THERMAL ANALYSIS OF A SPENT FUEL TRANSPORTATION CASK

P. Goyal*, Vishnu Verma, R.K. Singh & A.K. Ghosh

Reactor Safety Division
Bhabha Atomic Research Centre
Trombay, Mumbai-400085
INDIA

Email: pgoyal10@rediffmail.com

Keywords: Transportation cask, melting, fire, transient, thermal analysis

ABSTRACT

Spent fuel transportation casks are required to meet among others (test conditions), the regulatory thermal test conditions in order to demonstrate their ability to withstand specified accidental fire conditions during transport. This paper describes the transient thermal analysis performed with the above intention for a transportation cask. The analysis was carried out using COMSOL Multiphysics code employing the Finite Element Method (FEM). The computation covers normal transport condition, and half an hour fire test at 800°C. The objective of the analysis was to determine the maximum outer surface temperature for normal transport conditions and to assess the extent of melting of lead during fire period.

1. INTRODUCTION

Spent fuel bundles need to be transported from the nuclear power plant site to the fuel reprocessing plants. The spent fuel is transported in mechanically strong and well-shielded transportation casks. Design approval of such casks by the regulatory authority is subject to demonstration of compliance with a cumulative series of specified tests [1]. The thermal test, which is one of the tests in the series, needs to be carried out for the cask in order to show its ability to withstand specified accidental fire conditions during transport. The compliance to thermal test can be demonstrated either by an actual test or by detailed thermal analysis [2].

During the fire test, there is a possibility of melting of the shielding material i.e., pure lead used for shielding purpose. Therefore, the code employed for thermal analysis needs to handle phase change phenomena. COMSOL Multiphysics code was employed to determine the steady state temperature distribution in the transportation cask under normal condition. This distribution was then applied as the initial condition for carrying out the transient analysis to simulate fire at 800°C for 30 minutes. The objective of the analysis was to determine the maximum outer surface temperature for normal transport conditions and the temperature profiles across structural materials during fire period. The extent of melting of lead was also estimated, thereby checking whether the cask satisfies the regulatory design requirements from thermal point of view.

The present paper briefly describes the phase change model employed in the COMSOL code The results of steady state and transient analysis of spent fuel transfer cask are also presented in this paper.

2. NOMENCLATURE

A	Surface area (m^2)
Cp	Specific heat (J/Kg-K)
Gr	Grashoff Number
H	Enthalpy per unit volume (J/m^3)
h	Heat transfer coefficient (W/m^2-K)
k	Thermal conductivity (W/m-K)
L	Latent heat (J/Kg)
Nu	Nusselt Number
Pr	Prandtl Number
Q	Heat generation rate (W)
q	Heat flux (W/m^2)

Re	Reynolds Number
steady	Steady state conditions
T	Temperature (K)
t	Time (s)
x, y, z	Space coordinates

Greek symbol

α	Absorptivity
Δ	Increment
ε	Emissivity
ρ	Density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2-K^4)
∞	Normal ambient conditions

Subscripts

air	Air
ci	Cask Inner
co	Cask Outer
f	Fire
s	Surface
solar	Solar
ss	Stainless steel

3. DESCRITION OF TRANSPORTATION CASK

The cross sectional view of the cask and its side view are shown in Fig.1 and 2 respectively. The basic features of the cask are as follows [3]:

Shape: Cuboidal
Shielding thickness (Lead): 150 mm
Cavity size: 1600 mm×750 mm×920 mm
Outer dimensions: 2026 mm×1176 mm×1346 mm

4. MATHEMATICAL MODEL

4.1 Modeling phase change process in COMSOL code

Phase change i.e. melting problems are of moving boundary nature and are also non-linear due to latent heat effect. The grid philosophy plays an important role in modeling melting. The available algorithms can be categorized as Eulerian or fixed grid method, Lagrangian method and mixed Eulerian-Lagrangian method. In the present COMSOL code, to account for phase change, the energy equation employs a fixed grid philosophy wherein, both the solid and liquid regions are treated as one continuous region and the phase boundary is not explicitly determined. The fixed grid methods (also called single domain methods) may be further classified as effective specific heat method, and enthalpy method. Conventionally, melting is modeled in the conduction codes by one of the above methods. The main advantages of these methods are as follows:

(i) Ease of implementation in an existing conduction code
(ii) Interface tracking in each time step is not required.
(iii) Re-meshing and interpolation can also be avoided.
(iv) Complex multidimensional problems can be solved.

