Thermal Analyses of a Generic Rail Cask Model and Thermal Response of a Test Article Using Different High-Temperature Boundary Conditions*

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INTRODUCTION

Over the past several years, there have been ongoing discussions about the attempt to compare the thermal hypothetical accident environment in 10CFR71, the Nuclear Regulatory Commission (NRC) regulations for the packaging and transportation of radioactive materials and the thermal qualification test conditions in 49CFR179, the Department of Transportation's (DOT) thermal insulation specifications for tank cars. This paper discusses the purposes and differences of each test environment and shows the relative magnitude of error that can occur when applying these regulations inappropriately.

The NRC regulations governing the packaging and transportation of radioactive materials are outlined in 10CFR71. The purpose of these regulations is to assure that the transportation cask is designed safely and will protect the public in the event of an accident. In order to meet 10CFR71, radiological criteria, such as radioactivity release and radiation levels external to the cask, are specified. Contained in these regulations are severe performance standards which outline sequential mechanical and thermal loads that the package must be designed to withstand. The sequential nature of the tests are an important consideration. By the time a package is subjected to the thermal environment, it may already have sustained a significant amount of structural damage. The regulations do not define allowable structural or thermal damage to the package; instead the cask integrity must maintain stringent containment, shielding, and criticality specifications.

The DOT regulations outlining the transportation specifications for pressurized tank cars are contained in 49CFR179. These regulations are the result of a series of rail accidents involving uninsulated pressure tank cars carrying flammable materials such as propane and butane (Federal Register, Vol. 42 1977). Based on the results of experiments with full size tank cars, a test specification was developed to test previously undamaged insulation specimens. The purpose for insulating the tank cars is to allow sufficient time for a tank car engulfed in a fire to vent its contents before the tank car ruptures (Townsend, et al. 1974). The pass/fail criteria for these regulations is that the insulation must survive a simulated pool fire test as well as a torch fire test (49CFR179.105-4).

The following analysis shows the relative differences between these two thermal environments when each one is applied to a "generic" rail cask. Further examples are given of attempts to compare these environments using other methods.

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REGULATORY THERMAL ENVIRONMENTS

The DOT Thermal Environment

The purpose of the DOT regulation is to outline a test specification for evaluating insulating materials that will be used on tank cars. Only those materials that pass the test will be used to insulate the tank cars carrying hazardous materials, such as propane and butane. The insulation is used to reduce the heat flux to the liquid contents in the tank car and therefore, allow more time for the car to vent its contents before it ruptures.

The DOT thermal environment is a completely defined experimental (not analytical) simulation. A torch is used to simulate a "pool" fire. As stated in the regulations (49CFR179.105-4), the source of the simulated pool fire must be a hydrocarbon fuel with a flame temperature of 870 °C ± 38 °C throughout the duration of a 100 minute test (49CFR179.105-4).

Before a test is conducted, the torch is calibrated by exposing a previously undamaged, uninsulated square steel plate to the flame. The steel plate must have thermal properties equivalent to those of tank cars, and the dimensions must be at least 0.3 meters by 0.3 meters by nominal 15.8 mm thick. The torch is appropriately calibrated when at least two of the thermocouples located on the back of the steel plate indicate 427 °C after 12 to 14 minutes of fire exposure.

After the torch is calibrated, the thermal insulation system is tested (insulation covering one side of a steel plate identical to the one used for calibration). The pool fire simulation is conducted for a minimum of 100 minutes. Test requirements demand that the insulation retard the heat flow to the steel plate so that none of the thermocouples on the uninsulated side of the plate indicate a plate temperature in excess of 427 °C.

The NRC Thermal Environment

The NRC regulations were not designed to test one component of the system (such as the insulation); they specify performance standards for the system as a whole. They were developed to assure that the integrity of the transportation container is not compromised in the event of an accident. The cask integrity must be maintained with regards to strict containment, shielding, and criticality requirements. The cask must undergo sequential damage scenarios including impact, puncture, and thermal loads. The regulations do not specify allowable structural or thermal damage but rather define the containment and shielding integrity that must be maintained following sequential test scenarios.

