Comparison of HEATING Calculations with Furnace Test Results of ES-2M Package

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ABSTRACT
Thermal analysis of the ES-2M package has been conducted by using the HEATING computer code for both Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC). Good agreement was obtained between the HEATING calculations under NCT and the analysis reported in the Safety Analysis Report for Packaging (SARP). Prediction of the temperature history and the maximum temperatures of various components of the package agree very well with the results of the furnace test of an undamaged package under HAC.

I. INTRODUCTION
The ES-2 is a multiconfiguration, Type B fissile material package [1]. It uses a castable refractory material (Kaolite 1600™) as the primary impact limiter and thermal insulation. The ES-2 confinement vessel is based on a 208-liter (55-gallon) stainless steel drum. The three inner containers of the ES-2 package are designated as small (S), medium (M), and large (L). This arrangement permits three single-, two double-, and one triple-containment configurations. Currently, the ES-2M is being certified for transporting highly enriched uranium (HEU) metal cylinders. One ES-2M unit was thermally tested in a furnace to simulate a fire in an undamaged condition. This undamaged unit was equipped with 20 internal thermocouples, 10 on the inner liner and 10 on the containment vessel. The thermocouples were used to both verify the reading of the temperature-indicating labels and to provide a temperature history for the package.

In this paper, we describe the results of the ES-2M package thermal analysis that used the HEATING computer code [2] with appropriate boundary conditions. The analysis covered both the Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC). The HEATING calculation results are then compared with the Safety Analysis Report for Packaging (SARP) of ES-2M [3]. The major objective of this work was to validate the HEATING calculations with the data and analysis presented in the ES-2M SARP.

II. Normal Conditions of Transport (NCT)

Steady-state calculations were made for three types of boundary conditions. The first was for steady-state analysis in the shade, the second for steady-state analysis under the sun, and the third used alternating sun/shade boundary conditions until quasi-steady state was reached. The result of the shade analysis was used to determine the maximum surface temperature for exclusive or nonexclusive shipment; it was also used as the input (initial conditions) to the transient analysis for the HAC analysis. The steady-state analysis under the sun was used to determine the maximum temperatures and temperature gradients of the package under HAC because the transient solution of HAC approaches the steady-state solution under the sun. The quasi-steady state solution with periodic boundary conditions was used to determine the maximum temperature of the package under NCT.

II.1 Steady-State Analysis in the Shade

The geometry and materials in the model are shown in Fig. 1. The model is two-dimensional (r and z) and the drum is assumed to be in the vertical position. A total of 621 nodes were employed in the model. The heat generation rate in the content was 0.1042 w and the environment temperature was assumed to be 38°C (100°F). Because the heat generation rate was so low, the steady-state temperature distribution was fairly uniform and very close to the environmental temperature of 37.8°C (100°F). The calculated maximum external surface temperature was equal to the environmental temperature of 37.8°C (100°F) and the calculated maximum internal temperature was 38.1°C (100.6°F). Therefore, the temperatures of all accessible surfaces of the package were well below 50°C (122°F) and the package satisfies the requirement for nonexclusive shipment. This conclusion agrees with that of the SARP.

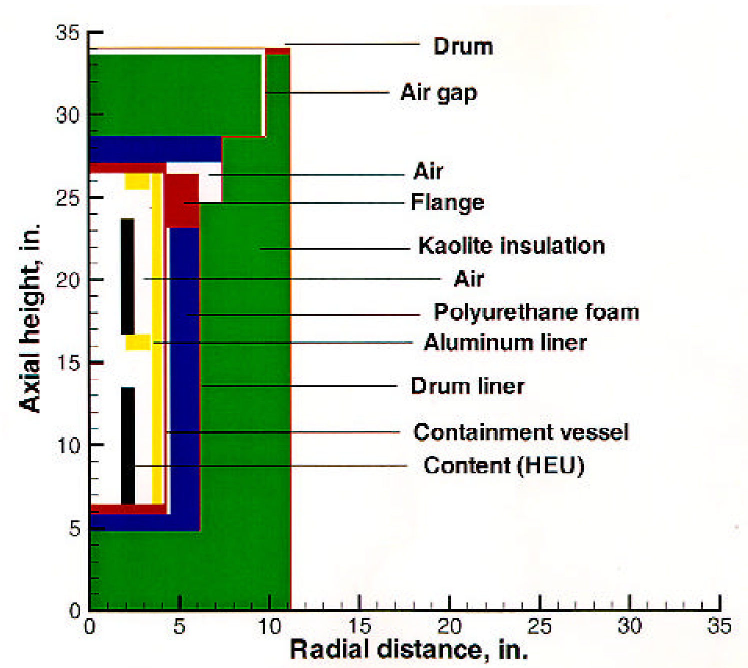

Figure 1. Geometry and materials of ES-2M package modeled in HEATING calculations

