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A TRANSIENT THERMAL ANALYSIS OF A SPENT FUEL TRANSPORTATION CASK UNDER SEVERE FIRE ACCIDENT

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Abstract*. All casks that contain radioactive materials must be evaluated to determine their expected normal operating temperatures and their responses to the accident conditions specified in the IAEA and domestic regulations. The main conditions the cask should satisfy, mainly by test, to be qualified are: a Hypothetic Accident Conditions – HAC - 9 m drop tests, a 30 min HAC thermal testes under 800 ^{o}C and a variety of leak tests including 10 m immersion tests; this work will focuses the thermal analysis. There are two approaches for evaluating the safety implications of a cask engulfed in a fire: the first is by experimental investigation and the second by numerical modeling. The former is clearly hazardous in nature, while the latter is safe, but must be verified against experience with controlled experiments. An issue of significant concern in nuclear area is the capability of compute codes to model pertinent physical phenomena without requiring extensive use of computer resources. In this work, specific conditions were imposed on a cask to evaluate the ability of a popular heat-transfer code, specifically, ANSYS code, to simulate realistic physical problem. The prototypic cask configuration consists of several different annular regions: Region I contains a volumetric heat source simulating irradiated fuel decay; Region II is a monolithic cask wall; Region III is a voided neutron shield; and Region IV is the thermal radiation shield. Regions II and IV exchange heat solely by thermal radiation. Heat is also exchanged with the surrounding environment from Region IV by thermal radiation. For simplicity, all surfaces and the environmental are assumed to be black. To simulate exposure of a cask to the regulatory fire three analyses were performed; first a steady-state solution, with radiant heat loss to a 54.4 ^{o}C environment was calculated; second, using the steady-state solution for the initial conditions, the fire was simulated by an increase in the ambient temperature to 800 ^{o}C for 30 min. The third analysis involved a cool-down period of 60 min following the fire as the ambient temperature returned to 54.4 ^{o}C. The main results are: (1) In the steady-state case the results of the numerical analysis agree well with the expected results; (2) In the 800 ^{o}C – 30 min the increase in temperature on the interface between Regions I and II of the cask was 4 % higher than the expected results; (3) In the cool-down period, the temperature on the interface between Regions II and III was 5 % higher than expected results*

Keywords*: cask, fire, thermal analysis, hypothetical accident condition, ANSYS*

1. INTRODUCTION

The cask used to transport radioactive materials is designed to maintain its integrity under the 800 ^{o}C – 30 min fire resistance test condition. There are two approaches for evaluating the safety implications of a cask engulfed in a fire: the first is by experimental investigation and the second by numerical modeling. An issue of significant concern in nuclear area is the capability of compute codes to model pertinent physical phenomena without requiring extensive use of computer resources. In this work, specific conditions were imposed on one cask configuration to evaluate the ability of a popular heat-transfer code, the ANSYS code, to simulate realistic physical problem.

2. THERMAL PROBLEMS

The NRC regulations, given in 10 CFR Part 71, define a thermal event as " exposure of the hole specimen for not less than 30 minutes to a heat flux not less than that of a radiation environment of 800 ^{o}C with a emissivity coefficient of at least 0.9. For purposes of calculation, the absortivity must be either that value which the cask may be expected to possess if exposed to a fire or 0.8, whichever is greater".

To model completely the thermal event requires simulating conduction, convection, and radiation (Glass, 2001); the problem included in this work will exercise these facets of the code. Additional phenomena, such as phase change and boiling-water heat transfer, are not included in this problem set.

2.1. Model A

Model A, which is shown in Fig. 1, is based on a prototypic cask configuration consisting of several different annular regions. Region I contains a volumetric heat source simulating irradiated fuel decay heat. Region II is a monolithic cask wall, Region III is a voided neutron shield, and Region IV is the thermal radiation shield. Regions II and IV exchange heat solely by thermal radiation. Heat is also exchanged with the surrounding environment from Region IV by thermal radiation. For simplicity, all surfaces and environment are assumed to be black.

