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Thermal Analysis for the Fresh Fuel Transport Container

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1. Introduction

New fuel assemblies are transported using the transport container from the fabrication facility to the nuclear power plant. The fresh fuel transport container (Fig. 1) which is to be loaded with two PLUS7 fuel assemblies shall be designed according to the MEST regulations [1] and/or the IAEA safety requirements [2]. This container is limited for use in transporting unirradiated and low enriched nuclear fuel assemblies.

During the design of the fresh fuel assembly transport container, the thermal evaluation is to be performed to ensure the suitability of the thermal insulation design under the hypothetical fire accident conditions described in 10 CFR 71 and IAEA regulation for the Safe Transport of Radioactive Material.

In this thermal evaluation, a CFD (Computational Fluid Dynamics) analysis was applied to investigate the heat transfer phenomena in the flames. The analysis was done by analyzing the temperature distribution in the transport container when exposed to 800°C external conditions with a fire emissivity of 0.9 for 30 minutes according to the acceptance criteria defined by 10 CFR71.73.

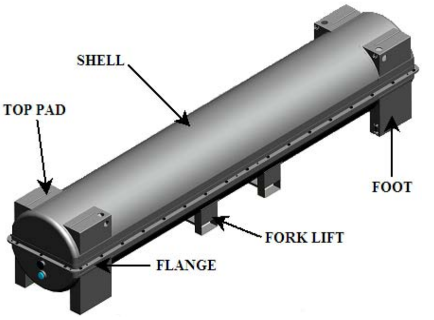


Fig. 1. The fresh fuel transport container for PLUS7 fuel assemblies

2. Simulation Methods and Results

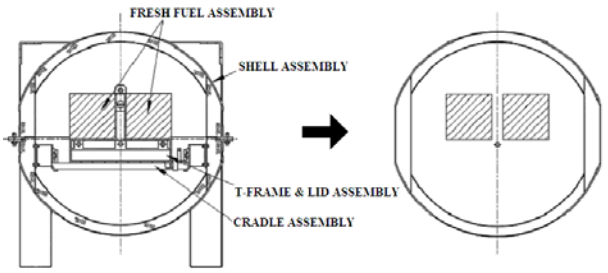
2.1 CFD Model and Boundary Conditions

The new fuel transport container consists of a double-wall, T-frame and cover. The transport container is fabricated primarily of the stainless steel and the flame retardant polyurethane foam sandwiched between the inner and outer shells. The dimensions of transport container are 5500 mm in length and 950 mm in out-diameter. The flange around the container is designed to keep dust and gas from getting inside under a fire.

The polyurethane foam properties change significantly, as the foam temperature increases. The polyurethane foam will be exposed to significantly high temperatures during a hypothetical accident. When charred at high temperature, it becomes low density carbon foam. For the analytical model, the room temperature specific heat and conductivity were applied up to 340 °C. Above 340 °C, for conservatism, the temperature-dependent conductivity of air was used instead. The polyurethane foam thickness in the end plates is twice of the sides to reduce the end effects.

The heat sink region mainly occupied by two PLUS7 fuel assemblies, weighing 638 kg, has an average specific heat of 0.261 kJ/kg·K and a smeared mixture density of 9518 kg/m^3. A volumetric average conductivity was calculated for fuel assembly region by generating the volume smeared conductivity by using the ratio of conductivity to volume for each material. This approximation is valid only because the heat input rate is very low, thus allowing the region to be almost isothermal, even with low conductivities.

For the purpose of this analysis, the transport container and internal components were simplified to a cylindrical volume. Simplifying the interior components and outer shell to be a simple cylinder is conservative in an aspect of heat capacity. Fig. 2 shows the process for creating the computational domain. A 3D model was created for the simulation. Quadrilateral and hexahedral meshes with approximately 247,000 cells were generated by using the mesh generating program, GAMBIT 2.4. Since the geometry of sides is symmetric, a quarter of the transport container volume was meshed considering a gravity direction and faces.



(a) (b)

Fig. 2. Cross-section of the transport container (a) relevant portion of cross-section, (b) simplified model for CFD analysis

The initial temperature of the transport container is assumed at room temperature. A uniform heat source of 800°C is applied on the outer shell. A pressure boundary condition is defined on the inner shell boundary.