II.2 Steady-State Analysis under the Sun

The analysis under the sun was similar to that of Section II.1 except that the surfaces of the package were subjected to insolation specified in 10 CFR 71.71 (c),(1). The environment temperature was 37.8°C he free convection condition (10 CFR 71.71 calls for still air, which means that no forced convection) was assumed on the external surfaces of the package.

This analysis was conducted because it is the final solution for HAC. If the fire stopped and the package was allowed to cool under the sun, it would eventually approach the solution of steady state under the sun. Therefore, the solution obtained here is the final steady-state solution of HAC. For NCT under the sun, 10 CFR 71.71(C) specifies the value of insolation for a period of 12 h. For most packages, 12 h is not enough to reach steady state. Therefore, one should also carry out the quasi-steady-state/transient analysis with alternating sun/shade boundary conditions for NCT. The 12-h transient analysis for NCT is not conservative because it did not even reach the quasi-steady state (periodic). One should conduct the calculation for several cycles to approach quasi-steady state. This is done in Section II.3 of this paper.

For steady-state analysis under the sun, the calculated maximum drum temperature was 127.4°C (261.4°F), at the top center of the drum. The minimum drum temperature was 49.6°C (121.3°F), at bottom center of the drum (there is no insolation at the bottom of the drum). The flange, where the O-ring seal is located, had a temperature of 98.2°C (208.8°F). To check that the maximum temperature is calculated correctly at the top of the drum, one can apply an energy balance at steady-state condition. Assuming that insolation (Q) is balanced by the combined radiative and natural convection heat transfer,

$$Q = \sigma\, \varepsilon\, (T^4 - T0^4) + a\, (T - T0)^{(1+b)}\ .$$

Substituting the appropriate numbers ($Q = 4.740\text{e-}4$ Btu/in^2-s, $\sigma = 3.306\text{e-}15$ Btu/in^2-s-F^4, $\varepsilon = 0.15$, T0 = 100°F, a = 4.224e-7, and b = 0.333) in the above equation, we can calculate the surface temperature T and the result is T = 130°C (266°F). The result from the HEATING calculation is T = 127.4°C (261.4°F) at the top surface of the drum. This hand calculation is an overestimate of the temperature because we neglected conduction heat transfer in the radial and the axial directions.

Figure 2 shows the calculated radial temperature distribution at four different elevations (Z = 0.0 cm [0.0 in.] is at the bottom of the drum, Z = 42.4 cm [16.7 in.] is near the mid-plane, Z = 64.8 cm [25.5 in.] is at the elevation where the flange is located, and Z = 86.4 cm [34.0 in.] is at the top of the drum). The radial temperature gradients at the bottom and the top of the drum are in opposite directions. This is because the top surface is exposed to an insolation greater than that of the side surface and that the bottom of the drum is totally shielded from solar heating. The radial temperature gradients at the mid-plane and near the flange (where the O-ring is located) are very small.

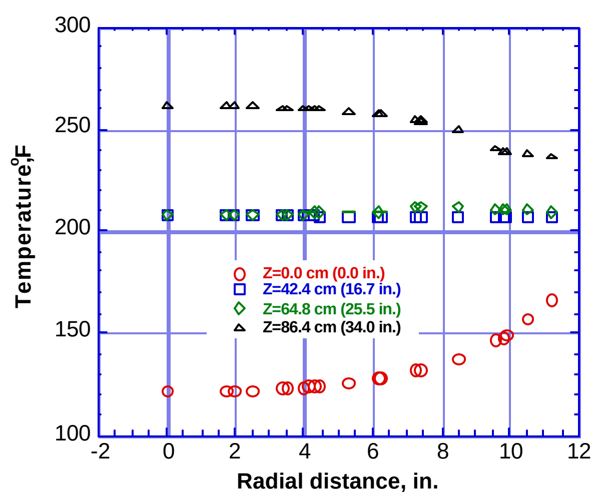

Figure 2. Calculated radial temperature distributions at different elevations of ES-2M package for steady-state analysis under the sun (NCT)

II.3 Transient (Quasi-Steady State) Analysis

The previous analysis was a 12-h transient calculation under the sun. The quasi-steady state calculation, which is more appropriate, assumes that the package is subjected to insolation for 12 h and no insolation for the next 12 h until quasi-steady state is reached.