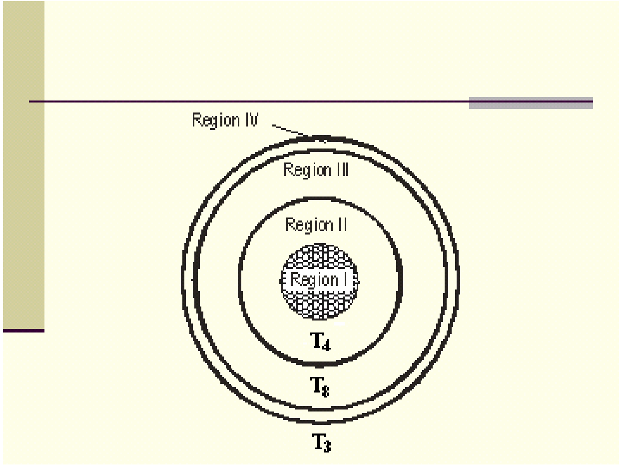

Figure 1. Model A – cask with annular regions (Glass, 2001)

The following problem simulates exposure of Model A to the regulatory fire and involves three analyses. First, a steady-state solution, with radiant heat loss to a 54.4 °C environment must be calculated; second, using the steady-state solution for the initial conditions, the fire is simulated by an increase in the ambient temperature to 800 °C during 30 minutes; the third analysis involves a cool-down period of 60 min following the fire as the ambient temperature returns to 54.4 °C. The geometric and thermal characteristics for Model A are given in Tab. 1.

Table 1. Model A – cask with annular regions: characteristics (Glass, 2001).

Characteristics	Region I	Region II	Region III	Region IV
Radius, r	16.51 cm	38.74 cm	53.98 cm	54.61 cm
Density, ρ	2707 kg/m^3	7832.8 kg/m^3		7832.8 kg/m^3
Specific heat, c_p	0.89×10^3 J/kg K	0.47×10^3 J/kg K		0.47×10^3 J/kg K
Conductivity, k	242 W/m K	45 W/m K		45 W/m K
Heat source, Q	38.32 kW/m^3			

3. RESULT ANALYSIS

3.1. Model A

This problem tests the ability of the code to simulate conduction and thermal radiation (Maxa, 2003). PLANE55 was used as plane element for thermal conduction capability; the element has four nodes with a single degree of freedom, temperature, at each node. For radiation analysis, the radiation link element LINK31 was used. This two-node element is used between nodes and requires specification of the area, form factor, and emissivity (Holman, 2002) as real constants. Heat generation rate was entered as element body load at the element one. The model was discretised using cylindrical coordinate system (Madenci and Guven, 2006); it was used seven elements and 11 nodes. The finite element grid is shown in the following Fig. 2 (Sacramento at al., 2008).

