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Probability Analysis of MCO Over-Pressurization During Staging

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Abstract: An estimate of the frequency that a Multi-Canister Overpack (MCO) will over-pressurize during staging at the Canister Storage Building is presented. The estimate is based on evaluating the limiting amount of water that can remain in an MCO following cold vacuum drying that, when fully reacted, will not result in over-pressurization of the container. The probability of having the limiting amount of water in a MCO is determined based on distributions of parameters that impact the amount of fuel particulate loaded and the water content of the fuel particulate. A Monte Carlo technique is used to vary the parameters over these distributions to produce a distribution for total water content in overpacks, which is evaluated at the limiting water amount to provide the probability for the occurrence of over-pressurization.

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During Staging

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PROBABILITY ANALYSIS OF MCO OVER-PRESSURIZATION DURING STAGING

1.0 PURPOSE

The purpose of this calculation is to determine the probability of Multi-Canister Overpacks (MCOs) over-pressurizing during staging at the Canister Storage Building (CSB). Pressurization of an MCO during staging is dependent upon changes to the MCO gas temperature and the build-up of reaction products during the staging period. These effects are predominately limited by the amount of water that remains in the MCO following cold vacuum drying that is available for reaction during staging conditions. Because of the potential for increased pressure within an MCO, provisions for a filtered pressure relief valve and rupture disk have been incorporated into the MCO design. This calculation provides an estimate of the frequency that an MCO will contain enough water to pressurize beyond the limits of these design features. The results of this calculation will be used to support further safety analyses and operational planning efforts.

2.0 SUMMARY OF RESULTS AND CONCLUSIONS

Under the bounding steady state CSB condition assumed for this analysis, an MCO must contain less than 1.6 kg (3.7 lbm) of water available for reaction to preclude actuation of the pressure relief valve at 100 psid. To preclude actuation of the MCO rupture disk at 150 psid, an MCO must contain less than 2.5 kg (5.5 lbm) of water available for reaction. These limits are based on the assumption that hydrogen generated by uranium-water reactions is the sole source of gas produced within the MCO and that hydrates in fuel particulate are the primary source of water available for reaction during staging conditions. The results of this analysis conclude that the probability of the hydrate water content of an MCO exceeding 1.6 kg is 0.08 and the probability that it will exceed 2.5 kg is 0.01. This implies that approximately 32 of 400 staged MCOs may experience pressurization to the point where the pressure relief valve actuates. In the event that an MCO pressure relief valve fails to open, the probability is 1 in 100 that the MCO would experience pressurization to the point where the rupture disk would actuate. Sensitivity analysis shows that the water content of fuel particulate is the most influential factor to these calculations. The results of continued study and analysis of the fuel particulate water content should be considered for future refinement of this analysis.

3.0 ASSUMPTIONS

The following is a summary of general assumptions used in this calculation which are described in greater detail in Section 5.0.

- 1) A conservative temperature of 285 °F was assumed for the MCO atmosphere based on the results of a two-dimensional thermal hydraulic model of the CSB during bounding steady state conditions documented in WHC-SD-SNF-ER-014 (WHC 1996). Assumed CSB operating conditions were storage of a high powered MCO (929 watts) during the hottest 8.5 days on record plus 15% to assure that bounding values were used. An additional 5°F was added for two-dimensional temperature variations in the CSB.
- 2) The uranium-water reaction is assumed to be the primary reaction that results in gas release for pressurization of an MCO. All other sources of gas release including uranium hydride reactions, radiolytic decomposition of water, fission product gases, and decomposition of organics or other compounds, are assumed to be negligible for conditions during staging. This assumption is justified since the expected CSB steady state temperatures are below those required for uranium hydride reactions and the relatively short duration of the staging period does not allow significant gas production from radiolytic decomposition or fission processes. Decomposition of organics and/or other compounds is expected to be negligible.
- 3) Water in the MCO that is available for reaction during staging is assumed to be in the form of hydrates of uranium oxide particulate. It is assumed that the CVD process will remove all free water and that the adsorbed water content will be negligible based on calculations provided in Plys 1997.
- 4) Chemical reactions within the MCO occur at a rate slow enough to allow dissipation of the reaction heat such that increases in MCO gas temperature due to reactions is negligible.
- 5) A minimum free gas volume (worst case) of an MCO is assumed to be 0.5 m³ based on an MCO filled with six E length Mk IV fuel baskets.
- 6) The MCO is initially filled with helium gas at 3 psig and a fill temperature of 10°C. The CSB storage tube is also pressurized with helium to 3 psig.
- 7) Over-pressurization of an MCO is defined for this analysis as venting the atmosphere of the MCO into the CSB storage tube. The pressure relief valve is assumed to crack open at 100 psid (117.7 psia). The rupture disk is assumed to actuate at 150 psid (167.7 psia). Over-pressurization occurs by either

exceeding the pressure relief valve set-point, or, if the relief valve fails to open, exceeding the rupture disk actuation pressure.

