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Estimates of Fire Environments in Ship Holds Containing Radioactive Material Packages

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INTRODUCTION

Fire environments that occur on cargo ships differ significantly from the fire environments found in land transport. Cargo ships typically carry a large amount of flammable fuel for propulsion and shipboard power, and may transport large quantities of flammable cargo. As a result, sea mode transport accident records contain instances of long lasting and intense fires. Since Irradiated Nuclear Fuel (INF) casks are not carried on tankers with large flammable cargoes, most of these dramatic, long burning fires are not relevant threats, and transport studies must concentrate on those fires that are most likely to occur. By regulation, INF casks must be separated from flammable cargoes by a fire-resistant, liquid-tight partition. This makes a fire in an adjacent ship hold the most likely fire threat. The large size of a cargo ship relative to any spent nuclear fuel casks on board, however, may permit a severe, long lasting fire to occur with little or no thermal impact on the casks. Although some flammable materials such as shipping boxes or container floors may exist in the same hold with the cask, the amount of fuel available may not provide a significant threat to the massive transport casks used for radioactive materials. This shipboard fire situation differs significantly from the regulatory conditions specified in 10 CFR 71 for a fully engulfing pool fire. To learn more about the differences, a series of simple thermal analyses has been completed to estimate cask behavior in likely marine and land thermal accident situations. While the calculations are based on several conservative assumptions, and are only preliminary, they illustrate that casks are likely to heat much more slowly in shipboard hold fires than in an open pool fire. The calculations also reinforce the basic regulatory concept that for radioactive materials, the shipping cask, not the ship, is the primary protection barrier to consider.

THERMAL CALCULATIONS

Thermal models that lump the radiation heat transfer into a few zones were derived to approximate the environment both in a fully engulfing pool fire and in the situation with a fire in an adjacent ship hold. The main purpose of the calculations was to gain some idea

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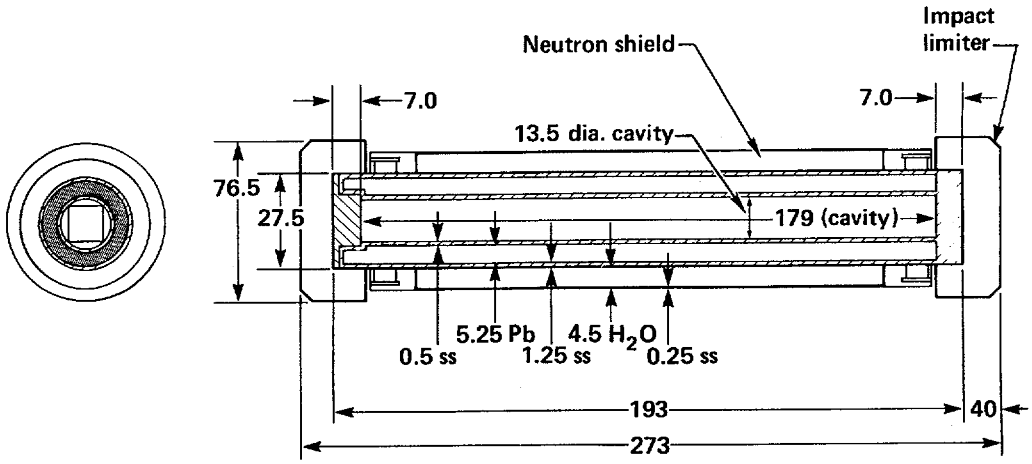

Figure 1. Modal study truck cask.

of the heating time differences between regulatory pool fire conditions and hold fires when similar assumptions are applied. Conservative assumptions, i.e., those leading to the most rapid heating of the cask given the situation, were made for hold fires. Even though simplifying assumptions were made, the models serve to illustrate the significant differences between regulatory conditions and shipboard fires, and give some initial estimates of the slower heatup characteristic of marine fires.

