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Thermal Analysis of a Mobile Hot Cell Cask

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ABSTRACT: A Mobile Hot Cell (MHC) Cask is subjected to a series of tests to be carried out on cask experimentally or demonstrated analytically as specified by relevant Atomic Energy Regulatory Board (AERB) & International Atomic Energy Agency (IAEA) codes (1), (2), for design approval. Thermal test is one of such test to be demonstrated on the cask to simulate postulated accident condition. A thermal test is demonstrated on MHC cask analytically in a manner as specified/suggested by relevant codes. The demonstration of thermal test is carried out by finite element analysis. Three tests have been carried out on MHC cask (1) steady state temperature distribution in cask without solar insolation, (2) steady state temperature distribution in cask with solar insolation and (3) thirty minute fire test followed by cooling at ambient temperature until temperatures in cask starts coming down in all the places. Objective of this test is to determine maximum surface temperature on cask in normal transport condition and finding temperature distribution in cask during fire and post fire condition. An estimate of percentage of molten lead is also presented.

KEYWORDS: Hot Cell Cask, finite element analysis, temperature distribution, solar insolation, fire test.

I. INTRODUCTION

Design approval of MHC Cask is subjected to a series of tests to be carried out on cask experimentally or demonstrated analytically as specified by relevant AERB & IAEA codes. Thermal test is one of such test to be demonstrated on cask to simulate postulated accident condition. A thermal test is demonstrated on MHC cask analytically in a manner as specified/suggested by relevant codes.

The demonstration of thermal test is carried out by finite element analysis. Three tests have been carried out on MHC cask:

1. Steady state temperature distribution in cask without solar insolation,
2. Steady state temperature distribution in cask with solar insolation
3. Thirty-minute fire test followed by cooling at ambient temperature until temperatures in cask starts coming down in all the places.

Objective of this test is to determine maximum surface temperature on cask in normal transport condition and finding temperature distribution in cask during fire and post fire condition.

II. MATERIALS AND METHODS

A. Brief Description of MHC Cask

The MHC-Cask is a possible design to use for storage and transport of up to 2kCi Cobalt-60 sources and other such radioactive materials. This cask can be used with Mobile Hot cell by installing the cask horizontally in MHC wall.

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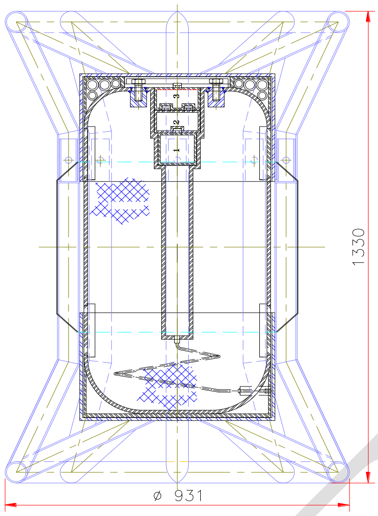

Fig.1. MHC Cask with Cage

Figures 1 and 2 show final design of MHC cask after modification and the mesh used in its thermal analysis. A cage is also provided to this cask so as to absorb maximum energy of impact and thus protecting cask from higher stress in case of impact. The cask consists of 3 lead plugs on the inside as shown in the figure. It also has an upper steel plate. On the right upper side, shock absorbers are present, and pipelines pass through.

