"Determination of the Time and Temperature for a Design basis Fire Involving a Bare Naval Canister in the IHF," Enclosure 7 to OCS:CMN-1199, June 25, 2007

Ref 4

ENCLOSURE 7

DETERMINATION OF THE TIME AND TEMPERATURE FOR A DESIGN BASIS FIRE INVOLVING A BARE NAVAL CANISTER IN THE IHF

1. Objective

The objective of this simple analysis is to determine a combination of fire temperature and duration that would constitute an adequate design basis for naval spent nuclear fuel (SNF) canisters being processed in the Initial Handling Facility (IHF). The design basis is established to ensure that the probability of canister failure due to a fire is less than 1×10^{-4} over the operational lifetime of the IHF. Assuming an operational lifetime of 50 years, the target probability of canister failure per year would be 2×10^{-6}/yr. For the purposes of this study, an additional safety factor of 2 is assumed, so the target probability of canister failure is 1×10^{-6}/yr.

The analysis reported in this paper provides conservative design basis fire conditions for the following three canister configurations: an SNF canister inside an unsealed M-290 transportation cask (i.e., a cask in which the lid has been removed), a bare SNF canister that has been removed from the transportation cask, and an SNF canister inside an unsealed waste package. As will be shown, disabling fire suppression greatly increases the potential heat load on the canister from the fire. To illustrate the benefit of using fire suppression, the analysis will be performed with and without fire suppression. Additional discussion is also provided regarding the pros and cons of using fire suppression in the IHF.

Continued conservatism was deemed prudent given the preliminary nature of much of the fire analysis, such as the determination of the fire ignition frequency. In addition to the safety factor of 2 used in establishing the target canister failure probability, a number of conservative assumptions have been used in the design basis heat load analysis. These additional conservatisms are identified in the following discussion.

2. Assumptions

In order to perform this analysis, it was necessary to make assumptions with respect to the frequency of fires in the IHF and the conditional probability that a container[1] is threatened by the fire. A detailed fire frequency analysis will be performed as part of the PCSA using the methodology outlined in references 1 and 2 and data reported in reference 3. Because the results from that analysis are not yet available, preliminary estimates of fire frequency will be used.

Based on initial calculations, it is assumed that the fire frequency in any of the YMP surface facilities is approximately 0.02 per year. Not all such fires will threaten a container. A fire that occurs in an area of the facility may occur at a time when no container is present or the container may be too far away from the fire to be affected.

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[1] The term *container* is used to represent a bare canister or a canister in either a waste package or transportation cask.

The current analysis considered only rooms in the IHF in which the naval SNF canister could be in one of the three configurations listed above. The fire frequency was determined for those rooms. When determining the frequency of fires that threaten an exposed SNF canister, the analysis also considered the relatively short period of time in which a canister would be in one of the three exposed configurations. The time during which the canister would be exposed was determined by reviewing the Preliminary Throughput Study for the Initial Handling Facility (dated April 27, 2007). The authors of this report indicated that the throughput information will change as the IHF design and operational information mature.

Table 1 shows the estimated frequencies of fires that threaten an exposed naval SNF canister. The total frequency of fires that threaten the exposed canister is estimated to be 9×10^{-6} per year. To meet the target canister failure probability of 1×10^{-6} per year, the canister would have to be designed such that it would fail less than 11.11 percent of the time. To ensure this, a design basis fire will be selected such that there is only an 11.11 percent probability that a more severe fire will occur. In other words, the design basis fire will be chosen such that it results in an 88.89-percentile heat load on the canister.