2.2 Computational Method

A CFD code, FLUENT 6.3 on UNIX system, was used in this analysis. FLUENT's pressure-based and unsteady solver is used to predict the thermal-hydraulic time-dependent flow behavior, which solves the continuity and momentum equations in the fluid domain. The energy equations are solved in both the fluid and solid domains. This problem involves a 3D turbulent flow with natural convective and conductive heat transfers. The standard k-ε turbulence model[3] is applied. At the inner shell wall of the container, enhanced wall functions[4] are used.

The computational assumptions for this analysis are that: (1) primary temperature variations occur evenly in the transport container outer shell, (2) no significant gas infiltration occurs, (3) no radiative heat transfer is considered but combined convective and conductive heat transfers are applied. Considering the relatively low temperature of inner shell wall for 30 minutes of a fire accident and the internal structures attenuating radiation by increasing absorption and scattering in actual practice, the effect of heat-radiation is ignored.

2.3 Results

The analysis results show that the outer skin of the transport container quickly rises to thermal equilibrium with the hypothetical fire temperature as shown in Fig. 3. It also shows temperature variations through the cross-section of the polyurethane foam and interior air plenum involving fuel assemblies for 30 minutes. The internal components heat up more slowly due to the insulation of the polyurethane foam. Temperatures of fuel assemblies and internal components remain below 100 °C.

Fig. 4 represents temperature distribution at 30 minutes after the initiation of fire accident. The fuel assembly temperature increases up to 99.3 °C. The inner face of flange is heated up to the maximum of 226.9 °C, but the flange hardly contributes to heating up the inside transport container since the heat transfer area is very thin and narrow.

Temperature limits of the primary material of transport container that affects structural integrity are provided in Table 1. The table also includes the calculated average temperatures of the transport container components fabricated of stainless steel and fuel assembly.

3. Conclusions

A CFD analysis was performed to evaluate the thermal insulation design of the fuel transport container assuming a fire accident. The results show the transport container has a sufficient insulation capability to protect the fuel assemblies from the fire accident.

REFERENCES

[1] The Ministry of Education, Science and Technology Notice No. 2008-69, "Regulations for the Package and Transport of Radioactive Material"

[2] IAEA Safety Standards Series No. TS-R-1.

[3] B. E. Launder and D. B Spalding, Lectures in Mathematical Models of Turbulence, Academic Press, London, England, 1792.

[4] B. Kader, "Temperature and Concentration Profiles in Fully Turbulent Boundary Layers", Int. J. Heat Mass Transfer, 24(9):1541-1544, 1981.

Table 1: Limits and analysis results of temperatures for the transport container

Description	Temperature limit (°C)	Average Temperature (°C)
Fuel Assy.	1148-1336	99.3 (max)
Upper Shell	N/A	284.7
Lower Shell	N/A	291.9
Interior Air	N/A	83.9
Flange	1400-1455	503.1

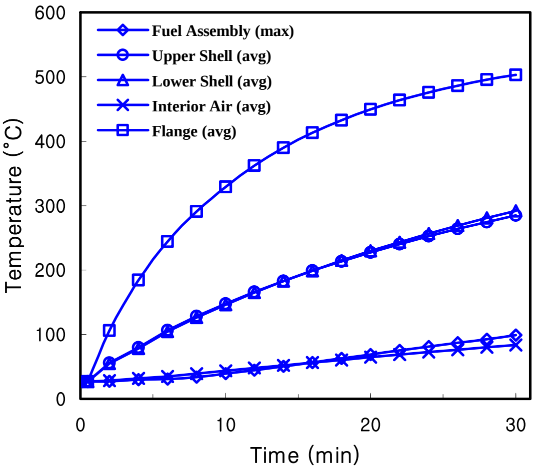


Fig. 3. Temperature curves for 30 minutes during the hypothetical fire accident conditions

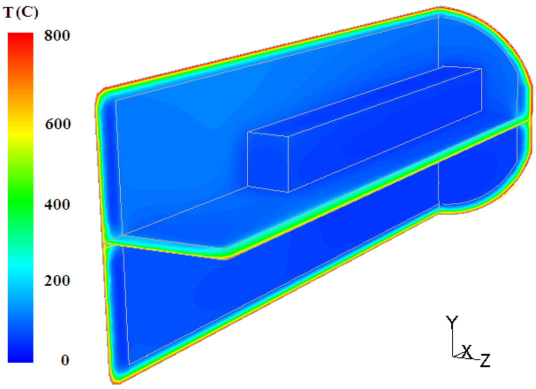


Fig. 4. Temperature distribution of transport container at 30 minutes after the initiation of fire