ANALYSIS OF THE EFFECTS OF PIPELINE AND RAILROAD FIRES ON LEGAL WEIGHT TRUCK TRANSPORTATION CASKS

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ABSTRACT

Questions specific to the safety of rail transportation of spent nuclear fuel have been raised. The purpose of this paper is to examine the fire environments that could occur in rail accidents involving typical casks and to determine whether rod burst and/or seal failure represent a problem under such occurrences. The method used to address these issues was a detailed three-dimensional finite-element computer simulation of torch and engulfing fire environments. The results are intended to provide details and information in a form that would be a useful reference for future risk-based studies of these accidents. The transportation cask that was studied has the overall dimensions of a typical legal-weight truck cask. Four different kinds of accidents were modeled for this study. These were: 1) a fire jet impinging at the center of the cask, 2) a fire jet impinging at the seal end of the cask (without impact limiter) from the side, 3) a vertical flare radiating to the side of the cask from about ten meters away, and 4) a fully engulfing fire. All fire scenarios were modeled assuming different fire temperatures to cover a wide range of fires that could be found in these accidents. All modes of heat transfer are included: radiation, conduction and convection. In Case 1, seal failure was not found to be a problem, whereas rod burst could be a problem after 2 hours and 20 minutes if the fire jet has a temperature of about 1200°C, after an hour and 30 minutes if the fire jet has a temperatures of about 1400°C, and after an hour for a fire jet temperature of about 1600°C. For Case 2, the temperature history plots showed that while seal failure could occur early, rod burst is not a problem. Case 3 did not represent a problem in terms of seal failure or rod burst during the simulated ten hours whereas Case 4 indicates that both seal failure and rod burst occur some time during the simulation.

INTRODUCTION

Shipments within the United States of spent nuclear reactor fuel returned from foreign countries under long-standing international agreements has sparked questions and comments from stakeholders. Because rail transportation has been used for these shipments, questions specific to the safety of rail transportation of spent nuclear fuel have been raised. The possibility of accidents involving severe pipeline breaks and tank car fires have been proposed by concerned parties. The purpose of this paper is to examine the fire environments that could occur in such accidents. The methods used to address these issues include detailed computer simulation of torch and engulfing fire environments. Besides examining the issues with current techniques and data, the results are intended to provide details and information in a form that would be a useful reference for future risk-based studies of such accidents.

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Consistent with the foreign reactor fuel shipments, a typical spent fuel cask designed for truck transport has been used for the study. For general studies of rail transport, this approach is conservative, because truck casks are smaller than casks intended exclusively for rail usage. Smaller casks heat more rapidly in fires so that if a failure occurs, it occurs sooner than with the larger casks designed exclusively for rail usage. In the fire simulations, all modes of heat transfer were included: radiation, conduction and convection. Information developed by the pipeline industry and in the offshore production of oil has been used, especially in modeling flame jet impingement on cask surfaces. Temperatures of critical cask components, such as seal areas and fuel bundle areas, are displayed as curves so that results may be adjusted for studies involving various types of seals and the various ages of spent fuel.

General Discussion

An unresolved issue for these types of accidents is the fire duration to be used for risk studies. Historical records of fires are not useful in this determination for several reasons. First, the fire duration is typically not recorded in the data reported from accidents. Even if the data were recorded, its accuracy and usefulness would be questionable. The reason for this is that fires may not burn at only one location, but move, causing a series of short duration fires that would be documented as one long fire. In the case of fires that involve releases from tank car relief valves, a tank car design objective is to permit a tank car fully engulfed in fire to relieve its hazardous cargo within 100 minutes, without an explosion. This indicates that for the small number of cases where relief valve outlet jets ignite and impinge on adjacent casks, a 100-minute duration may be a reasonable estimate. The 20,000 to 30,000-gallon capacity of railroad tank cars, known fuel recession rates, and estimated pool size can be used to estimate the duration of pool fires.

The duration of petroleum product pipeline fires is even more difficult to estimate than railroad tank car fires. Safety reports for pipeline fire accidents identify several variables controlling fire duration, including the size of the break and the distance from the compressor or pumping station. For some fires, the size and remote location of the rupture did not permit the pipeline operator to recognize the presence of a break or fire. Such occurrences could lead to fires that burn until reported to the operator. Enough operating transients occur during normal pipeline operations that operators are trained to attempt to restart transmission when a pump or compressor trips because of low discharge pressure. In such cases, the operator may make several tries to reestablish flow, thus prolonging fires at a break location.

To avoid the problem of estimating the fire duration, the fire environment data reported in this paper assume a continuous ten-hour fire both for tank car accidents and pipeline fires. Curves are presented in a manner that enables the determination of the times to degradation of the cask seals and times to rod burst of spent fuel. With these curves, and a distribution of fire duration, risk analysts can estimate the likelihood of cask releases in these accidents.