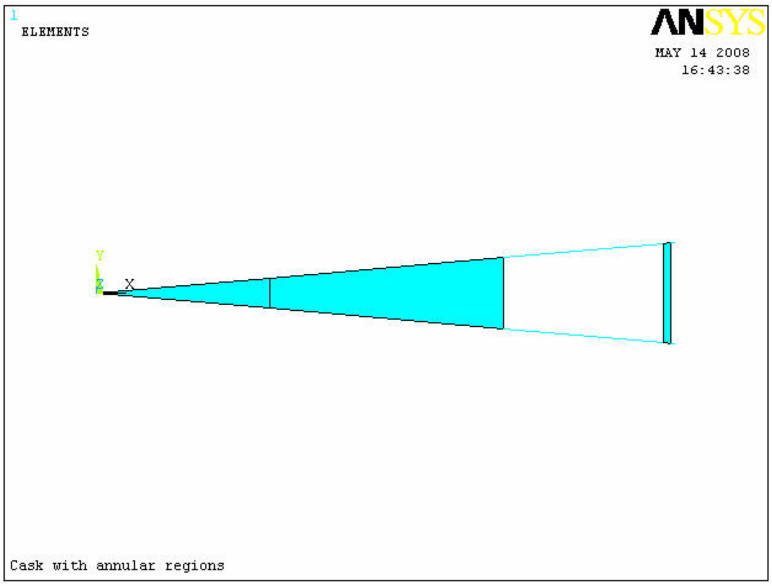

Figure 2. Domains for thermal analysis for the cask simulated with ANSYS

The temperature distribution of the cask is shown in Fig. 3; 213.6 ^{o}C is the temperature at the interface between Regions I and II; 204.3 ^{o}C is the temperature at the interface between Regions II and III, and 136.6 ^{o}C is the temperature at the outer surface. These calculated steady-state temperatures are used as the initial conditions prior to the start of the fire accident simulation.

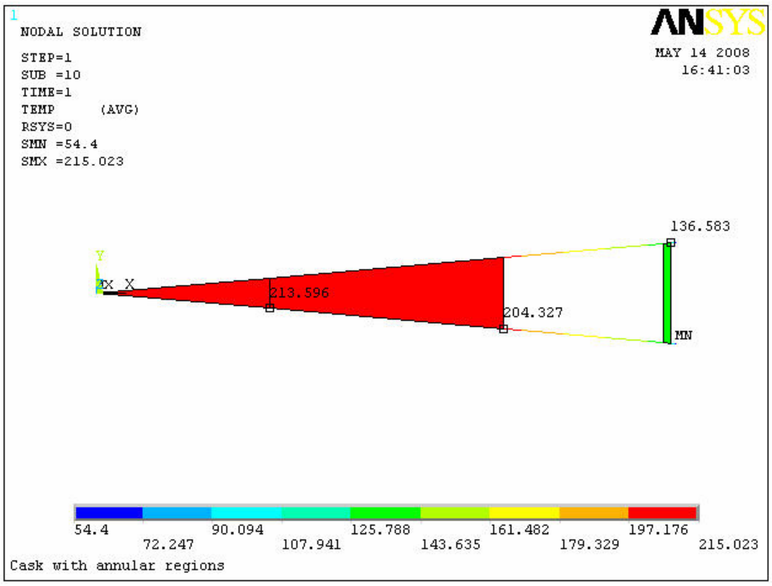

Figure 3. Temperature distribution of the cask simulated with ANSYS

The comparison of the numerical results, using finite element program ANSYS, and the expected results, revealed a very good agreement for the case involving conduction and thermal radiation; the results are given in the following Tab. 2.

Table 2. Model A – cask with annular regions: steady-state case results.

Position	TARGET Temperature (^{o}C)	ANSYS Temperature (^{o}C)	RATIO
T_4	214.0	213.6	1.00
T_8	204.0	204.3	1.00
T_3	137.0	136.6	1.00

For the 30 min transient case, the temperature range at the outer surface of the cask is shown in Fig. 4 bellow; the general trend of the temperatures in the model is similar to that found experimentally.