Unlike the DOT regulations which define an experimental simulation, 10CFR71 completely defines the thermal accident condition analytically. The thermal section states that the package must be exposed for not less than 30 minutes to a heat flux not less than that of a radiation environment of 800 °C with an emissivity coefficient of at least 0.9. For calculation purposes the surface absorptivity is assumed to be either that value which the package may be expected to possess if exposed to a fire or 0.8, whichever is greater. In addition, when significant, convective heat input must be included on the basis of still, ambient air at 800 °C.

RAIL CASK MODEL

A thermal model of a "generic" rail cask was developed to compare the relative effects of the DOT thermal insulation test conditions and the NRC thermal environment. The representative rail cask used for the analysis is 2.1 meters (m) in diameter, 5.26 m in length, and has a loaded weight of approximately 93 tons. As shown in Fig. 1, the cask consists of a 25.4 cm. thick austenitic stainless steel cask wall. The neutron shielding is provided by 7.5 cm of boron silicone attached to the outside of the cask and clad with a thin shell of steel. The cask cavity is sealed by a bolted stainless steel closure head 1.9 m in diameter, 19 cm thick, with an elastomeric O-ring seal. The outer lid, which is also made of stainless steel, is 2.2 m in diameter, 3.8 cm thick, and functions as a thermal cover. The outer lid protects the elastomeric seals from excessive temperatures during the hypothetical thermal accident. For simplicity, the cask is assumed to transport high-level waste with a total decay heat of 6.7 kW.

Description of Thermal Model

The thermal evaluation consists of a numerical thermal analysis using Q/TRAN (Rockenbach 1986). Q/TRAN is a thermal analysis code which solves heat transfer problems using a combination of the thermal network approach and the finite element method. Q/TRAN is integrated into PATRAN (PDA/PATRAN User's Guide 1984) which is a grid generating program using the finite element method. Linking capabilities between Q/TRAN and PATRAN include both pre- and post-processing, allowing graphic display of meshing schemes and thermal results. The Q/TRAN-PATRAN link uses finite element theory to translate the mesh data (with second order truncation error or linear elements) into a finite difference (resistor/capacitor) thermal analysis (Manteufel, et al. 1986). The link maps the higher-order finite element difference scheme exactly, as opposed to using a network approximation to finite element mesh. Therefore, Q/TRAN-PATRAN offers the ability to increase the complexity of the model over previous computer codes, improving the predicted response of nuclear shipping casks in varying thermal environments (Moya and Akau 1987).

From the geometric description of the cask, PATRAN is used to generate a two-dimensional axisymmetric finite element mesh. Due to symmetry only half of the cask is modelled. Fig. 2 shows the mesh used for the thermal model. The contents of the cask are not explicitly modelled in this analysis. However, the decay heat is assumed to be evenly distributed throughout the entire cask inner cavity, and the thermal properties of the cavity are assumed to be those of glass.

Heat is transferred from the waste to the cask body and through the cask wall and neutron shield by conduction. Heat loss from the exterior surface of the cask is assumed to be by free convection and thermal radiation. Heat transfer across the air gaps is assumed to occur by conduction and gray body radiation. The air gaps are located between the lid and neutron shield, and between the neutron shield and the thermal cover.

For the hypothetical accident condition, the cask was evaluated for exposure to a radiation environment of 800°C for a period of 30 minutes (10CFR71) and 870°C for a period of 100 minutes (49CFR179). The analysis continued beyond the specified thermal test duration, for an 8-hour cool down period, to examine the possibility of further temperature increase in the cask.

The pre-test steady-state temperature distributions defined the initial conditions of the package prior to exposure to the thermal environment. The pre-test temperatures were obtained by assuming the cask dissipates its decay heat to still ambient air at 38°C but neglects any solar insolation to the cask. For the hypothetical accident analysis, the neutron shield is assumed not to be present, due to its proximity to the radiant environment and its inability to withstand high temperatures.