- 8) Previous parameter assumptions for nominal particulate loading and generation from Pajunen et al. (1996 and 1997) were used for this analysis, with the exception of fuel particulate water content (developed in Section 5.2). The assumption that parameters are statistically independent, made in the previous analyses, is also assumed for this analysis.
- 9) Bounding fuel particulate water content values reported in Plys (1997) were assumed for the minimum (1.2 wt%), nominal (5.9 wt%) and maximum (10.7 wt%) values for the probability distribution for particulate water content (developed in Section 5.2).

4.0 SOURCES

- Pajunen, A. L., Cowan, R. G., Muhlestein, L. D., and Groth, B. D., 1996, *A Probabilistic Assessment of Fuel Particulate Contents of a Multi-Canister Overpack*, WHC-SD-SNF-RPT-013, Rev. 0, Westinghouse Hanford Company, Richland, Washington.
- Pajunen, A. L., Muhlestein, L. D., and Allen, M. R., 1997, *Particulate Inventory of a Multi-Canister Overpack*, HNF-SD-SNF-CN-008, Rev. A, SGN Eurisys Services Corporation, Richland, WA 99352.
- Plys, M., (1997), *Bounding Estimate of Fuel Oxide Water Content*, Letter to Joe Swenson, Duke Engineering & Services Hanford from Marty Plys, Fauske & Associates, Inc., dated February 3, 1997.
- Thurgood, M. J., 1997, *Sensitivity of CSB Staging Conditions to Reaction Rates and Fuel Surface Area*, HNF-SD-SNF-CN-005, Rev.0, Duke Engineering and Services Hanford, Richland, Washington.

5.0 CALCULATIONS

The approach taken for this calculation uses a combination of deterministic and probabilistic methods. The calculation begins with a deterministic calculation of the limiting amount of water that can remain within an MCO during staging that, when fully reacted, does not result in over-pressurization of the MCO. A probabilistic model

was then developed to evaluate the residual water content that could exist in an MCO during staging. Probability distributions, developed in previous analyses (Pajunen et al. 1996 and 1997), were used to represent each variable that affects the amount of fuel particulate that is present in an MCO following completion of the CVD process step. These distributions, combined with a distribution developed here for the weight percent water in the fuel particulate, were used to generate a probability density function for residual water in an MCO. This function was then evaluated for the probability of exceeding the limiting water quantities calculated using deterministic methods.

5.1 CALCULATION OF LIMITING WATER MASS

During staging, pressurization of an MCO can occur as a result of changes in the MCO gas temperature and the build-up of additional gases from ongoing chemical reactions. The primary reaction of concern is assumed to be the reaction between water and uranium. It is assumed that the CVD process will remove all free water from the MCO and that the primary source of water available for reaction during staging will be the remaining hydrates of uranium oxide particulate. Adsorbed water is assumed to be negligible based on calculations provided in Plys 1997. The reaction between water and uranium produces one molecule of hydrogen gas (H_2) for every molecule of water consumed according to the formula:

The equilibrium pressure of the MCO (the pressure the MCO will go to if all of the water is reacted and the MCO comes to thermal equilibrium with its environment) is a function of the hydrate water mass assumed to be in the MCO once it is sealed, the free gas volume of the MCO, the fill gas, the fill temperature and the steady state temperature of the MCO for a given environment. This relationship from the ideal gas equation of state is provided as:

$$P_{eq} = \frac{m_f R_f + m_{H_2O} \frac{M_{H_2}}{M_{H_2O}} R_{H_2}}{V_{free}} \times T_{eq} \quad (1)$$

where;

- m_f = mass of the fill gas,
- R_f = fill gas constant,
- m_{H_2O} = mass of H_2O ,
- M_{H_2} = molecular weight of H_2 ,
- M_{H_2O} = molecular weight of H_2O ,
- R_{H_2} = hydrogen gas constant,
- V_{free} = minimum free gas volume of an MCO, and
- T_{eq} = steady state temperature.