COMPUTER MODELING OF SELECTED FIRE ACCIDENTS

In trying to cover a wide range of possible fire scenarios as a consequence of a gas pipeline break, four different kinds of accidents were modeled for this study. These were: 1) a fire jet impinging at the center of the cask, 2) a fire jet impinging at the seal end of the cask from the side, 3) a vertical flare radiating to the side of the cask from about ten meters away, and 4) a fully engulfing fire. All the models were assumed to be under these fire conditions for a period of ten hours with the intention of providing the risk analyst with an idea of how long it takes for the specified accident conditions to represent a problem in terms of seal failure and/or rod burst due to excessive temperatures. This paper presents selected results from a more detailed report that will be published as a Sandia Report [1].

Description of the Computer Model

The transportation cask that was studied has the dimensions of a typical legal weight truck cask such as the NAC-LWT. Some of the dimensions were modified to simplify the finite element modeling. Overall dimensions used for the computer model are presented in Figure 1.

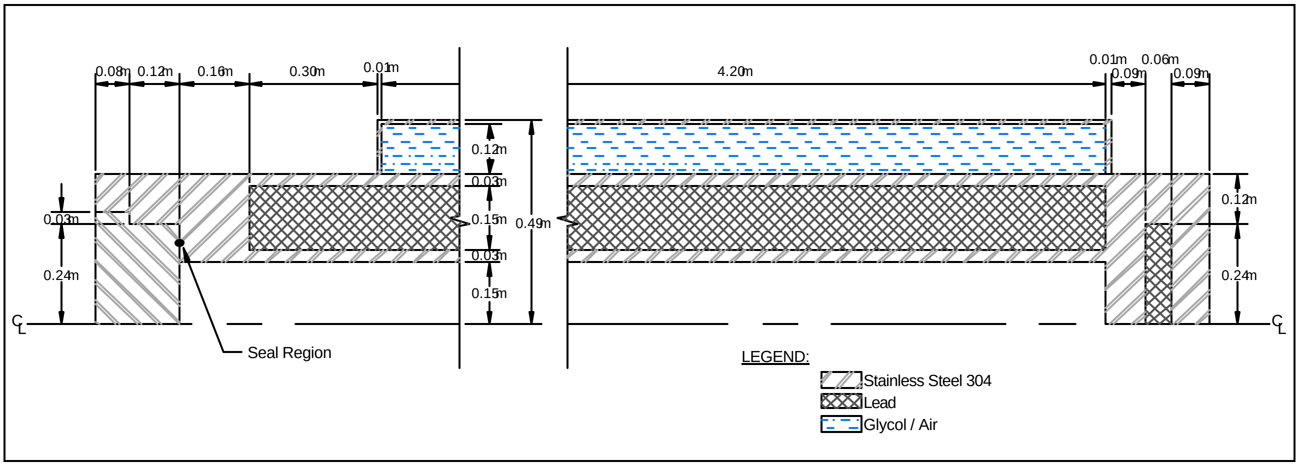


Figure 1. Overall dimensions of the studied cask.

Due to the complexity of the environments that were studied, a three-dimensional finite element model of the cask and boundary conditions had to be constructed. The computer programs used for this study were MSC PATRAN and MSC P/Thermal. The cask was represented with approximately 19,000 three-dimensional elements.

FINITE ELEMENT ANALYSES AND DISCUSSION

In this section each case will be presented and discussed individually. Boundary conditions and case-specific considerations will be included in the discussion of each subsection. Glycol, the neutron shield, was assumed to be present inside the neutron shield cavity for the estimation of the steady state temperature distribution. For all other cases, the Glycol was assumed to be lost due to the accident and air was assumed to be present inside the cavity.

All the temperature history plots that are presented next contain temperatures from the hottest outer wall node, the seal region, and the hottest internal wall node that was found at the center of the cask. This last may be used to estimate when fuel rod burst becomes an issue. Note that the rod bundle is assumed to be about 100°C hotter than the internal wall temperature of the cask. Therefore, if the rods burst at around 750°C, then the correspondent wall temperature of the cask would be about 650°C. The polymeric seal failure temperature is defined to be 350°C for the purpose of this report.

Steady State Under Normal Conditions

Spent fuel generates heat and this causes the cask to get hotter than ambient temperature. Therefore, a steady state analysis was run to estimate the initial temperature distribution of the cask under normal conditions. For this analysis, Glycol was assumed to be inside the external neutron shield cavity of the cask. The fuel rods were assumed to produce a uniform and constant internal heat load of 1.8 kW. For the external cask surface a convection heat transfer coefficient of 3.2 W/m^2-K (natural convection) and an ambient temperature of 38°C were assumed for this calculation. The steady state solution is presented in Figure 2.

In order to simplify the modeling of the time-varying cases, an average uniform temperature of 72°C was assumed as initial temperature based on the result from this simulation.