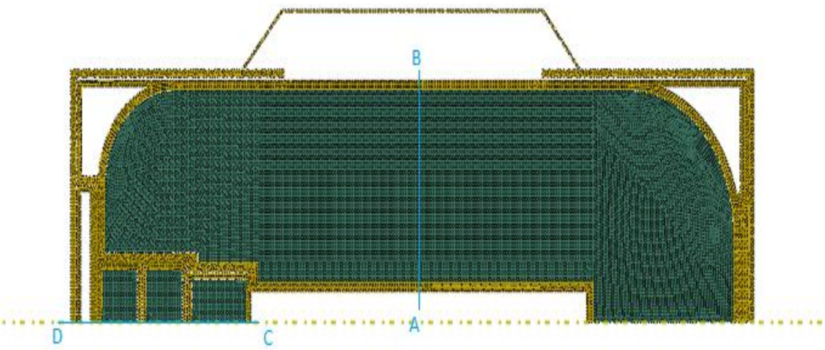

Fig. 2. Mesh used for computation

B. Materials Used

The cask is made up of two materials, i.e., lead and stainless steel. The thermal analysis was carried out using a code employing the finite element method. A 2D axi-symmetrical model of package was used for the analysis. A mesh was developed in the process. In figure 2, the green mesh represents the area taken up by lead, and the yellow mesh represents the area taken up by stainless steel. The outer cage is also made up of stainless steel. The material properties of lead and stainless steel type-SS 304L, used for analysis i.e. thermal conductivity, specific heat and density are given in table 1, 2 and 3.

Table 1. Material Properties

S.NO	Material	Density (kg/m^3)	Specific heat (J/kg.K)
1	Stainless Steel (SS 304L)	8000	460
2	Lead	11350	140

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Table 2. Variation of Thermal Conductivity of steel with temperature

Thermal Conductivity (W/m.K)	Temperature (°C)
14.8	30
15.9	100
17.4	200
18.9	300
20.4	400
21.9	500
23.5	600
24.9	700
26.5	800
28	900

Table 3. Variation of Thermal Conductivity of Lead with temperature

Thermal Conductivity (W/m.K)	Temperature (°C)
34.6	30
33.4	100
31.5	200
29.7	300
29.1	328
15.7	329
16.5	400
17.7	500
18.9	600
20.1	700
21.3	800
22.5	900
23.7	1000

C. Mathematical Modelling Method

There are some basic underlying assumptions to carrying out mathematical modelling for the mesh under consideration. These assumptions are:

1. A 2D axi-symmetrical model of transportation package is considered for thermal analysis
2. The total heat generated in the cask due to radioactive source is applied in terms of average heat flux on source cavity surface.
3. Cage pipe structure is neglected during thermal analysis
4. Natural convection heat transfer is considered in between cask and cage cavity

The steady state condition temperature distribution can be arrived by heat transfer analysis. Under normal conditions, total heat generated within the cask is dissipated from cask surface by convection and radiation heat transfer. The temperature distribution can be obtained by solving the following 2D heat conduction equation in cylindrical coordinates [3]

$$\frac{1}{\alpha}\left(\frac{\partial T}{\partial t}\right) = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(r\,\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2} \qquad (1)$$

where $T = T(r, z)$

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The following boundary conditions were applied to obtain temperature distribution under various conditions:

i. Normal Transport conditions

Two conditions were considered for normal transport condition. In first condition, solar insolation was not considered. Ambient temperature was considered as 38°C and surface emissivity for all the surfaces were considered as 0.3. Total heat generation is considered as 32W equivalent to 2kCi Co-60. This leads to an average surface flux value on source cavity to be 304.87 W/m^2. This flux was uniformly applied to cask cavity. Natural convection coefficient on cask and cage surfaces is taken as 5 W/m^2.K

In second condition solar insolation was also considered on exposed surface of package as specified in IAEA [1]. This value is taken as 200 W/m^2 at vertical package surfaces and 400 W/m^2 at other package exposed surfaces. Other parameters were taken same as above. The thermal analysis was carried out to get temperature distribution in cask and on package surface temperature.

ii. Fire Test Analysis

The steady state temperatures obtained from the above thermal analysis of cask with solar insolation are used as initial condition for evaluating temperature transits during fire test analysis. During this test ambient was considered to be at 800°C. Surface emissivity was considered as 0.8 as recommended by IAEA [1]. Solar flux was not considered during this analysis. Convection and conduction both phenomena were considered for heat input to cask in this analysis. Density and specific heat values for steel and lead were taken as in table 1. Thermal conductivity values for lead and steel were taken as temperature dependent and values were taken as in table 2 and 3. Heat transfer coefficient of air was considered as 10 W/m^2-K for exposed cask and cage surfaces. The above analysis was carried out for 30 minutes.