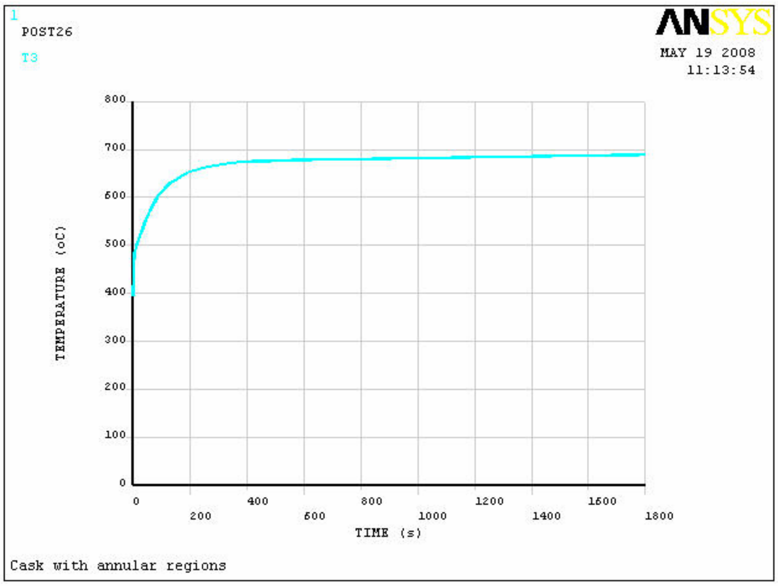

Figure 4. Temperature T_3 at cask surface versus time, simulated with ANSYS

The temperature distribution of the cask, for the 30 min transient case, is shown in the following Fig. 5; 274.4 ^{o}C is the temperature at the interface between Regions I and II; 375.7 ^{o}C is the temperature at the interface between Regions II and III, and 689.3 ^{o}C is the temperature at the outer surface.

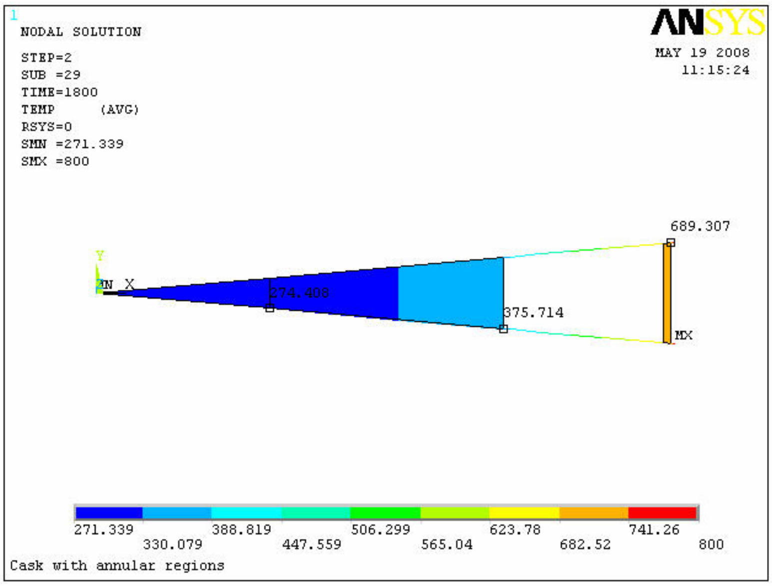

Figure 5. Temperature distribution of the cask simulated with ANSYS

The comparison of the numerical results using finite element program ANSYS and the expected results revealed also a very good agreement for the transient case; the results are given in Tab.3 below.

Table 3. Model A – cask with annular regions: transient case results, time = 30 min.

Position	TARGET Temperature (^oC)	ANSYS Temperature (^oC)	RATIO
T_4	263.0	274.4	1.04
T_8	376.0	375.7	1.00
T_3	689.0	689.3	1.00

For the 60 min transient case, the temperature range at the outer surface of the cask is shown in Fig 6 bellow; the general trend of the temperatures in the model is similar to that found experimentally.