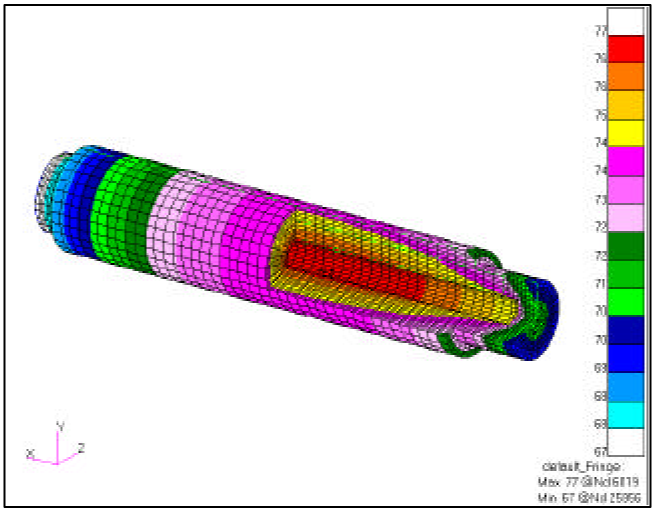


Figure 2. Steady state solution (in °C).

Case 1: A fire jet impinging at the center of the cask.

1204°C Fire Jet

The intention with this model was to represent the scenario where the transportation cask is impinged by a fire jet coming from a gas tank car next to it due to a release of gas through the relief valve. The boundary conditions for this case were:

- ambient temperature of 38°C,
- fire jet temperature of 1204°C (49 CFR 179),
- uniform internal heat load of 1.8 kW,
- convection heat transfer coefficient of 3.2 W/m^2-K (free convection),
- gap radiation inside the neutron shield cavity with surface emissivity of 0.33 (emissivity value for Stainless Steel [2]), and
- external radiation to the fire and the environment with emissivity values of 0.33 for the section of the cask that is not being impinged by the fire jet and 0.8 for the section that is, 0.9 for the flame, and unity for the enclosure representing the environment.

The temperature distribution at one hour is shown in Figure 3 and the temperature history plot of selected nodes is presented in Figure 4.

1400 and 1600°C Fire Jets

These two models are meant to be representative of fire jets impinging on the side of the cask due to a pipeline rupture. The boundary conditions for these cases were the same as the ones used in the previous model with the exception of the temperature of the fire jets, which were 1400°C and 1600°C. Temperature history plots are presented in Figures 5 and 6.

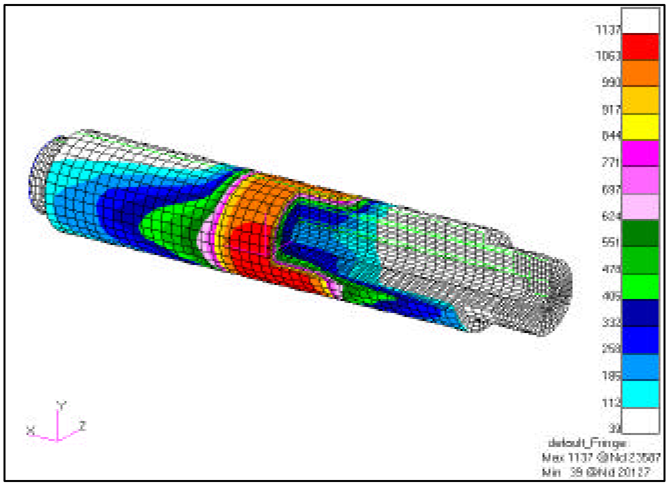


Figure 3. Temperature distribution after 1 hour (in °C). The impinging fire jet was assumed to flow in the positive z direction and hit the center of the cask.

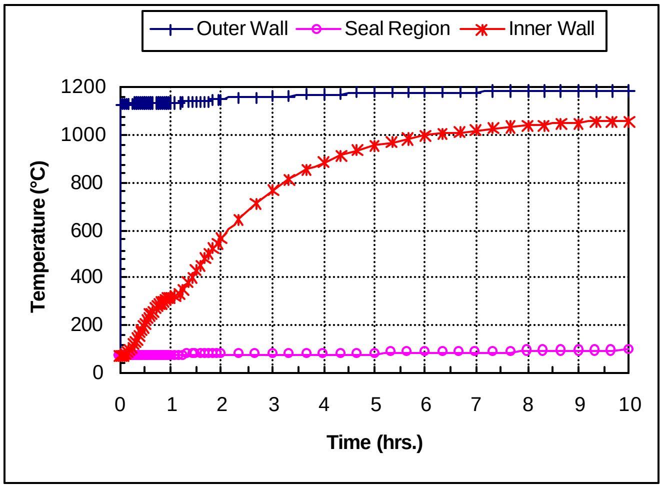


Figure 4. Temperature history of Case 1–1204°C.

