THERMAL ANALYSIS OF REGULATORY FIRE CONDITIONS ON A TRANSPORT PACKAGE FOR RADIOACTIVE MATERIAL

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By

Jefrey Ramsay
MDS Nordion Inc.
447 March Road
Ottawa, Ontario
Canada, K2K 1X8
Ph: (613) 592-3400 ext. 2044
Fx: (613) 591-6934
Jramsay@mds.nordion.com

ABSTRACT

MDS Nordion, a division of Canadian-based MDS Inc., maintains and operates transport packages for the distribution of radioactive materials used in the medical, sterilization and pharmaceutical industries. Each of these packages must be proven to meet international regulatory standards, often including the analysis of the packages under accident fire conditions. Actual physical fire tests are costly and time consuming. Therefore, it is beneficial to simulate such fire tests with numerical models validated against previous tests.

This paper describes the thermal simulation of the IAEA TS-R-1 regulatory fire conditions (800°C fire for a period of 30 minutes and left to cool naturally in the heat of the sun) on a transport package using the ANSYS finite element code. The analyzed transport package is a steel-encased cylindrical lead-filled radiation shield welded to a support frame. A cylindrical cavity in the center of the shield, sealed by a lead-filled shielding plug, holds the radioactive material. The radiation shield is wrapped in thermal insulation, which is held in place by wire mesh.

A two-dimensional, axi-symmetric model was developed to simulate the thermal behavior of the transport package during and after the regulatory fire. Mechanical deformations and stresses induced from the temperature distributions in the package are not considered in this paper. The mesh (solid model, radiation enclosure calculations, convection and radiation elements), material

properties (non-linear), boundary conditions (radiation and convection) and loading (thermal transient, heat generation) used in the ANSYS simulations are discussed. Test data from physical steady state and transient fire tests was used to develop and validate the model. The finite element model was then used to predict and evaluate the response of the package to the TS-R-1 fire transient.

INTRODUCTION

MDS Nordion, a division of Canadian-based MDS Inc., maintains and operates transport packages for the distribution of radioactive materials used in the medical, sterilization and pharmaceutical industries. Each of these packages must be proven to meet international regulatory standards, often including the analysis of the packages under accident fire conditions. Actual physical fire tests are costly and time consuming. Therefore, it is beneficial to simulate such fire tests with numerical models validated against previous tests.

This paper describes the thermal simulation of the IAEA TS-R-1 [1] regulatory fire conditions (800°C fire for a period of 30 minutes and left to cool naturally in the heat of the sun) on a transport package using the ANSYS finite element code [2]. Test data from physical steady state and transient fire tests was used to develop and validate the model. Mechanical deformations and stresses induced from the temperature distributions in the package are not considered in this paper.

The analyzed transport package, shown in Figure 1, is a steel-encased cylindrical lead-filled radiation shield welded to a support frame. A cylindrical cavity in the center of the shield, sealed by a lead-filled shielding plug, holds the radioactive material. The radiation shield is wrapped in thermal insulation, which is held in place by wire mesh.

FINITE ELEMENT MODEL

A two-dimensional axi-symmetric finite element model of the major components of the transport package was constructed, using the ANSYS finite element code, as shown in Figure 2. The density of the finite element mesh was selected to ensure convergence of the solution. When subjected to the regulatory drop tests, the major components of the packaging sustained no significant damage. Therefore, the package was modeled in the undamaged condition. The cavity was modeled as a material with a high thermal conductivity and low density, such that it would not retain heat or affect the heat balance. The heat generation from the sources, when required, was applied to these elements. Temperature dependent material properties for the lead and steel (thermal conductivity, specific heat and density) were taken from reference [3]. The properties for the insulation will be discussed in the following sections.

The heat flow within the package was assumed to be entirely by conduction. The heat flow on the outside of the package was assumed to be through radiation and convection.

The normal conditions of transport heat transfer coefficient for convection, Hnc, was calculated from reference [3], using steady state experimental data of the fully loaded package, as,

$$Hnc = 0.95(\Delta T)^{0.333} = 0.95(2)^{0.333} = 1.2 \text{ W/m}^2{}^\circ\text{C}$$

The accident conditions of transport heat transfer coefficient for convection, Hac, was calculated from reference [3] as,

$$Hac = k/D * C\,(uD/\nu)^n Pr^{0.333}$$

Where: D is the outside diameter of the transport package = 0.774 m
C, n are constants that depend on the Reynold's number (= uD/ν)
k = thermal conductivity of the fluid
ν = kinematic viscosity of the fluid
Pr = Prandtl number for the fluid
u = free stream velocity=10 m/s according to regulatory advisory material