For the 12-h transient calculation, the maximum drum temperature was 125.3°C (257.5°F) and the maximum containment vessel temperature (including the O-ring seal location) was 58.7°C (137.6°F). As expected. these temperatures are somewhat lower than those of the steady-state solution described in Section II.2, in which the maximum drum temperature was 127.4°C (261.
containment vessel temperature was 98.2°C (208.8°F). The drum external temperatures of these two cases were quite similar because the drum surface heats up quickly in both cases. However, the interior of the package (the containment vessel) heats up much more slowly and the temperature difference is great between the steady state and at the end of 12 h. As mentioned previously, the 12-h transient calculation is not conservative because it did not reach the quasi-steady state condition, which is more realistic in an actual environment.

Figure 3 shows the calculated temperature history of the package external wall, liner, and containment vessel for the quasi-steady state calculation. The drum external temperature reached quasi-steady state in about two days (172,800 s). But the interior components (the liner and the containment vessel took more than 5 days (432,000 s) to reach quasi-steady state. The maximum temperature of the drum external surface was 126°C (258.8°F) and the maximum temperature of the containment vessel was 75.0°C (167.0°F). As expected, these temperatures are somewhat lower than those obtained for steady state under the sun, where the maximum temperature of the drum external surface was 127.4°C (261.4°F) and the maximum temperature of the containment vessel was 98.2°C (208.8°F).

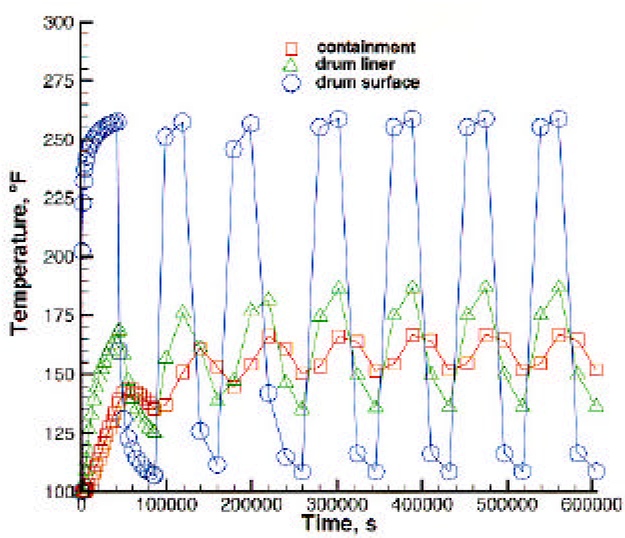

Figure 3. Calculated temperature history of various components of ES-2M package under quasi-steady-state (periodic) boundary conditions (NCT)

II.4 Cold Conditions

The cold condition under NCT is determined according to 10 CFR 71.71 (c),(2). The package is subjected to an environment temperature of -40°C (-40°F) in still air and shade. The package will reach the equilibrium temperature of -40°C (-40°F). This conclusion is conservative because the low heat generation rate in the content is neglected.

II.5 Comparison of Calculated Temperatures with SARP Results under NCT

Thermal evaluation of the NCT in the SARP is also by analysis. The calculation was performed by using the P/THERMAL 5.0 computer code [4]. The peak temperature was 236.2°F (113.4°C), at the top of the drum. The peak temperature of the containment vessel was near the O-ring location (in the flange area) and was 164.8°F (73.8°C). Both of these temperatures were somewhat lower than that of the quasi-steady-state solution obtained from the HEATING calculation. Several details in the model (such as convective heat transfer coefficient, emissivity, and material properties) may account for the differences between the HEATING calculations and the SARP results. The important conclusion is that both analyses show that the O-ring seal temperature did not exceed the allowable temperature of 250°F (121.1°C) during extended service. A summary of the comparison is shown in Table 1.