iii. Post Fire Test Analysis

Following to the fire transient for 30 minutes, post fire cool down analysis was also carried out to simulate cooling of cask after fire condition in natural air. Cask was allowed to cool down at 38°C ambient temperature for one hour, and temperature distributions in the cask were observed. Temperature distributions obtained after fire test were used as initial conditions for this analysis. The surface emissivity of cask and cage surfaces was maintained at 0.8. Heat transfer coefficient of air was changed back to natural convection with a value of 5W/m^2-K. Thermal conductivity values for steel and lead were taken as in table 2 and 3. Conductance value between gaps (0.5-1.0 mm) modelled between lead and cask was taken as 1x10^5 W/m^2.K.

III. EXPERIMENTAL RESULTS

A. Normal Conditions

Figures 3 and 4 shows the steady state temperature distribution of MHC package with and without considering solar insolation on outer package surfaces. When solar insolation is considered (see figure 3), the temperature on package surface varies between 55.2°C to 87.9 °C. Cask surface temperatures were found in the range of 58.3°C and 87.7°C.

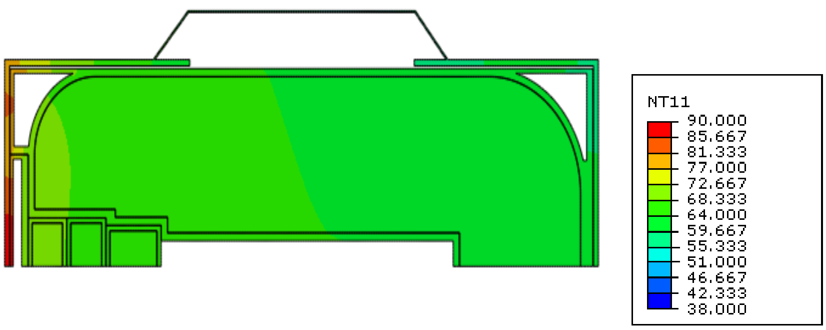

Fig. 3. Steady State Temperature Distribution in Cask with Solar Insolation

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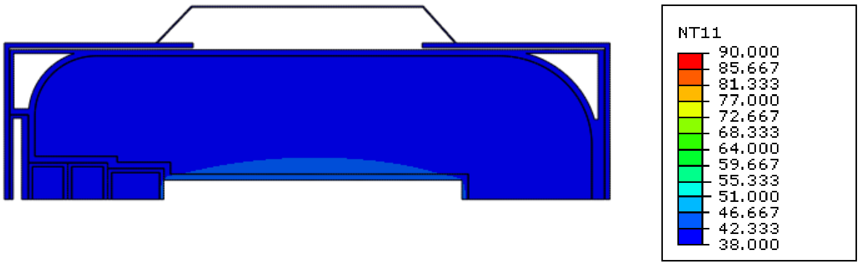

Fig. 4. Steady State Temperature Distribution in Cask without Solar Insolation

When solar insolation is not considered (see figure 4), the temperature on package surface varies between 38.2°C to 41.71°C. Cask surface temperatures were found in the range of 40.1°C and 42.0°C.

Figures 5-6 show the temperature variations across AB and CD with and without Solar Insolation at different distances.