Table 1. Frequency of Fires that Threaten an Exposed Naval SNF Canister

Configuration	Room/Area	Room/Area Fire Frequency (/yr) (1,2,3)	Fraction of Time Canister is Exposed[b]	Frequency of Fires that Threaten Canister (/yr)
SNF Canister in Open M-290	Cask Unloading Room	4×10^{-4}	0.001	4×10^{-7}
Bare SNF Canister	Canister Transfer Area[a]	8×10^{-3}	0.001	8×10^{-6}
SNF Canister in Unsealed Waste Package	Waste Package Loading Room	3×10^{-4}	0.002	6×10^{-7}
Total				9×10^{-6}

Notes:

[a] The canister transfer room (room 2005) is assumed to communicate directly with other rooms on the first floor (rooms 1002, 1009, and 1012) so fire ignition frequencies for these rooms are combined.

[b] This fraction is calculated by dividing the total exposure time for all 400 naval canisters by the assumed 50-year operating lifetime.

3. Calculation Approach

When calculating the heat load on the container, radiation is assumed to be the dominant mode of heat transfer between the fire and the container. The magnitude of the radiant heating of the container depends on the fire temperature, the emissivity of the container, the view factor between the fire and the container, the duration of the fire, and whether or not the fire suppression system has been actuated. Fire suppression affects both the duration of the fire and the heat transfer to the container.

The total radiant energy deposited in the container can be roughly estimated using the following simple equation:

$$Q_{rad} = \varepsilon F_{cf} \sigma (T_{fire})^4 A t F_{sup} \qquad (1)$$

where:

Q_{rad} = incident radiant energy over the fire duration (J)
ε = emissivity of the container
F_{cf} = container-to-fire view factor
σ = Stefan-Boltzmann constant ($W/m^2\ K^4$)
T_{fire} = equivalent blackbody fire temperature (K)
A = container surface area (m^2)
t = duration of the fire (s)
F_{sup} = reduction factor to account for effect of fire suppression

The following variables in this equation are treated as uncertainties: fire temperature, view factor, fire duration, and reduction factor due to suppression. The values and probability distributions used in the analysis are discussed below.

An Excel add-in, Crystal Ball, is used to sample from each of the probability distributions and to recalculate the radiant heat load for thousands of Monte Carlo samples. The 88.89-percentile value for the calculated radiant heat load is then determined from the resulting probability distribution. The combination of fire duration and temperature that would produce these heat loads are then calculated.

4. Model Inputs

4.1 Fire Temperature

A probability distribution for the fire temperature was developed based on consideration of test data reported in the Society of Fire Protection Engineering (SFPE) Handbook. A normal distribution is assumed with a mean and standard deviation of 1072 K and 172 K, respectively. This distribution applies to all fires whether they are fueled by solid combustibles or liquid hydrocarbon fuels.

Because the fire temperature distribution reflects combustion of both solid and liquid fuels and liquid fuels generally burn hotter, the fire temperature distribution would likely overestimate the fire temperature for rooms in which only solid or noncombustible liquids would be present. When the final fire analysis is performed for the PCSA, separate fire temperature distributions will be developed for rooms with and without combustible liquids.

4.2 Emissivity of the Container

In the current analysis, the emissivity of the container is assumed to be 0.8. This value does not affect the resulting calculation of fire temperature or duration because it is used both in the initial calculation of radiant heat load and the subsequent calculation of the fire temperature required to produce the design basis heat load.

4.3 View Factor

Canister designers generally analyze canister response to a fire by assuming the canister is engulfed in the fire. For this condition, the view factor is 1.0. In the fire fragility model to be used in the PCSA, it is not always assumed that the fire engulfs the canister. Instead, it is assumed that the canister is engulfed some fraction of the time and, at other times, the fire is some distance away. For small rooms, it is assumed that the fire engulfs all or part of the canister 50 percent of the time, whereas for large rooms, it is assumed that the fire engulfs the canister 10 percent of the time.

A probability distribution for the view factor was calculated using Crystal Ball. This analysis assumed a range of distances and a range of fire sizes (height and diameter). Figure 1 presents the resulting cumulative probability distribution for the view factor from the canister to the fire.