The property values of k, ν and Pr are evaluated at the film temperature, which is defined as the mean of the wall and free stream fluid temperatures. At the start of the fire, the outside insulation temperature is assumed to be 40°C, based on the temperature differential from ambient in the steady state experiments and the ambient temperature required by the regulations (38°C). The film temperature is, therefore, (800+40)/2 = 420°C. From reference [3] the property values are k = 0.052 W/m°C, ν = 6.5e-5 m^2/s and Pr = 0.684. This yields a Reynold's number of about 120,000. At this Reynold's number, the constants C and n are 0.0266 and 0.805, respectively [3]. Substituting these values into the equation above yields,

$$Hac = 0.052/0.774 * 0.0266 * (10*0.774/6.5e\text{-}5)^{0.805}*(0.684)^{0.333} = 19 \text{ W/m}^2{}^\circ\text{C}$$

After the fire an average value of the before and during heat transfer coefficients was used, (1.2 + 19)/2 = 10 W/m^2°C.

The emissivity of the outside surface was assumed to be 1.0. The view factor was also assumed to be 1.0 to maximize the radiation heat transfer, worst case for accident conditions of transport.

LOAD CASES

Three load case scenarios were simulated as follows.

1. Simulation of Steady State Physical Test

   This load case was used to determine the steady state behavior of the model. The simulated results were matched against steady state temperature measurements from a physical experimental test with radioactive material loaded into the transport package. No solar load was applied as the test was conducted indoors.

The ambient temperatures on the outside of the package from the experimental test data were used in the simulation. The thermal conductivity of the insulation covering, taken from the manufacturer's specifications, was adjusted by a constant factor until the inside and outside temperature of the container matched those in the experiment. This was required since the insulation is not perfectly applied as it is in the model, resulting in more heat transfer in reality than would occur in the model where the insulation completely isolates the container from outside conditions.

2. Validation Against Physical Fire Test

Once the insulation properties were obtained from the steady state simulation, the fire transient shown in Figure 3 was applied to the model and the results compared to temperature measurements from a previous experimental test of the package subjected to this fire transient. For the physical fire test, no radioactive material was used inside the transport package, and no solar load was applied as the test was conducted indoors. The initial conditions for the simulation were taken from the physical test data.

3. Simulation of IAEA TS-R-1 Regulatory Fire Transient

Finally, the IAEA TS-R-1 regulatory fire transient (Figure 3) and pre and post fire conditions were applied to the model. An internal heat generation corresponding to 26,000 Ci of cobalt was applied throughout the transient and an insolation load of 800 W/m^2 was applied after the end of the fire (30 minutes into the transient). Solar loading was applied during the cool-down period after the 30 minute, 800°C fire. Initial conditions and ambient temperatures were set as per the regulations

RESULTS AND DISCUSSION

1. Simulation of Steady State Physical Test

As discussed above, this simulation was performed to determine the thermal conductivity of the insulation covering required to correctly balance the heat within the package.

2. Validation Against Physical Fire Test

The temperature transient calculated on the outside of the steel (inside the insulation) is shown in Figure 4 and is compared to that measured in the physical test at a similar location. The results show that the model bounds the experimental temperature transient in the critical part of the transient and, therefore, provides a conservative estimate of the container surface maximum temperature.

3. Simulation of IAEA TS-R-1 Regulatory Fire Transient

   The calculated temperature transient on the outside of the steel is shown in Figure 5. The maximum lead shielding temperature reached in the simulated IAEA TS-R-1 fire was 260°C, well below the melting temperature of lead, 327°C. MDS Nordion requires that there be no lead melt in the transport package during or after the fire. Note that, coincidentally, this temperature is almost exactly the same as the maximum temperature reached in the previous experimental fire test (Figure 4). This occurs because the thermal conductivity of the insulation increases with temperature. Consequently, more heat is transferred to the package by conduction through the insulation in the previous fire test where the ambient temperatures were higher (up to 870°C). This results in about the same maximum temperature being reached even though the temperature did not reach 800°C until 15 minutes into the transient.

CONCLUSION

Test data from a steady state and a transient fire test was successfully used to develop and validate a finite element model to predict and evaluate the behavior of a transport package subjected to the IAEA TS-R-1 regulatory fire test. Good agreement between the experimental measurements of the transport package and the simulation results was obtained. The results of the simulated IAEA TS-R-1 regulatory fire test on the transport package showed no temperatures in the lead shielding above the melting point of lead, a requirement for all MDS Nordion transport packages during or after the fire.