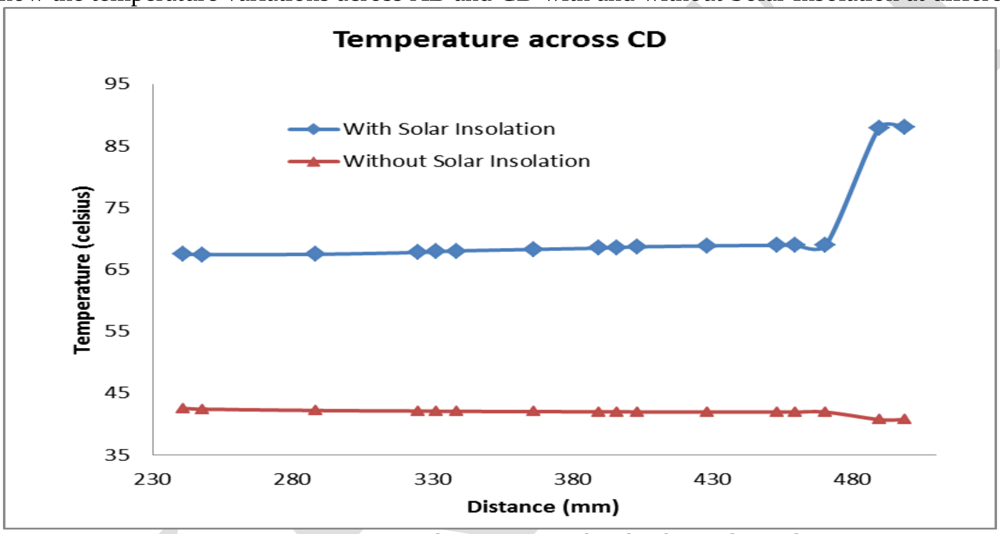

Fig. 5. Temperature Variations along Line CD with and without Solar Insolation

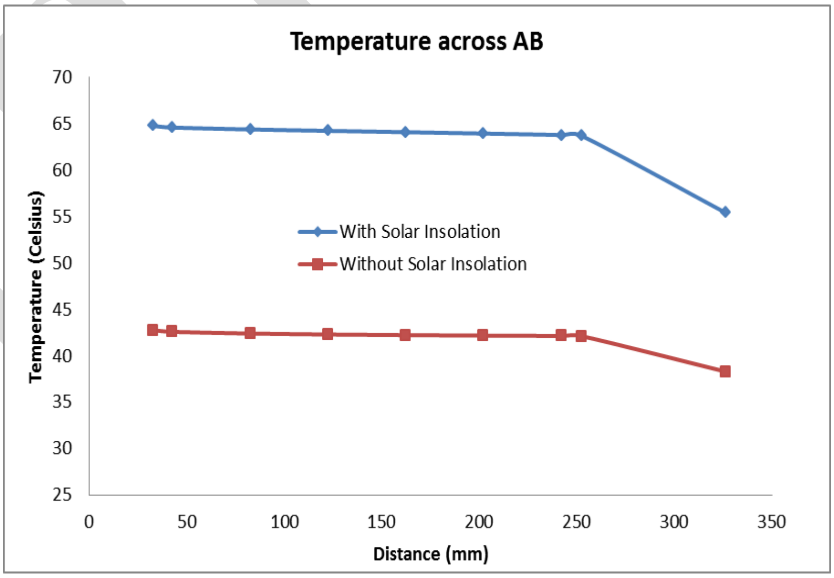

Fig. 6. Temperature Variations along Line AB with and without Solar Insolation

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B. Fire Test Analysis

Steady state temperatures obtained from above analysis was taken as initial condition for fire test analysis to evaluate temperature transits in cask during fire test.

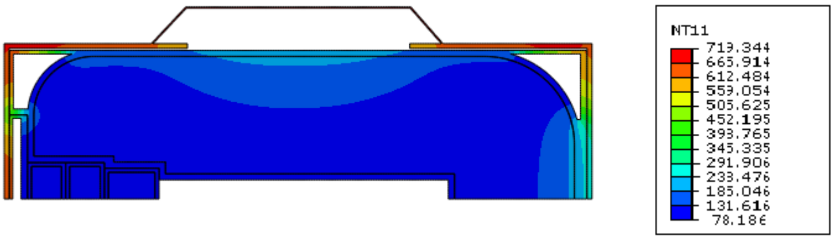

Fig. 7. Temperature Distribution in Package after 10 minutes in Fire

Figure 7, 8 and 9 show temperature distribution in cask at 10 min, 20 min and 30 minutes respectively after initiation of fire test. The maximum temperature was found to be 775.8°C on package surface and 768.1°C on cask surface during fire test.