Thermal Results

Fig. 3 shows the system temperatures as a function of radial distance through the mid-plane of the cask for the pre-test steady-state conditions, the 30 min. 800°C environment at the end of 30 minutes, and the 100 min. 870°C environment at the end of 100 minutes. As would be expected with such a large thermally massive object, the cask inner cavity is not affected by the external thermal environment.

Containment is generally a function of seal integrity, and seal performance is a function of its temperature history. The seals are not explicitly modelled; however, are assumed to be located at the interface between the cask wall and the lid. Fig. 4 shows the seal temperature as a function of elapsed time. For the DOT insulation test environment, the peak seal temperature would be around 147°C while the NRC thermal environment produces a peak seal temperature around 97°C. Both of these temperatures are below the continuous use limit for most elastomeric seals.

Comparing Effective Flame Temperatures

A difficulty in comparing the two thermal environments is that the DOT regulation is a test specification while the NRC regulation is an analytical specification. Trying to apply the DOT test specification analytically is difficult as not all of the parameters (such as environment emissivity and package absorptivity) are specified. One way of overcoming the difficulty is by reducing the DOT requirements to an NRC-type specification using NRC values for emissivity and absorptivity. The result of this analysis is an effective DOT flame temperature which can then be compared to the NRC flame temperature (Longenbaugh and Sanchez 1987).

The heat flux to the front face of the steel plate in the DOT specifications can be calculated from the calibration specifications in the regulations: the back face temperature of a 15.8 mm thick steel plate, initially at 0 °C, shall reach 427 °C in 12 to 14 minutes as the result of the front face exposed to a flame. Once this flux is calculated (75-80 kW/m^2, blackbody), assuming an emissivity of 0.9 and a surface absorptivity of 0.8, the flame temperature can be calculated.

The result of this analysis produces an effective flame temperature of 810 °C, assuming an insulated backface boundary condition and 830 °C, assuming a radiative backface boundary condition. These temperatures are only slightly higher than the NRC specified value of 800 °C.

Experimental Comparisons

Radiant heat and wind-shielded fire experiments were performed on a 3.6 cm thick test article fabricated of 1010/1020 mild steel and packed with Cera-Blanket insulation (Longenbaugh 1988). The outer surface of the test article was coated with PYROMARK 2500 paint to obtain a surface absorptivity greater than or equal to 0.8. The test article was approximately 0.91 m long with an outside diameter of 0.46 m. Three different tests were conducted to determine the thermal response of this test article under different conditions: 800 °C radiant heat test for 30 minutes, a 870 °C radiant heat test for 100 minutes, and a wind-shielded engulfing fire for 100 minutes.

Not surprisingly, the results indicate that the longer 870 °C, 100-min. radiant heat test produces greater heat input to the test article than the 800 °C, 30-min. radiant heat test or the wind-shielded engulfing fire test. The average total heat input to the test article is 140 MJ/m^2 for a 870 °C, 100-minute radiant heat environment; 88 MJ/m^2 for a 800 °C, 30-minute radiant heat environment; and 125 MJ/m^2 for the wind-shielded engulfing fire environment. The flame thickness was less than 1 meter; therefore, the emissivity of the flames was less than 1. This explains why the wind-shielded facility produced less heat input than the radiant heat environment.

SUMMARY AND CONCLUSIONS

From the previous section, it is clear that there are several ways to compare the DOT thermal test conditions with the NRC thermal environment. Each method of comparison produces different results. The apparent discrepancy results because the DOT thermal environment is a test specification that is not defined in an analytical manner. Thus, many assumptions must be made when trying to apply it analytically. For instance, in order to apply it as a radiative boundary condition to a thick-walled cask, an environment emissivity and surface absorptivity must be assumed. Using an inconsistent set of assumptions, such as the NRC optical properties with the DOT flame temperature, obviously produces greater temperatures and heat fluxes because the flame temperature is higher, and the duration is longer. In contrast if an effective DOT flame temperature is calculated using NRC specified emissivity and absorptivity, the environments look very similar, the DOT environment being slightly more severe. Each attempt at a comparison is likely to produce completely different results.