Table 1. Comparison of calculated temperatures from HEATING with SARP results under Normal Conditions of Transport

Parameter	SARP	HEATING	Allowable
Minimum package temperature, °C (°F)	-40 (-40)	-40 (-40)	-40 (-40)
Maximum drum temperature, °C (°F)	113.4 (236.1)	126.0 (258.8)	-----
Maximum containment temperature, °C (°F)	73.8 (164.8)	75.0 (167.0)	148.9 (300.0)
Maximum O-ring temperature, °C (°F)	73.8 (164.8)	75.0 (167.0)	121.1 (250.0)

III. Hypothetical Accident Conditions (HAC)

In the ES-2M package SARP, test results for Hypothetical Accident Conditions were described. Test units 1 and 2 were drop-tested before the fire test. Test unit 3 was not drop-tested and represents the fire test of an undamaged package. A number of internal thermocouples were used to measure the drum liner and the containment vessel temperatures for test unit 3. The results from test unit 3 provide useful data for comparison with the analysis. Thermal tests under HAC were conducted in a furnace to simulate the fire. After the fire, the package was left in the rack to cool naturally without insolation. Because the more recent guideline calls for the package to cool with insolation after the fire, heating calculations were carried out first for the fire and then for the package to cool both in the shade and under the sun. This latter case is more conservative and will be used to determine the maximum temperatures of the undamaged package. However, for comparison with experimental results, the analysis from cooling in the shade is employed because it is identical to the experimental condition.

Figure 4 shows calculated external drum temperatures at various locations. It shows that the drum surfaces heat quickly to the fire temperature of 800°C (1472°F) and that the temperatures of these surfaces remain close to 800°C for the duration of the fire (30 min). Immediately after the fire, the surface temperatures begin to drop sharply; 30 min after the fire, most of the surface temperatures have dropped to about 150°C (300°F). The results shown in Fig. 4 compare favorably with those from the furnace test reported in the SARP.

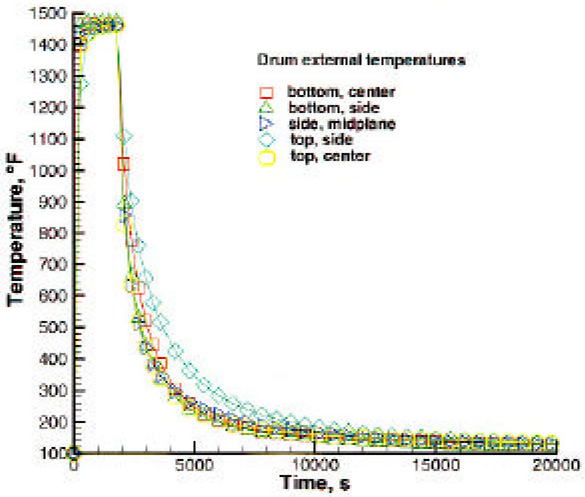

Figure 4. Calculated temperature history at various locations on drum surface under HAC

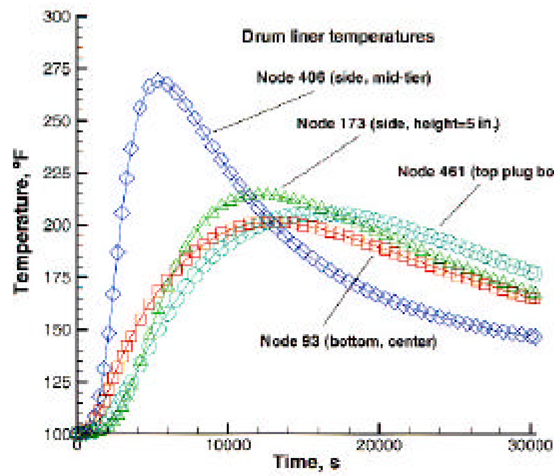

Figure 5. Calculated temperature history at various locations on drum liner under HAC

Figure 5 shows the calculated temperatures of the inner liner of the drum at various locations. With the exception of node 406, most liner locations reached a maximum temperature of 93-102°C (200-215°F) in about 200 min (12,000 s). Node 406 is located at a higher elevation, where the Kaolite insulation is thinner than that at lower elevations (based on the three-tiered configuration of the Kaolite). This is why node 406 showed a higher maximum temperature in a shorter time than did other liner locations. Figure 5 also shows that for the first 30 min (1,800 s) of the test when the package is subjected to a fire of 800°C, the liner temperatures at various locations changed very little. This is because in such a short time, the heat from the fire had not yet propagated to the liner. The characteristic time of thermal diffusion is $\tau = \alpha / w^2$, where w is the characteristic length of the system and α is the thermal diffusivity of the material. The Kaolite thickness is approximately w = 12.8 cm (5 in.) and the Kaolite has a thermal diffusivity of $\alpha = 3.40 \times 10^{-7}$ m^2/s. Substituting these values into the above equation, we found that $\tau = 48{,}188$ s (803 min). This characteristic time is one order of magnitude greater than the duration of the fire (30 min). Therefore, during the fire, the liner and its contents (including the containment vessel) should show very little increase in temperature. This is exactly what happened and is confirmed by the calculations. The test result showed that the peak liner temperatures occurred at less than 100 min, instead of the 200 min calculated by HEATING. The probable reason for this is that the package was heated above 800°C (1472°F) for more than 30 min during the test. However, most of the maximum liner temperatures were in the range of 210-215°C in the test, very close to the calculated maximum liner temperature range of 200-215°C.