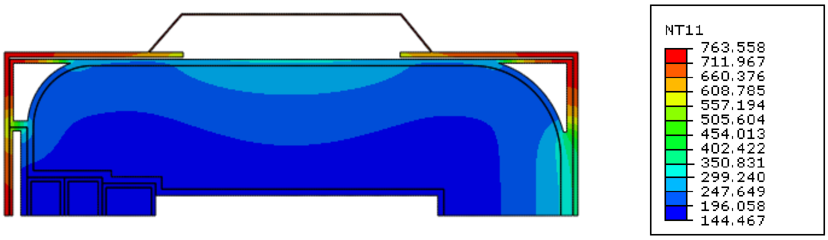

Fig. 8. Temperature Distribution in Package after 20 minutes in Fire

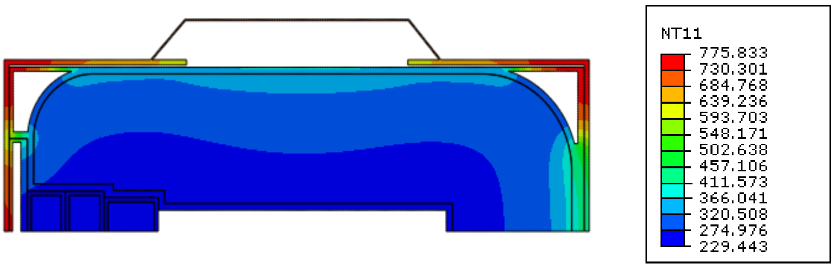

Fig. 9. Temperature Distribution in Package after 30 Minutes in Fire

Figure 10 shows the temperature distribution of the lead part of the cask where maximum temperature observed was as high as 413.3°C.

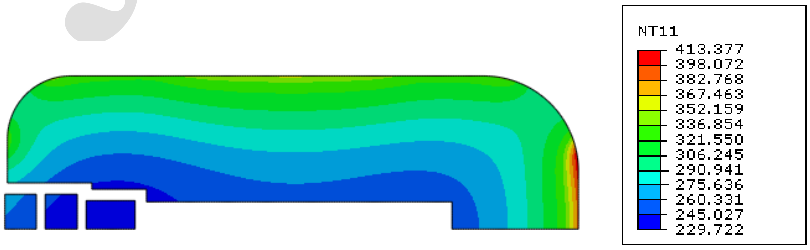

Fig. 10. Temperature Distribution in Lead after 30 Minutes in Fire

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Figure 11 shows molten portion of lead in the cask and its temperatures after completion of 30 minutes fire exposure to the package. Here, it can be clearly seen that the inner half of lead hasn't reached the melting point and it remains in the solid state.

Fig. 11. Temperature Distribution in Molten Lead after 30 Minute in Fire

C. Post Fire Analysis

The post fire transient analysis was carried out after completion of fire test for 30 minutes. This simulates cooling of package in ambient temperature until temperatures in cask at all places starts reducing. This analysis was run for 60 minutes after fire test where it was observed that all the temperatures started coming down.