Three simple models based on the principle of conservation of energy were derived: 1) a fully engulfing pool fire, 2) a cask exposed to a hot compartment bulkhead, and 3) a cask inside a shipping container exposed to a hot compartment bulkhead. The cask design chosen as a basis is the same as the truck cask used for the "Modal Study" (Fischer, et al 1987), and is shown in Figure 1. This cask was chosen as a typical example of a range of possible designs. A truck cask was chosen rather than a rail cask because it is less massive, and therefore responds more rapidly to fires. For purposes of rapid calculation, a uniform temperature is assumed throughout the cask at all times, that is, the cask is modeled as a lumped mass. This represents what would happen with a highly conductive cask material, but is conservative in that resulting cask surface temperature is lower than would be calculated from a more detailed model. The lower surface temperature in turn leads to higher radiative and convective heat transfer, especially during early times in the fire development when temperature differences between the cask and the heat source are the highest. In all cases, 4 kW of decay heat from the spent fuel in the cask and an initial cask temperature of 100°C are assumed. For purpose of calculation, the values of density and specific heat for the cask are taken to be that of stainless steel. Adding some lead or depleted uranium densities and specific heats to the model to represent gamma shielding would lead to longer heating times for all cases, but the ratios of heating times among cases would remain the same.

Model 1: Fully Engulfing Pool Fire

The model for the fully engulfing pool fire is shown in Figure 2. The fire parameters shown are those specified both in IAEA Safety Series 6 and 10 CFR 71. The cylindrical cask is surrounded by flames at 800°C with a flame emissivity of 0.9. Both radiation from the flames and convection from still air at 800°C are included in the model. The cask weight and dimensions are taken from the truck cask design of Fischer et al 1987. The

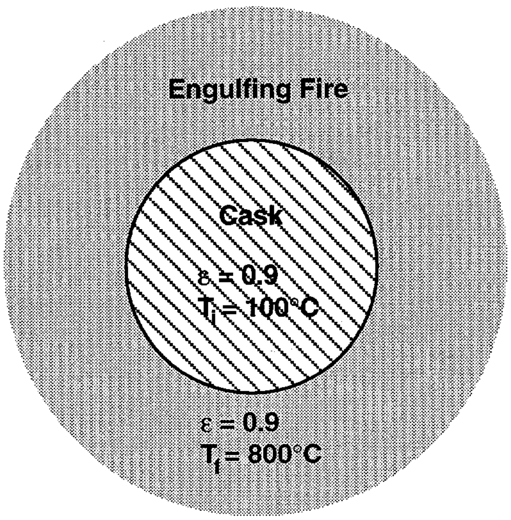

Figure 2. Fully engulfing pool fire.

surface emissivity of the cask is taken to be 0.9, which is greater than the value required by 10 CFR 71, but was chosen to be consistent with the emissivities used for shipboard fires.

Model 2: Cask in Ship Hold

The two-dimensional model assumed to analyze fires in an adjacent ship hold is shown in Figure 3. For this case the shipping container is neglected so that the cask long axis is directly exposed to heat flux from the hot bulkhead and other hold bulkheads. A fire with the same temperature and emissivity as the regulatory pool fire is assumed to occur in the adjacent hold. The hold is assumed to be 6 m x 18 m x 15 m for purposes of calculation. The centerline of the cask is assumed to be 2 m from the hot bulkhead. Thermal radiation to both the hot bulkhead adjacent to the fire and to the other bulkheads is assumed. Hold bulkhead temperatures are estimated from a simple radiation model shown in Figure 4 with view factors for infinite parallel plates assumed. As shown in Figure 3, hot and back bulkhead temperatures of 680°C and 530°C result. View factors between the cylindrical

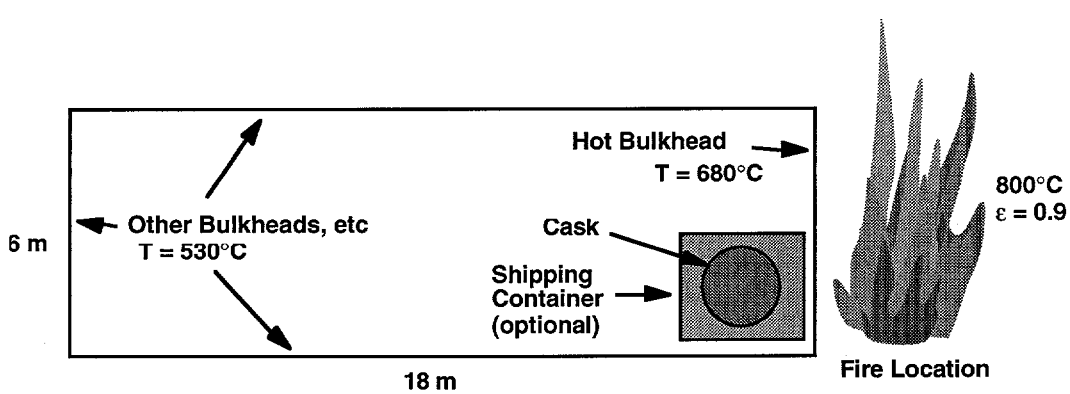

Figure 3. Hold fire configuration.