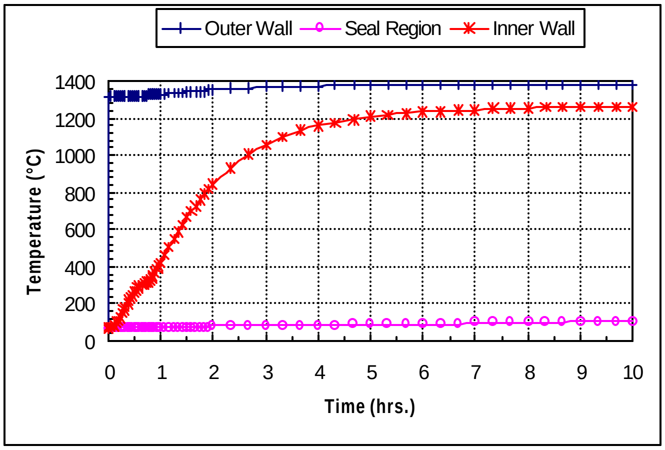


Figure 5. Temperature history of Case 1-1400°C.

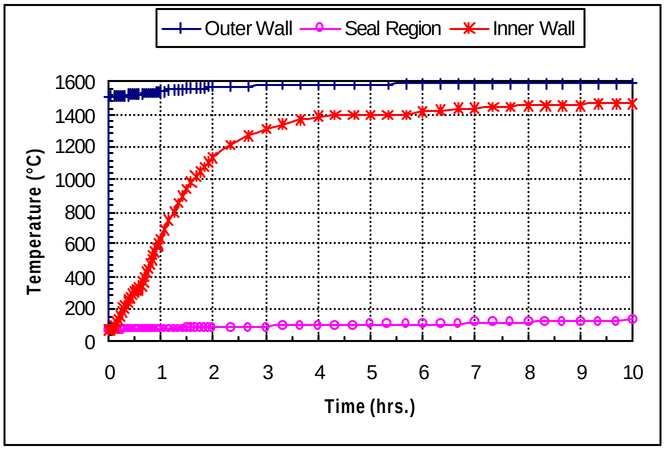


Figure 6. Temperature history of Case 1-1600°C.

Discussion of Case 1 Results

The temperature history plots presented in Figures 4, 5, and 6 show that seal failure is not a problem in this case. On the other hand, rod burst is a problem after 2 hours and 20 minutes if the fire jet has a temperature of about 1200°C and after an hour and 30 minutes and an hour for fire jet temperatures of 1400°C and 1600°C, respectively.

Case 2: A fire jet impinging at the seal of the cask.

1204°C Fire Jet

Similar to Case 1-1204°C fire jet, this model represents a fire jet coming from a petroleum tank car impinging the seal end of a cask next to it due to a release of gas through the relief valve. The boundary conditions for this case were:

- ambient temperature of 38°C,
- fire jet temperature of 1204°C,

- uniform and constant internal heat load of 1.8 kW,
- convection heat transfer coefficient of 3.2 W/m^2-K on areas that were not impinged by the fire,
- convection heat transfer coefficient of 45.3 W/m^2-K on cylindrical areas that were impinged by the fire [3],
- convection heat transfer coefficient of 70 W/m^2-K on flat areas that experienced the flow of fire over them (turbulent flow over a flat plate [2]),
- gap radiation in the neutron shield cavity with surface emissivity of 0.33, and
- external radiation to the fire and the environment with emissivity values of 0.33 for the section of the cask that is not being impinged by the fire jet and 0.8 for the section that is, 0.9 for the flame, and unity for the enclosure representing the environment.

The temperature distribution at one hour is shown in Figure 7 and the temperature history plot of selected nodes is presented in Figure 8.

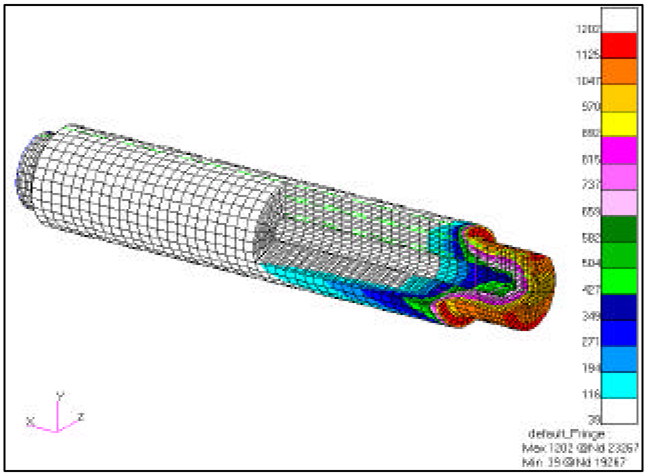


Figure 7. Temperature distribution after 1 hour (in °C). The impinging fire jet was assumed to flow in the positive z direction and hit the seal end.