Two important parameters in the evaluation of any thermal specifications are the temperature and the heat flux. In the case of a thin-walled object, such as a rail tank car, the temperature is the dominating factor. The thin wall temperature will rise very quickly reducing the total heat flux to the object. In this case there will be very little difference between a 30-minute test and a 100-minute test. In contrast for a thick-walled object, heat flux will be the dominating factor. The temperature of a thick wall will not rise quickly as the energy is transferred through the wall. Consequently, a thick-walled object can absorb more thermal energy than a thin-walled object. In this case the duration of the test is very important as more energy will be absorbed in 100 minutes than in 30 minutes. This point is evident on the earlier analysis of the generic rail cask where the seal temperature was somewhat higher for the DOT test conditions than for the NRC thermal environment (more energy was absorbed).

In conclusion, it is difficult to compare these thermal environments. Each is developed for a specific purpose, both being concerned with the safety of the public. The DOT specification is a component test designed to test insulation for tank cars and should be used in this manner. It is not a performance specification for an entire shipping package. The NRC regulations are not intended to represent specific fire environments but are intended to produce levels of damage in packages representative of the damage which could be sustained in most severe transportation related accidents.

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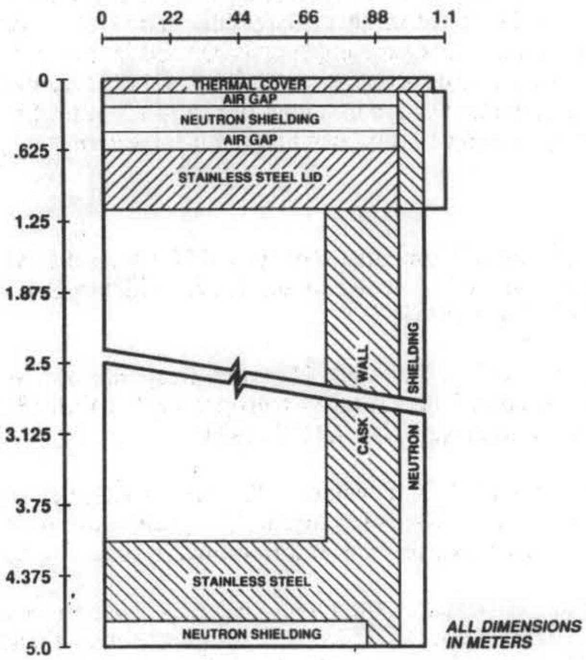