However, the method also has a few disadvantages as given below:

(i) Inaccurate prediction for interface location
(ii) The energy balance is approximate in some cases. For a given grid, proper choice of time step may be required for an accurate balance.

In the present code, the effective specific heat method was employed [4]. The latent heat effect, which accompanies the phase change from solid to liquid, was approximated by specifying a rapid variation of specific heat over the 'mushy' zone within a small temperature range of $\Delta T \approx 1.0°C$ at the melting point (see table 1).

The specific heat was assumed to vary linearly within the temperature interval. An adjusted value of specific heat equal to L/ΔT = latent heat of the material, was used in the melting zone. This results in a slope discontinuity at the melting point. The integration time step needs to be very small and hence the code uses a variable time step during the melting process.

4.2 Mathematical model for transportation cask

Assumptions

1. Due to geometrical and thermal symmetry, a 3-dimensional model representing 1/8th part of the cask was considered.
2. To reduce the computational effort, the fuel bundles, trays, lifting arrangements and supports were not modeled.

3. The internal heat generation in the spent fuel was applied in terms of average heat flux on the inner surface of the cask.
4. The secondary heat generation due to interaction of gamma radiation with lead, carbon steel and SS liner was found to be insignificant and hence neglected.
5. Differential expansion of molten lead and outer shell during fire test condition was not accounted.

Under normal conditions, the entire heat generated within the cask gets dissipated to the surroundings from its outer surface by the natural convection and radiation mechanisms. Under the specified ambient conditions, the cask outer surface also receives solar radiation, which is dissipated to the surroundings. The temperature distribution can be obtained by solving the following 3-D conduction equation in Cartesian coordinates for all the materials.

$$\rho Cp \frac{\partial T}{\partial t} = \nabla.(k \nabla T) + Q \quad (1)$$

Where, T ≡ T (x, y, z, t)

Boundary conditions:

The following boundary conditions were applied to obtain the temperature distribution under normal conditions.

Inner surfaces (cavity)

The total heat generation rate in the fuel bundles are given as 576.0 W. Based on this the average heat flux on inner surface area is found to be 85.66 W/m^2. The following condition was applied on the inner surface.

$$-k_{ss} \frac{\partial T_{ci}}{\partial n} = q_{ci} = \frac{Q}{A_{ci}} \quad (2)$$

Where, 'n' is the direction normal to the heat transfer surfaces. By neglecting the thermal inertia of cask contents and directly applying the heat flux on the inner surface a conservative approach has been adopted.

Outer surfaces

$$-k_{ss} \frac{\partial T_{co}}{\partial n} = h_{co,\infty}(T_{co,s} - T_{\infty}) + \sigma \varepsilon_s (T_{co,s}^4 - T_{\infty}^4) - \alpha_{co,s} q_{co,solar} \quad (3)$$

4.2.1 Fire Test

Internal heat flux given by equation (2) remains valid. However, for the outer surface, solar flux was not considered and following boundary condition applies:

$$k_{ss} \frac{\partial T_{co}}{\partial n} = h_{co,f}(T_f - T_{co,s}) + \sigma \varepsilon_f T_f^4 - \sigma \alpha_{co,s} T_{co,s}^4 \quad (4)$$

Data used for Analysis: The thermal properties of various construction materials of the cask are given in Table-1 taken from references [4] and [5].

6. NUMERICAL ANALYSIS

5.1 Normal conditions

The IAEA regulations specify that the thermal tests should be carried out after conducting the drop tests to account for effect of reduced thermal paths. However, the present computations were done considering original dimensions of the cask as per the requirement of the designers. The model was discretized into approximately 300000 tetrahedral elements. Fig.3 shows the mesh used for computation.