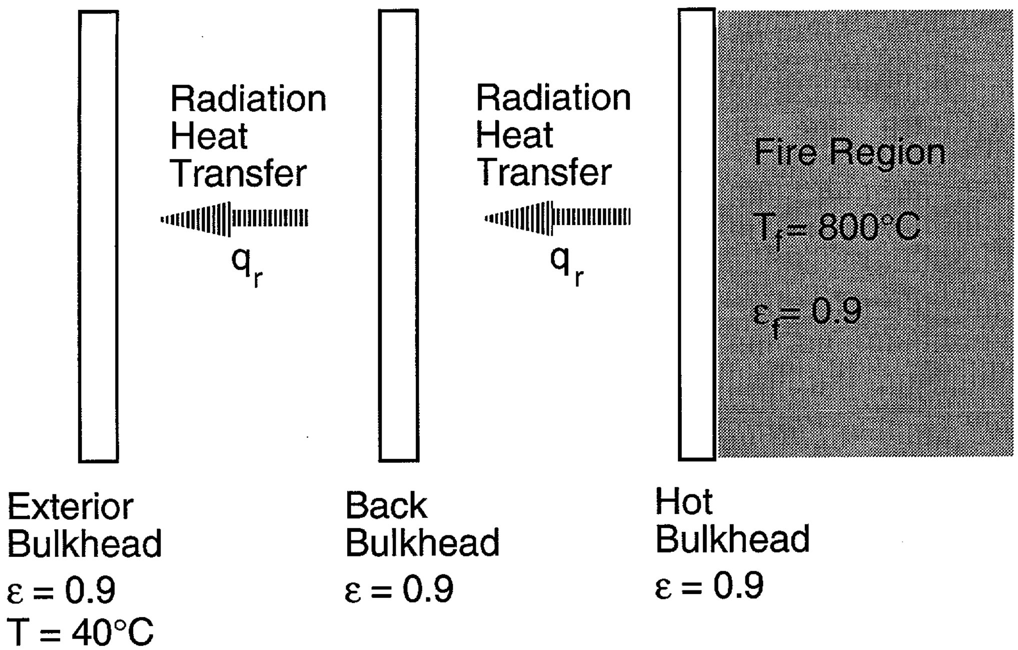

Figure 4. Model for estimating hold bulkhead temperatures.

cask and the bulkheads are calculated from text book values (Siegel and Howell 1992). Natural convection to the cask is assumed with the air temperature taken to be the same as the other hold bulkhead temperature (530°C). Convective film coefficients for a cylinder surrounded by air at 530°C are used (McAdams 1954).

Model 3: Cask in Ship Hold in Shipping Container

The third model is the same as Model 2, except that the cask is enclosed in a shipping container that is used frequently for ease in handling. The shipping container acts as a radiation shield between the bulkheads and the shipping container (see Figure 3). A simple radiative energy balance is used to calculate the container wall temperature, which lies between the hold bulkhead temperatures and the cask temperature, and slows the heating of the cask. View factors between cask and container, and container and bulkheads are textbook values from Siegel and Howell 1992 for planes and cylinders, with two shipping container walls viewing the hot bulkhead, and the other two walls viewing the cooler (530°C) bulkheads. Convection to the cask from air at the average temperature of the container walls is also included.

MODEL ASSUMPTIONS

For rapid analysis, several simplifying assumptions were made. Besides simplifying the analysis, the assumptions make the calculations more conservative in that they lead to a more rapid heating of the cask than would occur if a more detailed model were used. Besides the assumptions described in the previous section, these assumptions are the following.

1) The fire in the adjacent compartment is fully involved at the start of the analysis; that is, at the start of the analysis, all hold bulkheads have reached a steady state temperature.

2) No temperature gradients (no thermal capacitance or resistance) in the hold bulkheads.

3) No sprinkler system in hold, and no emergency response to fire.