REFERENCES

1. IAEA Safety Standard, Safety Series No. TS-R-1 (ST-1 Revised), "Regulations for the Safe Transport of Radioactive Material", 1996 Edition.

2. "ANSYS User's manual, Revision 5.5, ANSYS Inc., Houston, PA, 1998.

3. Holman, J.P., "Heat Transfer", McGraw-Hill Book Company, 5th Edition, New York, 1981.

FIGURES

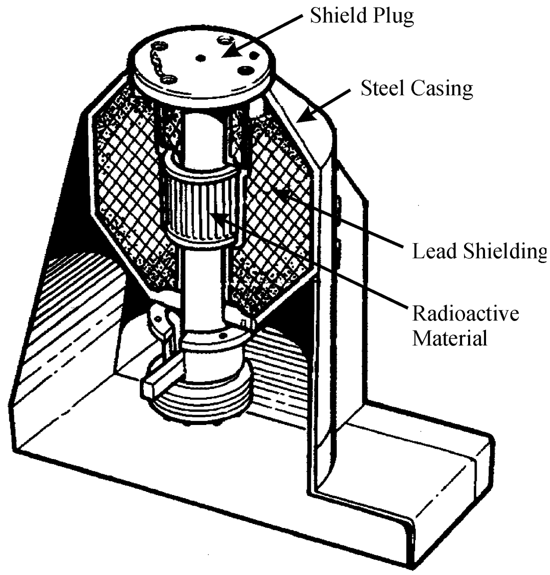

Figure 1
Transport Package
(Jefrey Ramsay – MDS Nordion)

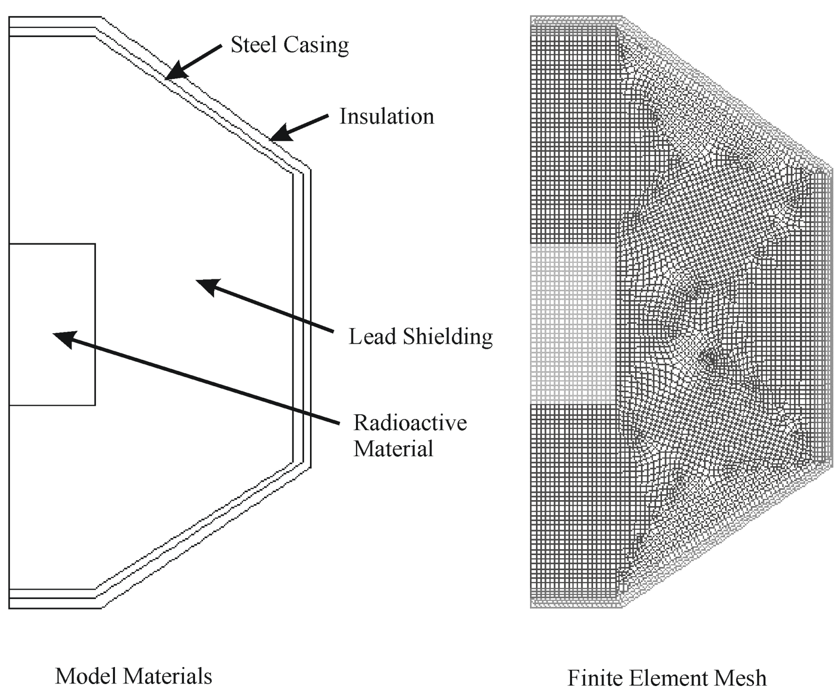

Figure 2
Transport Package Two-Dimensional Axi-Symmetric Finite Element Model
(Jefrey Ramsay – MDS Nordion)