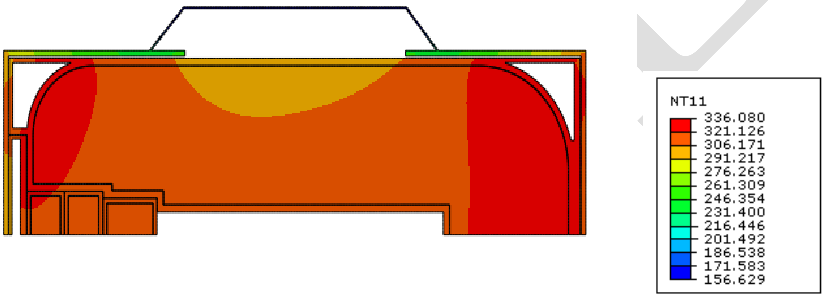

Fig. 12. Temperature in Package after 20 Minutes into Post Fire

Figures 12-13 show temperature contours of cask during post fire analysis. The highest temperature remains as high as 336°C after 20 minutes into post fire. The highest temperature drops down to about 316°C after 40 minutes into post fire.

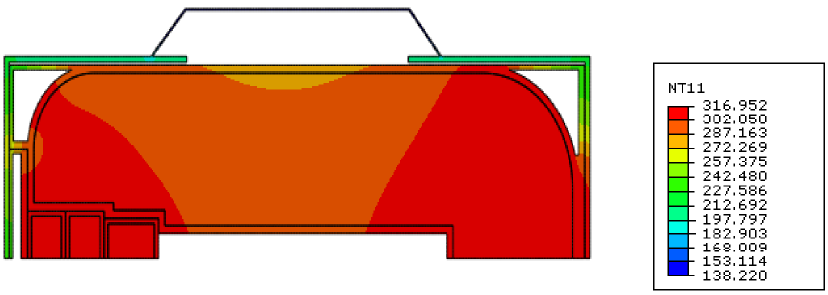

Fig. 13. Temperature Profile in Package after 40 Minutes into Post Fire

In figure 14, the highest temperature comes down to about 296°C after 60 minutes into post fire condition.

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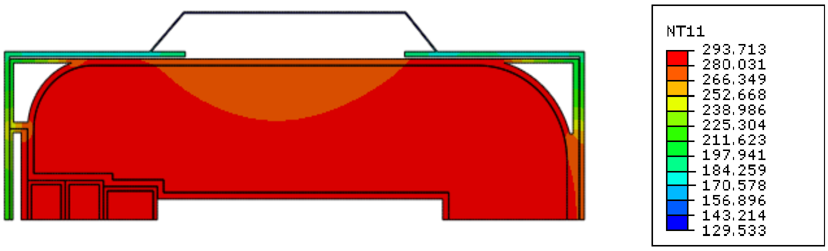

Fig. 14. Temperature Profile in Package after 60 Minutes into Post Fire

Figures 15-17 show the temperature profiles of lead part only molten part of lead where the molten part is highlighted. As expected, the volume of lead in the molten state remains the highest after 2 minutes into post fire.

Fig. 15. Temperature Profile in Molten Lead after 2 Minutes into Post Fire

Fig. 16. Temperature Profile in Molten Lead after 7 Minutes into Post Fire

Soon after 2 minutes into post fire, the temperature of molten lead starts decreasing and it starts getting solidified. This can be seen clearly in Figures 16-17 where the amount of molten lead highlighted as decreased drastically.

Fig. 17. Temperature Profile in Molten Lead after 31 Minutes into Post Fire

After approximately 34 minutes of cooling all the lead in cask gets solidified. Figure 18 shows the temperature profile of lead part only showing after one hour into post-fire.

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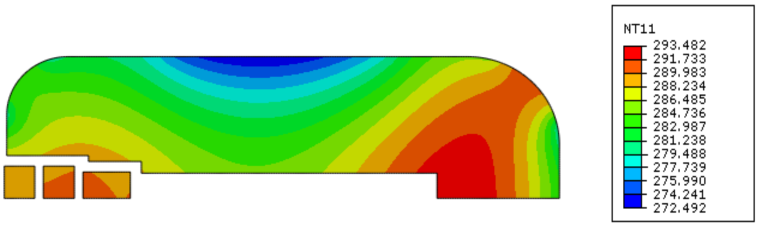