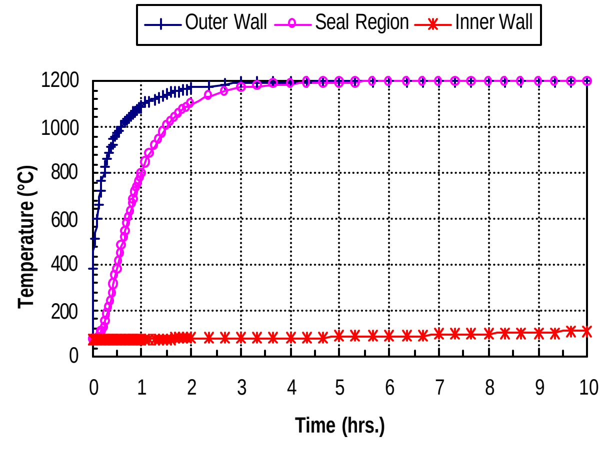


Figure 8. Temperature history of Case 2–1204°C.

1400 and 1600°C Fire Jets

These two models are representative of fire jets impinging on the seal end of the cask due to a pipeline rupture. The boundary conditions for these cases were the same as the ones mentioned in the 1204°C-jet model with the following exceptions:

- fire jet temperatures of 1400°C and 1600°C,
- convection heat transfer coefficient of 48.7 W/m^2-K for the 1400°C case and of 52.5 W/m^2-K for the 1600°C case on cylindrical areas that were impinged by the fire [3], and
- convection heat transfer coefficient of 75 W/m^2-K for the 1400°C case and of 80 W/m^2-K for the 1600°C case on flat areas that experienced the flow of fire over them [2].

The temperature history plots for these two scenarios are presented in Figures 9 and 10.

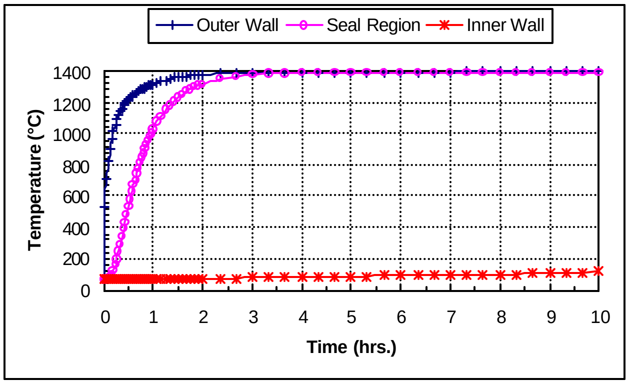


Figure 9. Temperature history of Case 2-1400°C.

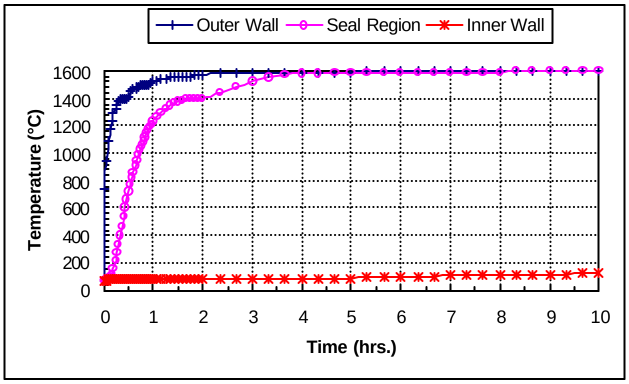


Figure 10. Temperature history of Case 2-1600°C.

Discussion of Case 2 Results

Contrary to the results of Case 1, the temperature history plots of this section showed that while seal failure could occur early, rod burst is not a problem. After 28 minutes the seal region was over 350°C when the seal end of the cask was impinged by a 1200°C-fire jet. The same temperature level was reached at the seal region after 22 minutes with the 1400°C-jet and after 18 minutes with the 1600°C-jet. Note that, because the rods did not reach the rod burst temperature, the consequence of the seal failing are not large.

Case 3: Vertical Fire Flare(s) Radiating to the Side(s) of the Cask.

The One-Flare Model

A one-flare model was created to represent the event where a pipeline rupture provokes a vertical flare that irradiates directly to the cask. A two-flare model was also created with the intention of representing the hypothetical cask response to the accident of August 2, 2000 in Las Vegas, Nevada where a double-tanker carrying 8,700 gallons of gasoline ignited creating what would be an environment for the cask similar to the one shown in Figure 11. The boundary conditions for the two-flare model were the same as the ones for the one-flare model except that this time there were two flares present. The boundary conditions for both of these models were:

- ambient temperature of 38°C,
- flare temperature of 1000°C,
- uniform and constant internal heat of 1.8 kW,
- convection heat transfer coefficient of 9.5 W/m^2-K [3],
- gap radiation in the neutron shield cavity with surface emissivity of 0.33, and
- external radiation to the plume and the environment with emissivity values of 0.8 on the surface of the cask, 0.9 for the flare, and unity for the enclosure representing the environment.