Figure 1. Representative Rail Cask

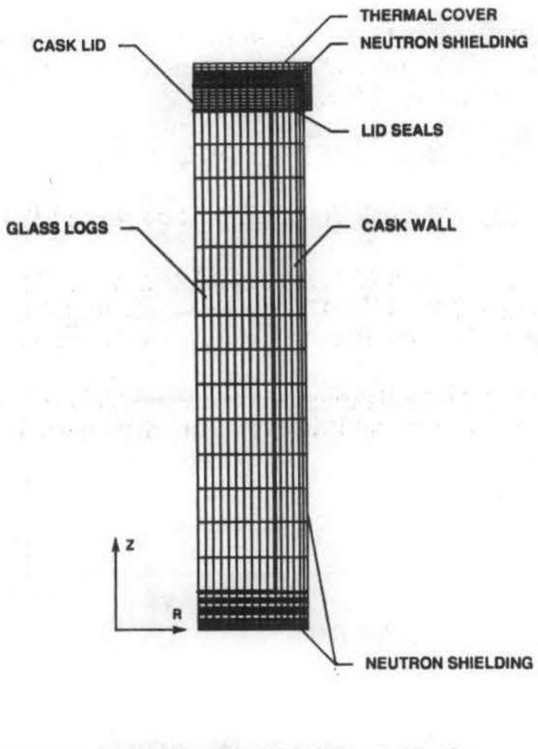

Figure 2. Finite Element Mesh

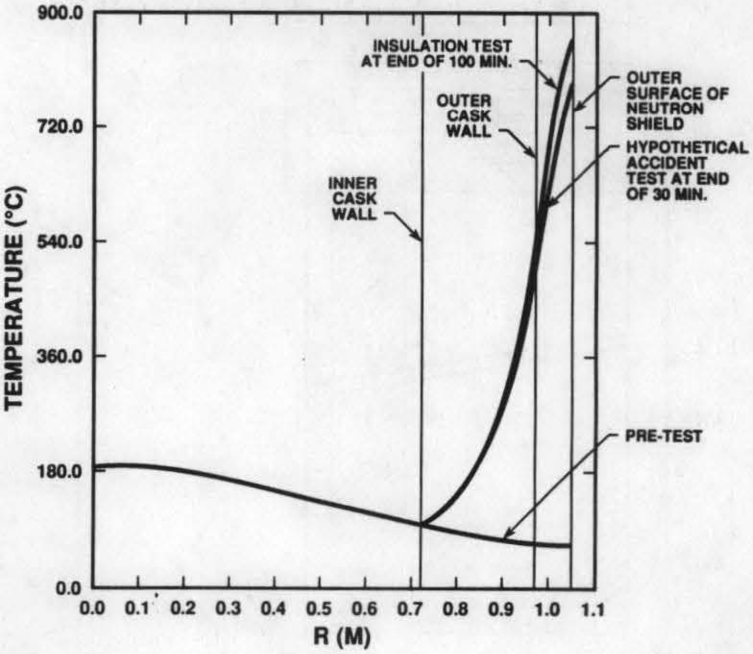

Figure 3. Mid-Plane System Temperatures

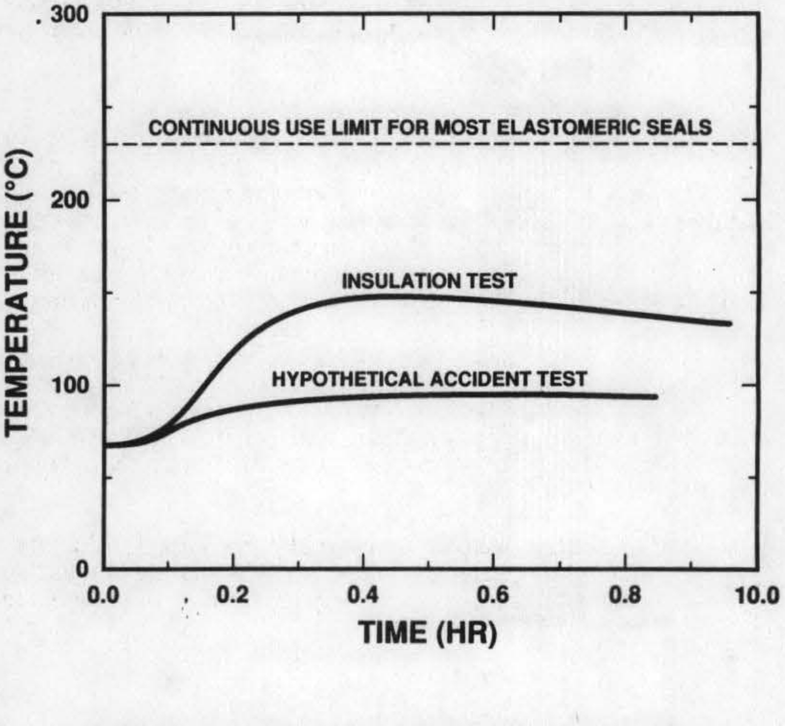

Figure 4. Transient Seal Temperatures