Regulations [1] specify ambient temperature condition of 42°C with a specified insolation to account for solar heat flux incident on the outer surface of the cask. The specified maximum solar flux values for top and vertical surfaces are 800 W/m^2 and 400 W/m^2 respectively. It is assumed in the present analysis that the cask would attain thermal equilibrium under conditions of exposure to solar flux prior to fire test. A cyclic variation of solar insolation has not been considered. The above assumption of constant flux may be more conservative. The absorptivity for solar radiation was assumed as 0.3. The outer surface of cask is radiating heat to the environment and was given an emissivity value of 0.3. The convective heat transfer coefficient from outer surface to ambient was calculated based on natural convection and orientation of surfaces as given in [5, 6]. Typical values range from 3 to 4 W/m^2-K. The normal (pre-fire) conditions defined above, was used to obtain steady state temperature distribution for the cask.

5.2 Fire Test Analysis

To carry out the fire test analysis, it is required that the cask must be in thermal equilibrium with its surroundings. Subsequent to the above steady state analysis, the cask was subjected to a fire transient, which consisted of the following conditions: Internal heat generation same as in case of normal conditions, an ambient temperature of 800°C, no solar heat flux, surface absorptivity of 0.8 and flame emissivity of 1.0. Although the regulation specifies heat input under quiescent conditions, the calculations were conservatively performed assuming forced flow conditions. The convective heat transfer coefficient was calculated using the Colburn relation for forced convection as given below [2].

$$Nu = 0.036 \Pr^{\frac{1}{3}} \mathrm{Re}^{0.8} \qquad (6)$$

Convective heat transfer coefficient of about 15 W/m^2-K based on a gas velocity of 10 m/s was used. During fire analysis, only the shielding material lead is expected to melt owing to its low melting point of 600 K (327°C). The solid and liquid regions were treated as a single continuous phase having identical density. Temperature dependent variation of thermal conductivity was considered for all the materials. Implicit scheme with a variable time stepping procedure was employed for solving the governing equation. The fire condition described above was used to obtain transients for 30 minutes duration.

For solving transient problems in COMSOL, there are two methods : (i) Backward Differentiation Formula (BDF) method and (ii) Generalized Alpha method. Generalized Alpha method is found to be more suitable for problems involving melting in which there is a sharp discontinuity due to variation in specific heat at the melting point.

6. RESULTS AND DISCUSSION

6.1 Normal Conditions

Fig. 4 shows the temperature distribution in the cask under normal conditions. The maximum and minimum outer surface temperatures of the cask were found to be 351.5 K (78.5°C) and 348.3 K (75.3°C) respectively. The maximum outer surface temperature is well within the prescribed limit of 85.0°C.

6.2 Fire Test Analysis

Fig. 5 shows the temperature distribution in the cask at the end of 30 minutes fire test. The maximum temperature is found to be 804.8 K (531.8°C), which occurs at the corner of the cask on the outer surface of steel lining. The minimum temperature is 527.3 K (254.3°C), which occurs on the inner steel lining. Fig. 6 shows the liquid fraction of the lead at the end of fire test. The liquid fraction of 1 indicates that the lead has fully melted. It is estimated that about 20 % V/V of lead has melted at the end of fire test.

The steady state as well as fire test analysis was also carried out using CFD code CFD-ACE [7] available with BARC. The results obtained using COMSOL and CFD-ACE are in excellent agreement with each other. It shows that COMSOL can be used as a useful tool to carry out thermal analysis of casks involving melting.

7. CONCLUSION

A transient thermal analysis of a typical transportation cask has been performed using COMSOL to assess its ability to withstand specified accidental fire conditions during transport.. The maximum outer surface temperature under steady state condition was well within the prescribed limits and is influenced by solar insolation only. At the end of fire test, maximum melt penetration occurs at the corner portion. Although the results were obtained from a theoretical assessment, it predicts the possibility of extensive melting of shielding lead. It is estimated that about 20 % V/V of lead has melted at the end of fire test.

REFERENCES

[1] "Code for Safety in Transport of Radioactive Material", 1986, AERB Code No. SC/TR-1

[2] "Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material," Safety Guide No. TS-G-1.1 (ST-2)

[3] Private communications-NRG, BARC

[4] COMSOL 3.5a Multiphysics Reference Manual

[5] Ozisik, M.N., 1999,"*Heat Transfer-A Basic Approach,"* Tata McGraw–Hill

[6] Holman, J.P., 1997,"*Heat Transfer,"* 8th ed., McGraw–Hill.

[7] CFD-ACE+ Version 2009.2 User Guide, ESI CFD Inc., Huntsville.