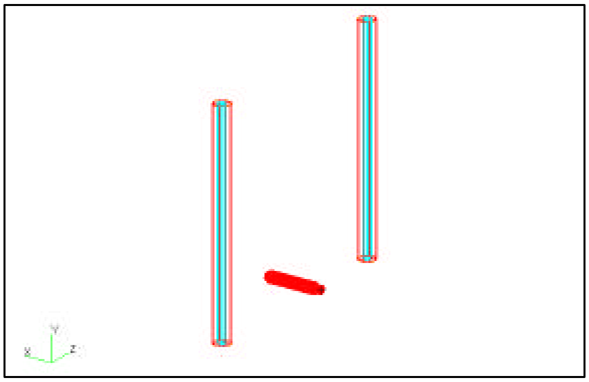
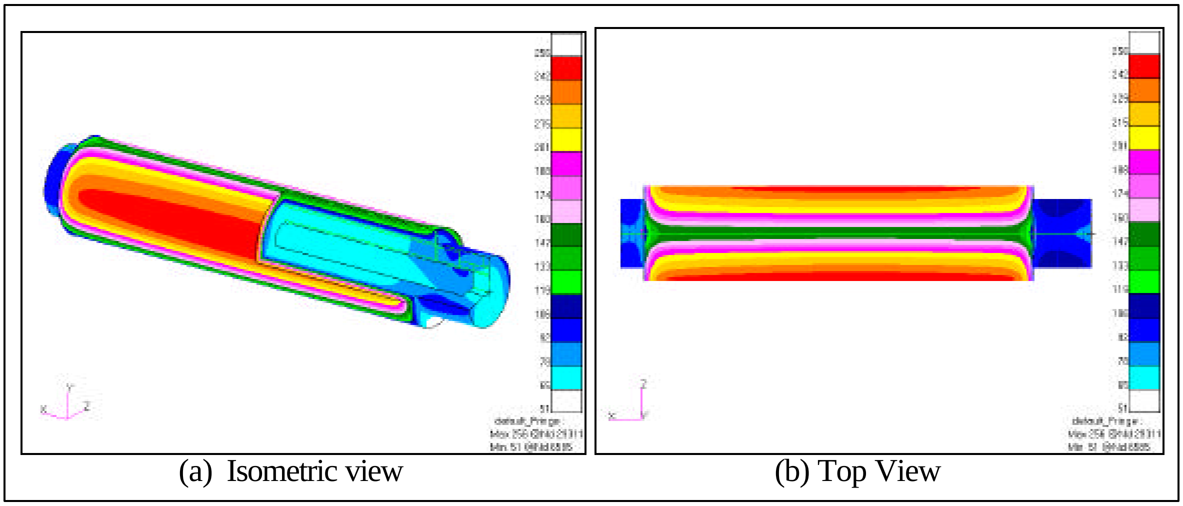


Figure 11. The two-flare model. The cask is located in between the two 20-meter tall, 2-meter diameter flares. The flares are 10 meters away from the cask, center to center.

Due to the fact that the studied transportation cask has a large thermal mass, both simulations gave very similar results. Therefore, only those results obtained from the two-flare modeling are presented in this paper. Nevertheless, in the two-flare model, the cask reached slightly higher temperatures. A temperature distribution plot is presented in Figure 12 and the temperature history plot is shown in Figure 13.



(a) Isometric view (b) Top View

Figure 12. Temperature distribution plots for the two-flare model at 1 hour.

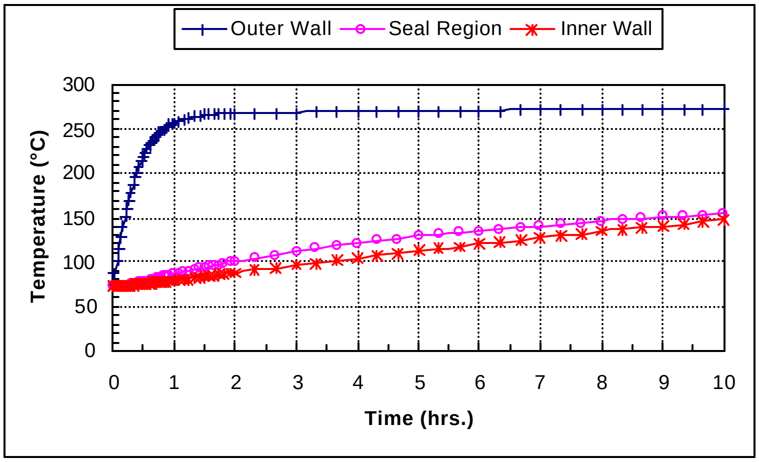


Figure 13. Temperature history for the two-flare model.