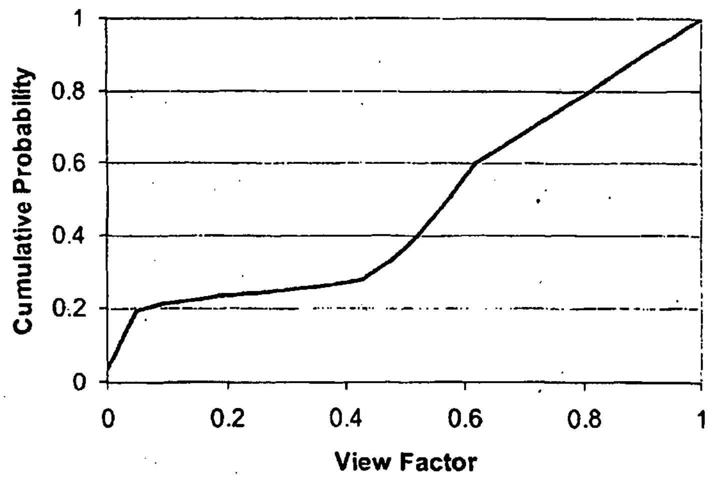

Figure 1. Cumulative Probability Distribution for the View Factor from the Canister to the Fire

4.4 Duration of the Fire

Separate probability distributions for fire duration have been developed for conditions with and without fire suppression. These probability distributions were developed based on consideration of test data reported in references 4 through 7. Both fire duration distributions are assumed to be log-normal. The log means and log standard deviations for the two distributions are shown below.

Table 2. Log-Normal Distribution Parameters for Fire Duration

Distribution Parameters	Without Suppression	With Suppression
Log Mean	3.19	2.85
Log Standard Deviation	0.69	0.43

The two fire duration distributions shown in Table 2 are considered applicable for most industrial facilities. During the design of the YMP preclosure facilities, special attention is being paid to limiting the quantity and type of combustible material that may be present. For that reason, potential fires in the YMP facilities may be shorter in duration than assumed in the current analysis. The fire duration distributions will be refined as part of the PCSA.

4.5 *Effect of Fire Suppression on Heat Transfer*

In addition to affecting the duration of the fire, test data indicate that fire suppression reduces the effective heat transfer from the fire to objects in a room. This was accounted for in the analysis using a scale factor, which was treated using a probability distribution. The probability distribution for the scale factor is assumed to be log-normal with a log mean and log standard deviation of -2.144 and 0.703, respectively.

5. Results

A Monte Carlo analysis was performed in which the probability distributions for the uncertain model parameters were repeatedly sampled and Equation 1 was solved for each sample. In order to determine the impact of fire suppression on the design basis conditions, calculations were performed with and without fire suppression.

In calculations with fire suppression, it was assumed that the fire suppression system would actuate 99.9 percent of the time (i.e., it would fail to actuate 0.1 percent of the time). Therefore, in 99.9 percent of the Monte Carlo samples, the suppression scale factor was sampled and the fire duration was sampled using the distribution appropriate for fire suppression. In the remaining 0.1 percent of the samples, the suppression scale factor was assumed to be 1.0 and the fire duration distribution without suppression was sampled.

Table 3 shows the calculated upper 88.89-percentile values for Q_{rad} with and without fire suppression. Based on these values for Q_{rad}, the equivalent blackbody temperature for an engulfing fire can be estimated using Equation 2

$$T_{fire} \doteq \left(\frac{Q_{rad}}{\varepsilon \sigma A t} \right)^{1/4} \quad (2)$$

Table 3 shows the calculated fire temperatures if the duration of the fire is assumed to be 30 minutes. The table shows that use of fire suppression substantially reduces the design basis heat load on the canister.