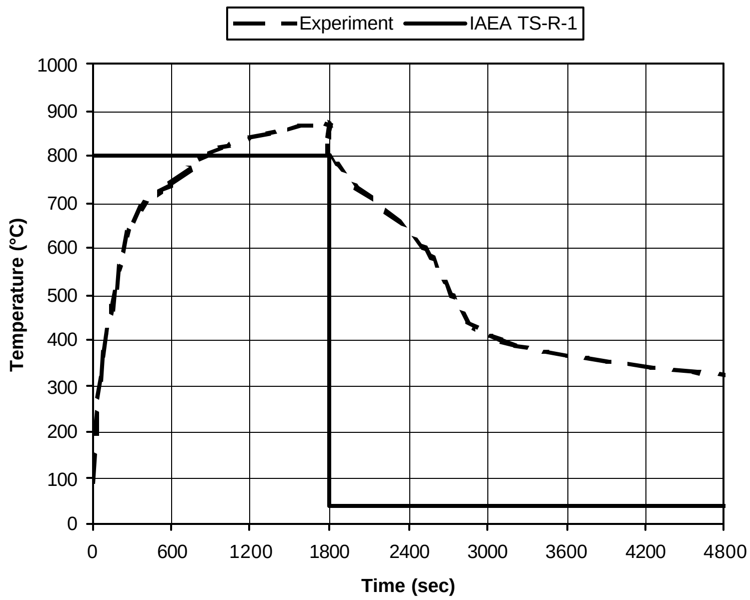

Figure 3
Experimental Fire Transient and
IAEA TS-R-1 [1] Regulatory Fire Test Transient
(Jefrey Ramsay – MDS Nordion)

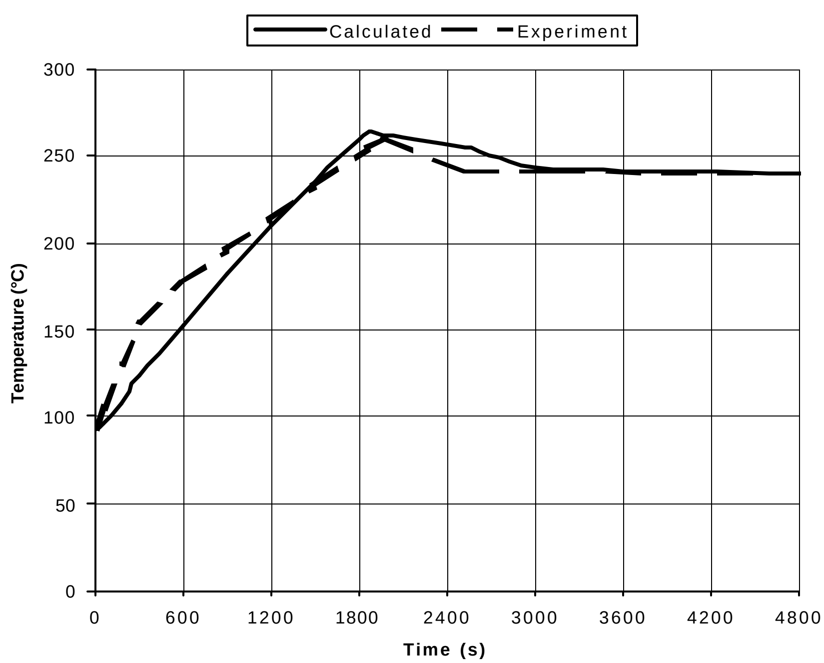

Figure 4
Calculated and Experimental Temperature Transient on Outside Surface of Transport Package

(Jefrey Ramsay – MDS Nordion)

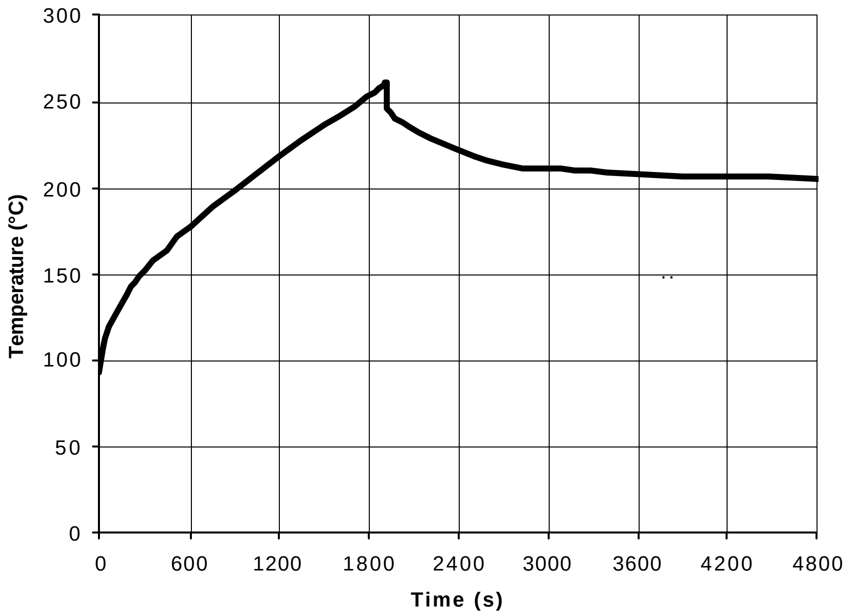

Figure 5
Calculated Temperature Transient on Outside Surface of Transport Package for IAEA TS-R-1 [1] Fire Transient
(Jefrey Ramsay – MDS Nordion)