Discussion of Case 3 Results

Despite the fact that the two-flare model produced slightly higher temperatures than the one-flare model, the two-flare model results do not represent a problem in terms of seal failure or rod burst.

Case 4: A Fully Engulfing Fire.

This case is probably the least likely to occur of all the cases that were studied because a pipeline break would have to be large enough to fully engulf the cask. Nevertheless the natural gas pipeline fire accident that occurred in Carlsbad, New Mexico on August 19, 2000 suggests the consideration of the event. From the four fire temperatures that were studied, three are discussed in this paper; 800°C, 1000°C, and 1200°C. Other boundary conditions included:

- uniform internal heat load of 1.8 kW,
- convection heat transfer coefficient of 9.5 W/m^2-K,
- gap radiation in the neutron shield cavity with surface emissivity of 0.33, and
- external radiation to the fire with emissivity values of 0.8 on the surface of the cask and of 0.9 for the fire.

The temperature distribution at one hour is shown in Figure 14. Temperature history plots for all the different fire temperatures of this case are presented in Figures 15 through 17.

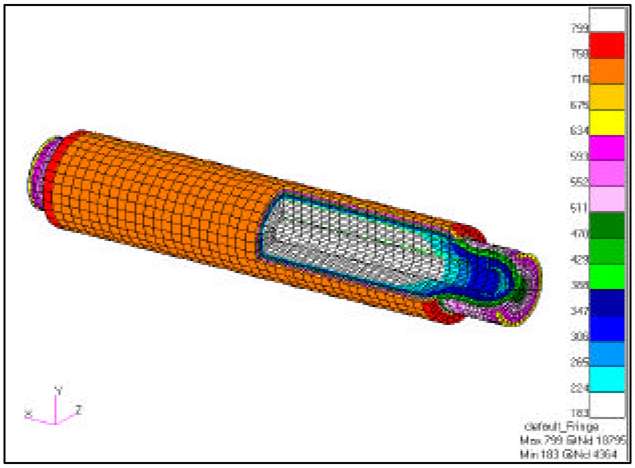


Figure 14. Temperature distribution after 1 hour (in °C) for the 800°C fully engulfing case.

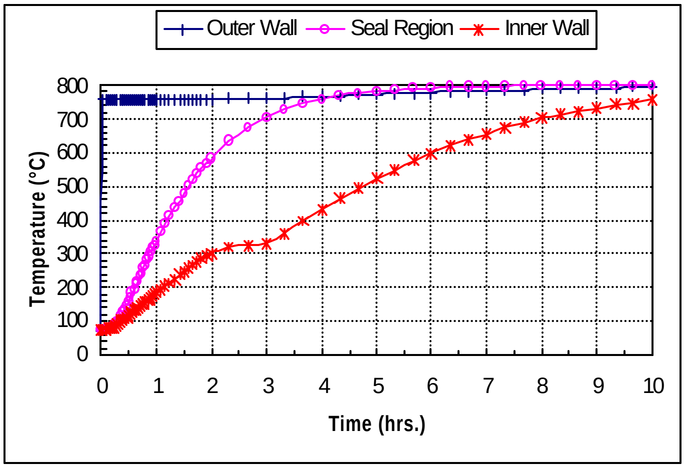


Figure 15. Temperature history of Case 4–800°C fire.

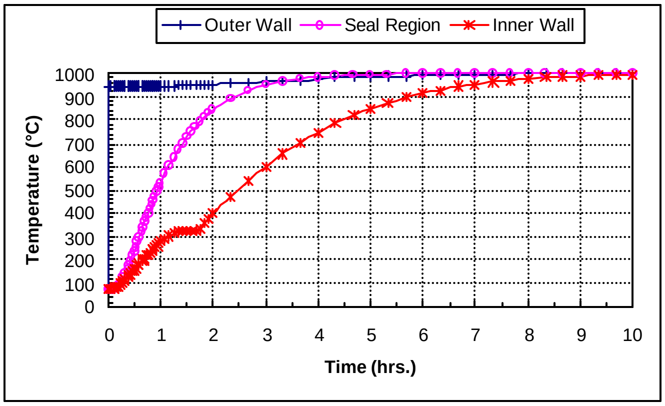


Figure 16. Temperature history of Case 4-1000°C.

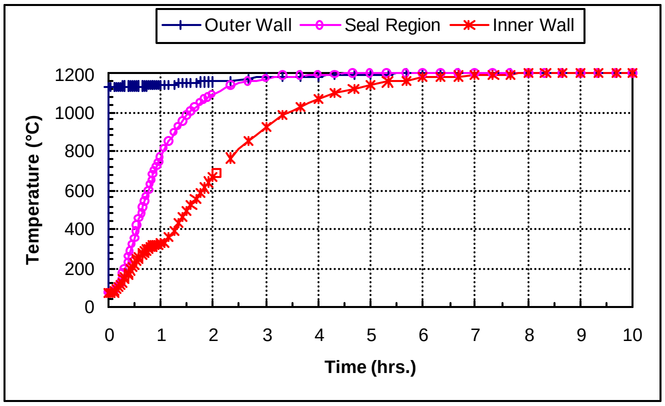


Figure 17. Temperature history of Case 4-1200°C.