Table 3. Calculated Design Basis Fire Temperature for Exposed Naval Canisters with and without Fire Suppression (30 minute Fire)

	Without Suppression	With Suppression
Q_{rad} (MJ)	4,050	380
For a 30 minute fire		
T_{fire} (K)	1085	635
T_{fire} (C)	812	362

It should be noted that Equations 1 and 2 neglect heating of the container by the fire. As the container heats up, the net radiation heat transfer to the container is reduced. However, because the fire temperature is likely to be much higher than the container temperature and the magnitude of the radiation heat transfer depends on the fire temperature raised to the fourth power, neglecting heatup of the container is not likely to introduce substantial errors in the calculation.

6. Pros and Cons of Using Fire Suppression in the IHF

The current operational concept for the IHF is to enable fire suppression only when the naval SNF canister is sealed either in the M-290 transportation cask or in the waste package. This could be accomplished by 1) disabling fire suppression only when the canister is exposed or 2) permanently disabling fire suppression in all rooms in which the canister may be exposed.. Disabling fire suppression only when the canister is exposed would require repeated manual operations to disable and then enable fire suppression and would introduce additional potential for human error. Always disabling fire suppression in any room in which the canister could be exposed would increase fire risk by increasing the probability that fires in those rooms grow to much larger fires. In either case, disabling fire suppression greatly increases the heat load on the canister and increases the risk of fire associated with the building.

The applicable fire initiating event probability during times in which an exposed naval SFC is present, over the preclosure period, was determined to be approximately 9×10^{-6}/yr × 50 yrs = 4.5×10^{-4}. This places the initiating event into Category 2. If fire suppression is allowed to proceed, then the low fire temperature provides a high conditional probability that a fire induced breach does not occur and there would be no water introduction into the SFC. If fire suppression is not allowed to occur, the probability of fire induced breach is higher. In either case, a probabilistic failure analysis appears to be appropriate to demonstrate under 10 CFR 63 that the conditional probability of breach given the fire is less than 20%. BSC has a probabilistic fire damage method which would require working with NNPP to define a heat flux or temperature breach criterion and to calibrate the probabilistic model to the NNPP calculations.

Another event sequence is the potential for inadvertent actuation of the fire suppression system at a time when the canister has been breached. For example, consider the following scenario: a) a canister is dropped and breaches and b) the fire suppression system actuates inadvertently before the canister can be cleared from the area. The probability that the canister is dropped is likely to be approximately 4×10^{-3} for 400 canister operations. Since the fire suppression system is being designed specifically to avoid inadvertent actuation, the likelihood of an inadvertent actuation during the time period that the canister is bare or in an open overpack is likely to be extremely small ($<10^{-4}$). Taken together, these two events are likely to result in an event sequence probability that would be well below 10^{-4} over the preclosure period.

Another event sequence would involve a canister drop and a fire followed by intentional activation of the fire suppression system. If these events occur independently, then the joint probability would be on the order of $(4 \times 10^{-3}) \times (9 \times 10^{-6})$/yr $\times$ (1/12) yr. In this calculation, 4×10^{-3} is the probability that a canister is dropped during the preclosure period, 9×10^{-6}/yr is the probability per year that a fire occurs, and 1/12 yr is the assumed time that the canister would be present before being removed from the facility (1 month). The resulting probability is much less than 10^{-4} over the preclosure period.

There is a postulated event sequence in which a fire occurs within the shielded transfer bell during the time that the canister is inside the transfer bell. During lift and translation of a canister, CTM gearboxes would be located over the bell and, for a short time, the gearboxes would also be located over the cask. For this event sequence to occur, a gearbox failure and fire would have to occur during the short time interval that this configuration exists (~ 0.1% of the time). With proper inspection and maintenance, gearbox mean time between failures would be on the order of 1 million hours. Using biannual inspection/repair on the CTM, the joint probability of this event sequence would be on the order of $(1 \times 10^{-3}) \times (1 \times 10^{-6}$/hr) $\times$ 2 yrs $\times$ 8760 hrs/yr or 2×10^{-5} over the preclosure period. It should be noted that this simple calculation assumes that the fire occurs and does not consider the inherent inflammability of the lube oil.

7. References

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