Table-1 Material properties

Material	Conductivity ($Wm^{-1}K^{-1}$) k	Density (kgm^{-3}) ρ	Sp. Heat ($Jkg^{-1}K^{-1}$) C_p
Mild Steel	43.0 (293 K) 43.0 (373 K) 42.0 (473 K) 40.0 (573 K) 36.0 (673 K) 33.0 (873 K) 29.0 (1073 K)	7860	473
Stainless Steel	15.0 (293 K) 17.0 (373 K) 17.0 (473 K) 19.0 (573 K) 19.0 (673 K) 22.0 (873 K) 27.0 (1073 K)	7830	460
Lead	35.0 (293 K) 33.4 (373 K) 31.5(473 K) 29.8 (573 K) 29.0 (600 K) 19.0 (800 K) 22.0 (1000 K)	11373	130 (0-600 K) 26500 (600-601 K) 130 (> 601 K)

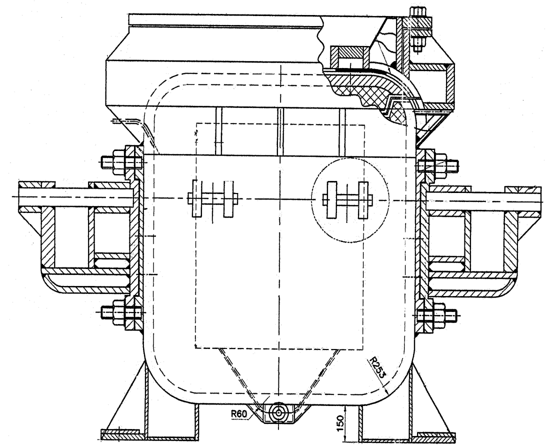

Fig.2 Side view of the cask

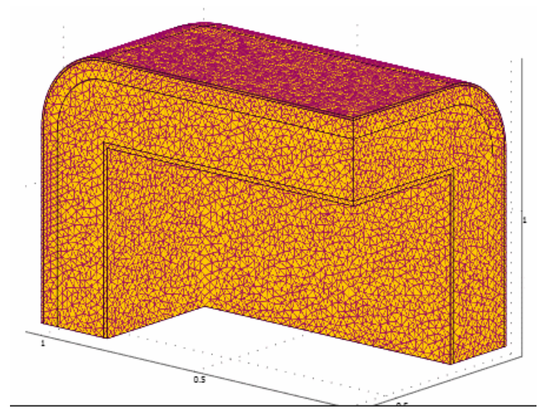

Fig. 3 FEM Mesh considered for the analysis