Discussion of Case 4 Results

Contrary to all previous cases, Case 4 indicates that both seal failure and rod burst occur some time during the fully engulfing fire simulation. As shown in the temperature history plots, rod burst may occur after 7 hours for the 800°C fire, after 3 hours and 20 minutes for the 1000°C fire, and after 2 hours for the 1200°C fire. Due to the fact that internal peak temperatures occur some time after the fire is out, a simulation of the regulatory environment was performed as per 10CFR71.73 to estimate when peaking occurs and what is the change in temperature of the internal wall of the package. The results from this simulation are presented in Figure 18.

As shown in Figure 18, the seal region reaches its peak temperature of 262°C forty minutes after the fire was out. This represents a total temperature change of 102°C over the forty-minute period. In contrast, the internal wall did not seem to reach a peak within the period of study. The internal wall temperature went from 117°C to 141°C within 24 minutes after the fire was out and, from there, it only increased about 2° to the end of the simulation. Note that neither seal failure nor rod burst were a problem under these circumstances. Similar time and temperature offsets could be applied to estimate seal failure and rod burst for fires of various duration.

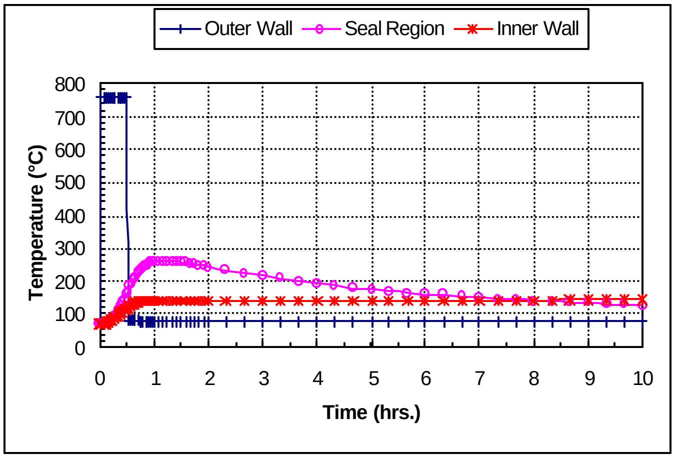


Figure 18. Temperature response of the studied cask when exposed to the 10-CFR-71.73 regulatory fire conditions.

SUMMARY

The low likelihood, but potentially severe thermal conditions caused by turbulent mixing of oxygen into the fire plume, cause pipeline accidents to fall into the category of very low probability, high consequence events. Such accidents are not normally included in risk assessments because they do not contribute significantly to the total risk. Nonetheless, the data presented in this paper allow analysts to determine when fire exposure to a typical truck cask can lead to seal degradation or fuel rod burst pressures.

The results from Case 1 indicate that rod burst could be a problem after 2 hours and 20 minutes if the fire jet has a temperature of about 1200°C, after an hour and 30 minutes if the fire jet has a temperatures of about 1400°C, and after an hour for a fire jet temperature of about 1600°C. However, in this case the seals do not fail so the spent fuel released to the cask cavity from the burst rupture is contained in the cask. The results from Case 2 indicate that seal failure could occur, however, because there is no rod failure, no significant release is expected. Without rod failure, the only radioactive material that can be released is CRUD. The CRUD can only be released if the internal cavity of the cask is pressurized due to heating before seal failure. The results from Case 4 indicate that rod burst could occur after 7 hours if the fully engulfing fire has a temperature of about 800°C, after 3 hours and 20 minutes if the fire has a temperatures of about 1000°C, and after 2 hours for a fire temperature of about 1200°C. In this case rod burst rupture is a much larger problem because the seal has already failed and some of the spent fuel released from burst rupture will be swept out of the cask in the depressurization of the rods. Neither seal failure nor rod burst occurred in Case 3 during the simulated ten-hour fire.

REFERENCES

[1] Lopez, C., J. A. Koski, and G. S. Mills, Analysis of the Effects of Pipeline and Railroad Fires on the Transport of Radioactive Materials, SAND Report (to be published).

[2] Incropera, F. P. and D. P. DeWitt, Fundamentals of Heat and Mass Transfer, 4th ed., John Wiley & Sons, Inc., 1996.

[3] Churchill, S. W. and M. Bernstein, “A Correlating Equation for Forced Convection from Gases and Liquids to a Circular Cylinder in Cross Flow”, Jour. Ht. Trans., Vol. 99, May 1977, pp. 300-306.