4) Other effects neglected:
   Insulating value of impact limiters
   Thermal protection from the neutron absorber material
   Phase change of a lead gamma shield
   Convective cooling of the ship hold
   Possible shielding from thermal radiation by intervening objects

RESULTS

The calculated heating of the models is shown in Figure 5. The temperature after 30 minutes in a fully engulfing fire is identified, and a horizontal line extended to estimate the times for the other models to reach the same temperature. The heating rate of the cask in the ship hold is at least three times slower than for the fully engulfing fire described by 10 CFR 71. Note that the 30 minute temperature in an engulfing fire does not necessarily indicate a cask failure. Extra regulatory tests of shipping casks in pool fires of up to 100 minutes have shown survival without failure (Cashwell, et al 1990). Note that a shipping

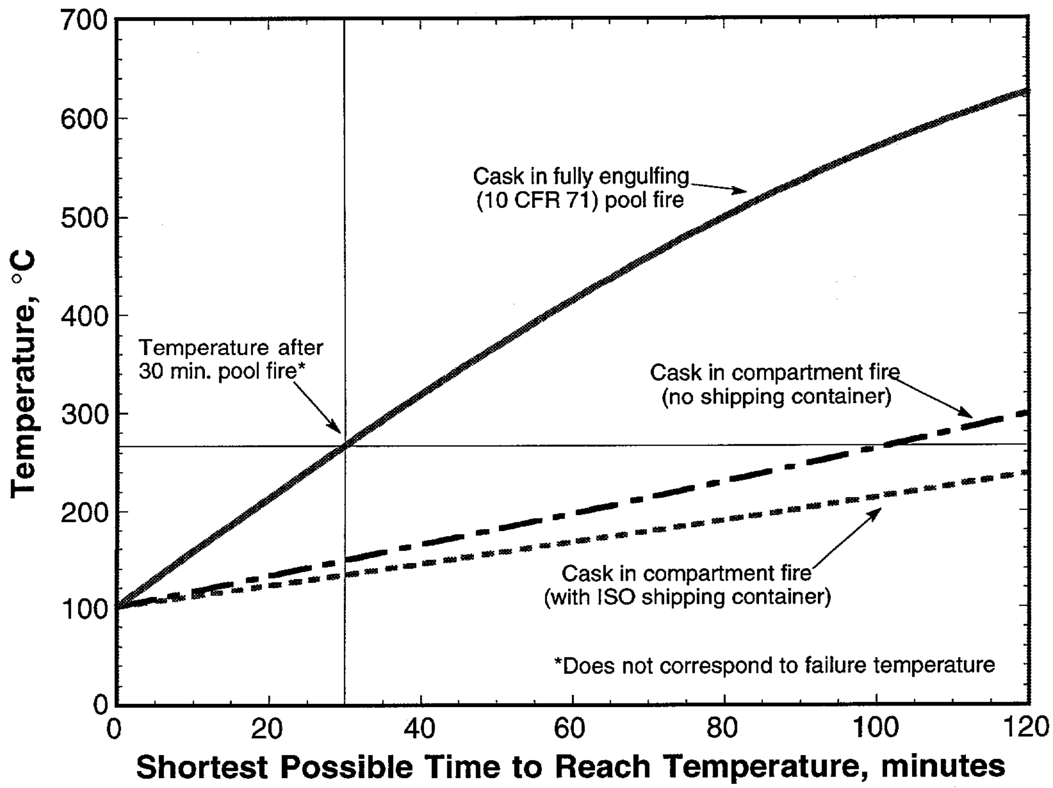

Figure 5. Comparison of heating times.

container surrounding the cask further slows the heating rate. As stated above, these results are intended only to show the approximate relative heating rates. More detailed analyses are required to refine the accuracy of the estimates.

CONCLUSIONS

The calculations demonstrate that fully engulfing pool fires and fires in adjacent areas to ship holds are not equivalent events. Because the casks heat much more slowly, at least three times more slowly in the conservative simplified calculations above, when subjected to shipboard fires in adjacent holds than in fully engulfing fires, much longer fires can be sustained without damage. This result should be considered in risk analyses for marine transport. Further protection of the cask is offered by neutron shields, impact limiters, shipping boxes, etc., but was neglected for these calculations. In addition, unlike the instantaneous hold fire used in the calculations, shipboard fires often require time to grow, and in many cases, limited oxygen may limit the rate of combustion of such fires to lower heat release rates than freely burning pool fires. To better quantify the relative heating rates, a more detailed study of the factors involved is indicated.

Experimental and improved analyitical studies are in progress to further assess the shipboard fire environment. Experiments on an actual ship at the Coast Guard facility at Mobile Bay, Alabama have been conducted simulating the hold fire scenario described above, as well as cargo fires in the same hold. These experiments will serve to bench mark computataional fluid dynamics models that include convection, radiation, and conduction. Once the validation process is complete, the computer code can then be used to examine other fire environments of interest.

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