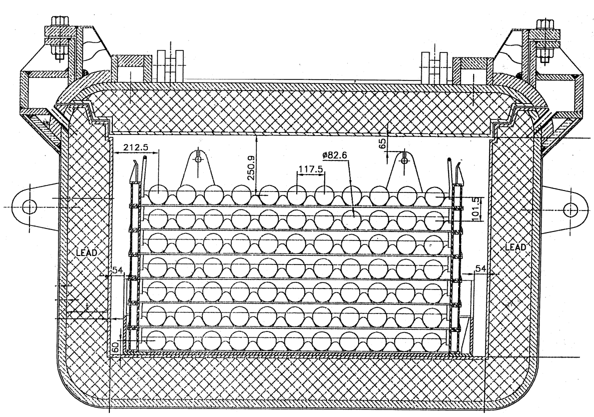

Fig.1 Cross sectional view of the cask

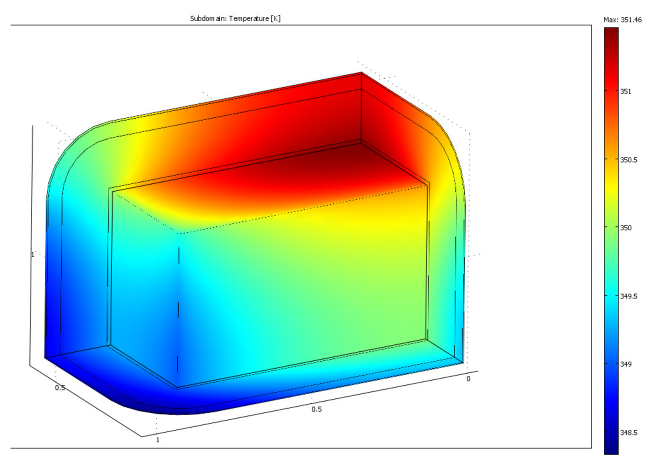

Fig. 4 Temperature Contour Plot in the cask under normal conditions

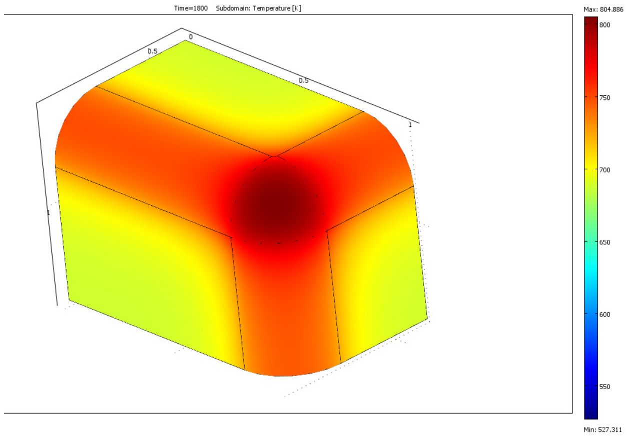

Fig. 5a : Temperature Contour Plot in the cask at the end of 30 minutes fire test

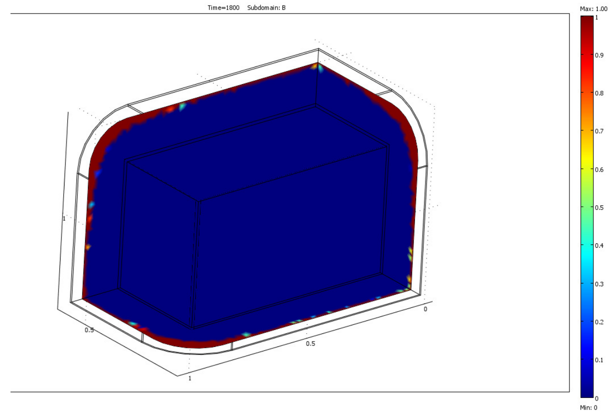

Fig.6 *Contors of liquid fraction in lead portion of the cask*

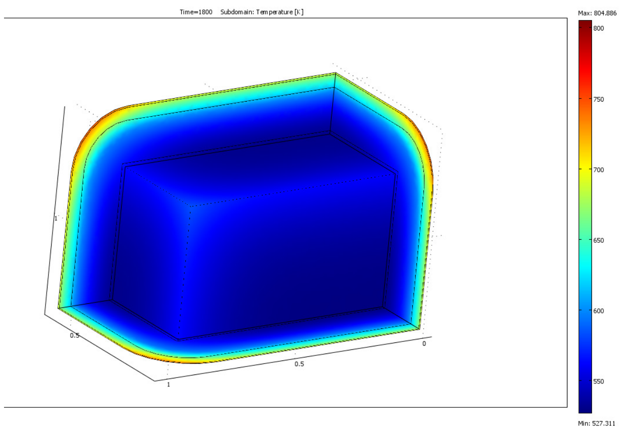

Fig. 5b : Temperature Contour Plot in the cask at the end of 30 minutes fire test

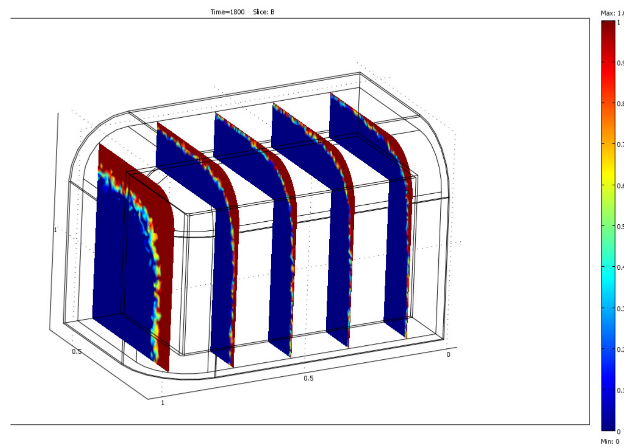

Fig. 7 : X-Slice plot of liquid fraction in lead portion of the cask