Figure 6 shows the calculated temperatures of the containment vessel at various locations (including the flange where the O-ring seal is located). The maximum containment temperatures at various locations were 66.6 to 68.9°C (152 to 156°F), reached in about 28,000 s (466 min). The time required to reach maximum temperature for the containment is, of course, longer than that for the liner, because the polyurethane foam between the liner and the containment vessel also provided a thermal barrier through which the heat must pass before reaching the containment vessel. The measured temperatures showed strong asymmetric effect. Maximum containment temperature varied from 61.1 to 67.8°C (142 to 154°F), and the time to reach maximum temperature varied from 180 to 450 min. The smaller time constant of the test compared to that of the calculation is most likely due to the effect of overheating the package in the furnace. However, the range of measured maximum temperature of 61.1 to 67.8°C is very close to the

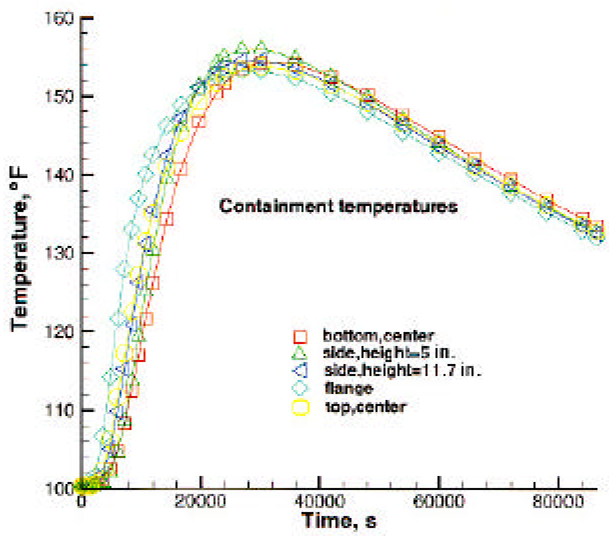

Figure 6. Calculated temperature history at various locations on containment vessel under HAC

Table 2 is a summary of the comparison of the calculated maximum temperatures with the test results of the undamaged package under Hypothetical Accident Conditions. It can be observed that the calculated maximum temperatures of various components agree very well with the results from the furnace test.

Table 2. Comparison of calculated temperatures with furnace test results of undamaged package under Hypothetical Accident Conditions

Parameter	Furnace test	Heating calculation
Maximum drum surface temperature,* °C	815.5 - 843.3	796.0 - 799.0
Maximum liner temperature, °C	210.0 - 215.0	200.0 - 215.0
Maximum containment temperature, °C	61.1 - 67.8	66.6 - 68.9

*In the furnace test, the surface of the package was heated (conservatively) above 800°C.

SUMMARY

Thermal analysis of the ES-2M package was carried out by using the HEATING computer code. The analysis covers both the Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC). Table 1 summarizes the results of HEATING calculations under NCT and the results reported in the SARP by using the computer code P/THERMAL 5.0. In general, agreement is good between HEATING and P/THERMAL 5.0 calculations. Relatively small differences between the results of these two calculations may be caused by the differences in several parameters employed in the models (such as convective heat transfer coefficient, emissivity, and material properties).

The results of HEATING calculations under HAC are compared with the results of furnace testing reported in the SARP. One ES-2M unit was thermally tested in a furnace to simulate a fire in an undamaged condition. This undamaged unit had been equipped with 20 internal thermocouples, 10 on the inner liner and 10 on the containment vessel, that provided not only maximum temperatures but also the temperature history for the package. The predicted temperature history at various locations of the package (Figures 4 to 6) compares favorably with the results of the furnace test. Calculated maximum temperatures at various locations of the package agree very well with the results of the furnace test (Table 2).

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