the support plate has not enough margin to the limit. For the weld plate type as shown in Table 3, the stresses of the major components stay well within the limit. The stresses of the receptacles and the neutron absorber except the support plate do not show big differences between the two types as seen in the Table 2 and Table 3.

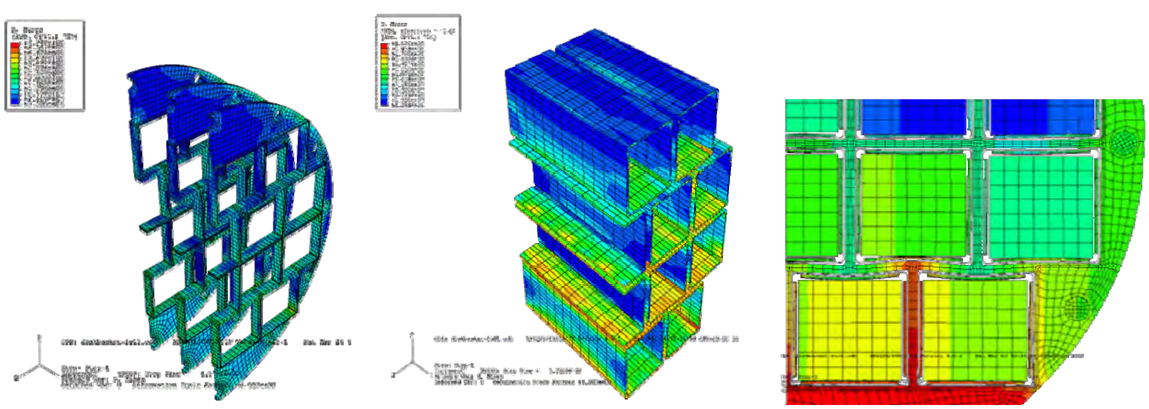


Fig.5 Stress and deformed shape of the basket system for insertion plate type

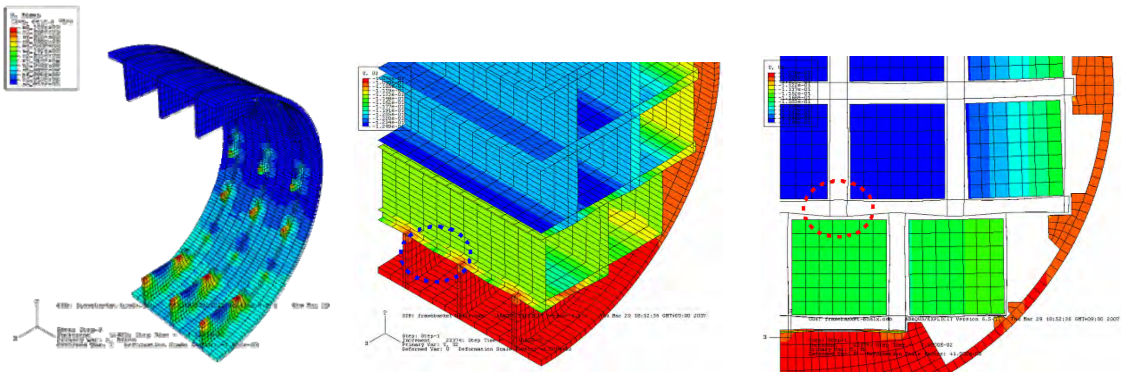


Fig.6 Stress and deformed shape of the basket system for weld plate type

Table 2 Evaluation of stress for insertion plate type

	Material	σ $_y$ (MPa)	σ $_u$ (MPa)	Result (MPa)	Limit (MPa)
Receptacle	SA240/321	167	641	181	449
Support Plate	SA240/321	167	641	408	449
Neutron Absorber	BORAL	20	47	22	33
* ASME Sec. III, Div.1, App. F (Pm < larger of 0.7 Su or Sy + 1/3(Su-Sy))					

Table 3 Evaluation of stress for weld plate type

	Material	σ $_y$ (MPa)	σ $_u$ (MPa)	Result (MPa)	Limit (MPa)
Receptacle	SA240/321	167	641	191	449
Support Plate	SA240/321	167	641	230	449
Neutron Absorber	BORAL	20	47	21	33
* ASME Sec. III, Div.1, App. F (Pm < larger of 0.7 Su or Sy + 1/3(Su-Sy))					

Table 4 shows comparison of the analysis results of the two types of support plates not only for the stress but the displacement. The minimum pitch size from the criticality analysis is compared for the two types at first, and the resultant stress and displacement are compared with the total weight estimated by the given sizing data. If the deformation of the support plate exceeds the minimum required space between the fuel assembly and plate, it should be corrected to a safe level by adding some reinforcement. As we can see from the analysis results, the weld plate type shows better performance in viewpoint of structural integrity.

Table 4 Comparison of the analysis results

	Criticality Analysis		Structural Analysis			Total Wt.
	L1	L2	Calculated (MPa)	Allowable (MPa)	Max. Displ.	
Insertion plate type	17	19	408	449	3.7	112
Weld plate type	22	22	230	449	3.8	109

By the way, as the weld plate type design assumes the wall structure surrounding the receptacles is closed type plate, it is very uncomfortable and difficult to weld between the receptacle system and the support plates around the whole body. Because it is hard to access by the welding mechanism, it needs some design change to solve this problem basically. In case of the insertion plate type, it is not tough to weld between the receptacle system and the support plates in the field. However, it would hard to assemble all the receptacles into all the slots of the insertion plate in case it is fabricated with rough tolerance.

5. CONCLUSIONS

As results of drop analysis and engineering review for the two different types of support plate in the basket structure, the structural integrity of the basket in the spent fuel shipping cask is guaranteed for all the evaluated cases. And among the design options of the support plates to locate the receptacle assembly, the insertion plate type design turns out to be the better in both viewpoints of stress and fabrication, in spite of tough tolerance required for each part of the basket component for smooth assembly. However, more distinct result could be obtained later because this is a result from preliminary analysis where a lot of simplification is done in modeling procedure.

References

[1] IAEA Safety Standards Series, No. TS-R-1, “Regulations for the Safe Transport of Radioactive Material”, 2005.
[2] Regulatory Guide 7.6, “Design Criteria for the Structural Analysis of Shipping Cask Containment Vessels,” Revision 1., 1978.
[3] ASME B&PV Code Section Ⅲ, Division 1&3, 1998.
[4] Jung S. H. and et. Al., “Structural Evaluation on HIC Transport Packaging under Accident Conditions,” J. of the Korean radioactive waste society, 2005.
[5] Goo J. H. and et. Al., “Free drop impact analysis of large scale spent nuclear fuel shipping cask, Proceeding of KNS meeting, 1997.
[6] ABQUS/Explicit User's Manual Ver 6.5, H.K.S. Inc.