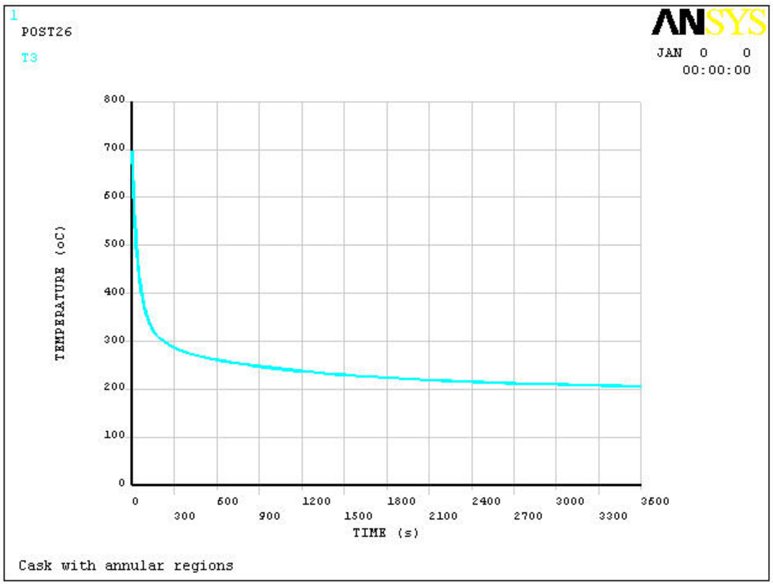

Figure 6. Temperature T_3 at cask surface versus time, simulated with ANSYS cool-down period

The temperature distribution of the cask, for the 60 min transient case, is shown in the following Fig. 7: 317.6 ^{o}C is the temperature at the interface between Regions I and II; 282.2 ^{o}C is the temperature at the interface between Regions II and III, and 205.8 ^{o}C is the temperature at the outer surface.

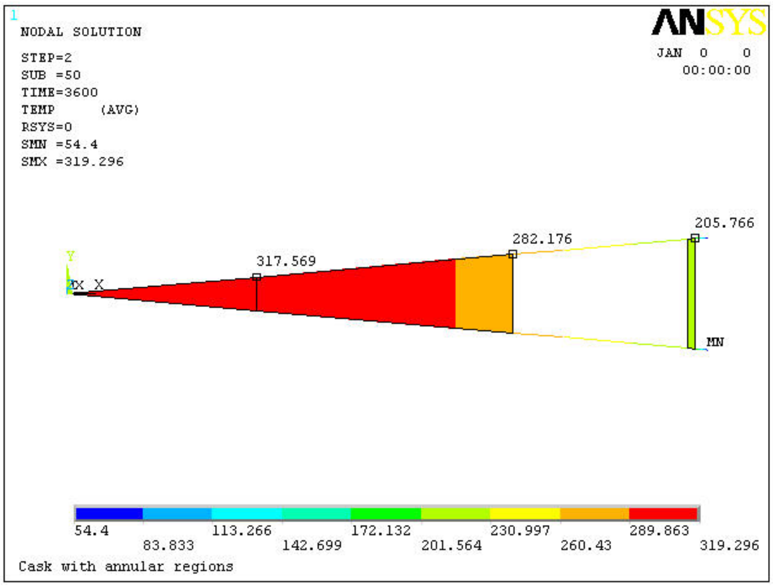

Figure 7. Temperature T_3 at cask surface versus time, simulated with ANSYS cool-down period.

The comparison of the numerical results using finite element program ANSYS and the expected results revealed also a very good agreement for the transient case; the results are given in Tab. 4 below.

Table 4. Model A – cask with annular regions: transient case results, time = 60 min.

Position	TARGET Temperature (^{o}C)	ANSYS Temperature (^{o}C)	RATIO
T_4	313.0	318.0	1.02
T_8	298.0	282.0	0.95
T_3	203.0	206.0	1.01

4. CONCLUSION

The purpose of this study was to create a computer model capable of predicting the thermal behaviour of a cask involved in a fire. To achieve this goal a 2D model, using the finite element code ANSYS, was developed. For the model, the peak centre temperature under steady-state conditions is determined by the heat generation rate and the thermal conductivity of the cask; during the 30 min of the fire, the change in center temperature is relatively small. However, the outer surface responds rapidly to exposure to the fire. In the steady-state case the results of the numerical analysis agree well with the expected results; in the 800 ^{o}C – 30 min the increase in temperature on the interface between Regions I and II of the cask was 4 % higher than the expected results; in the cool-down period, the temperature on the interface between Regions II and III was 5 % higher than the expected results. The analysis of the results, obtained by the present work, shows that ANSYS code presents sufficient ability to simulate thermal problems involving conduction and thermal radiation.

5. ACKNOWLEDGEMENTS

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