Fig. 18. Temperature Profile in Lead after 60 Minutes into Post Fire

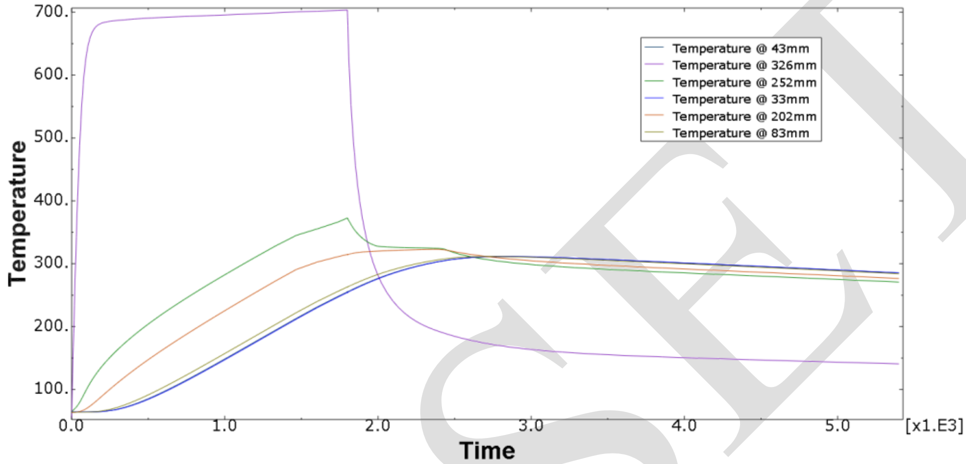

Fig. 19. Temperature Profiles in Cask along Line AB

Figures 19-20 show the temperature variations across line AB and line CD during fire and post fire. Here, AB and CB lines are taken as shown in figure 2. The temperatures correspond to each of the different finite elements along AB and CD, taken with respect to time.

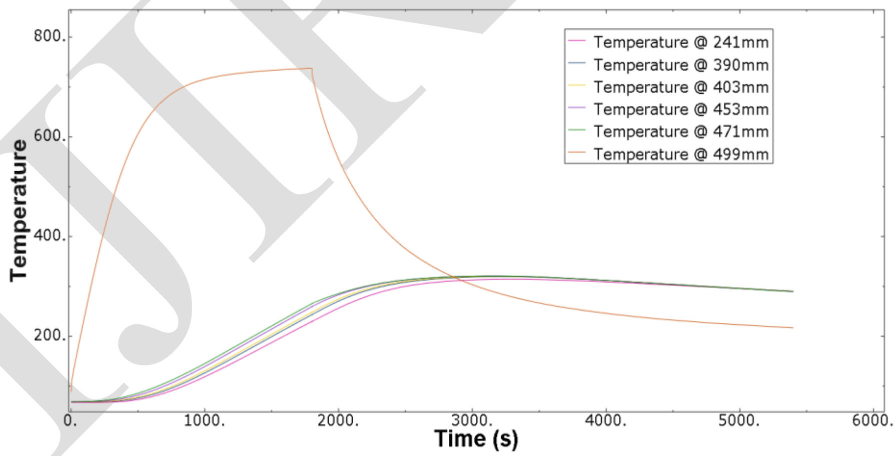

Fig. 20. Temperature Profiles in Cask along Line CD

IV. CONCLUSION

A finite element numerical assessment was carried out to access the temperature variations in cask at various conditions, and temperature distributions were evaluated for these different conditions including fire test. Without solar insolation, the maximum temperature in the cask was found to be 42.1°C which is well within the acceptable limits for type B(U) package., and with solar insolation, the maximum temperature was found to be 87.7°C. The maximum temperature was

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found to be 775.8°C on package surface and 768.1°C on cask surface during fire test. The temperature profiles of lead part only depicting molten lead were shown. And it was derived that after approximately 34 minutes of cooling, all the lead in cask gets solidified.

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