Assuming that the MCO is filled with helium at 3 psig (17.7 psia) and an initial temperature of 10°C (50 °F), the mass of the fill gas in the MCO before any water reactions take place is calculated as:

$$m_f = \frac{P_{abs} V_{free}}{R_f T_f} \quad (2)$$

where; P_{abs} = absolute gas pressure (17.7 lbf/in²),
 V_{free} = minimum free gas volume of an MCO (0.5 m³),
 R_f = fill gas constant (386 ft-lbf/lbm-°R), and
 T_f = fill gas initial temperature (510 °R).

$$m_f = \frac{[(17.7 \frac{\text{lbf}}{\text{in}^2}) \times (\frac{12 \text{ in}}{1 \text{ ft}})^2] [0.5 \text{ m}^3 \times (\frac{1 \text{ ft}}{0.3048 \text{ m}})^3]}{(386 \frac{\text{ft-lbf}}{\text{lbm-R}}) (510 \text{ R})} \quad (3)$$

$$m_f = 0.2286 \text{ lbm} \times \frac{0.4536 \text{ kg}}{1 \text{ lbm}} \quad (4)$$

$$m_f = 0.1037 \text{ kg} \quad (5)$$

The equilibrium temperature, T_{eq} in equation 1, is taken to be the steady state temperature of the MCO atmosphere. Steady state temperatures of the CSB and MCO components have been modeled using a two-dimensional thermal-hydraulic model documented in WHC-SD-SNF-ER-014 (WHC 1996). The model includes conservative assumptions and develops bounding steady state temperatures expected during staging. A high powered MCO of 929 watts was assumed using the bounding MCO decay heat of 835 watts (DESH 1997) plus approximately 10% to assure a bounding value was used. Operational assumptions used were the hottest 8.5 days on record plus 15% to assure that bounding values were used. An additional 5°F was added for two-dimensional temperature variations in the CSB.

The results for MCO structures are presented in Figure 7.2 of WHC-SD-SNF-ER-014 (WHC 1996). The results indicate that steady state temperatures of MCO components are being approached after approximately 90 hours of storage in the CSB. Component temperatures range from approximately 245 °F at the MCO wall to about 285 °F at the center support. The MCO gas temperature would fall somewhere in between these values, but for conservatism, the higher center support temperature of 285 °F will be assumed for the MCO gas temperature during steady state conditions. The verification and validation of the CSB steady state modeling, by

comparisons with hand calculations and comparisons with other codes, has been performed and will be documented separately.

Setting P_{eq} equal to the rupture disk actuation pressure of 167.7 psia and T_{eq} to the steady state gas temperature of 285 °F, Equation 1 can be solved for the maximum amount of water that can remain in an MCO that precludes actuation of the rupture disk. Rearranging Equation 1 to solve for m_{H_2O} gives:

$$m_{H_2O} = \frac{(M_{H_2O}) \left(\frac{P_{eq} V_{free}}{T_{eq}} - m_f R_f \right)}{M_{H_2} R_{H_2}} \quad (9)$$

where; m_f = mass of the fill gas (0.2286 lbm),
 R_f = fill gas constant (386 ft-lbf/lbm-°R),
 P_{eq} = MCO rupture disk actuation pressure (167.7 psia),
 M_{H_2} = molecular weight of H2 (2.016),
 M_{H_2O} = molecular weight of H2O (18.016),
 R_{H_2} = hydrogen gas constant (766.4 ft-lbf/lbm-°R),
 V_{free} = minimum free gas volume of an MCO (0.5 m³), and
 T_{eq} = steady state temperature, T_{avg} (745 °R).

$$m_{H_2O} = \frac{(18.016) \left(\frac{(167.7 \frac{\text{lbf}}{\text{in}^2} \times (\frac{12 \text{ in}}{1 \text{ ft}})^2) (0.5 \text{ m}^3 \times (3.28 \frac{\text{ft}}{\text{m}})^3)}{745 \text{ R}} - (0.2286 \text{ lbm}) (386 \frac{\text{ft-lbf}}{\text{lbm-R}}) \right)}{(2.016) (766.4 \frac{\text{ft-lbf}}{\text{m-R}})} \quad (10)$$

$$m_{H_2O} = 5.6 \text{ lbm} \times \frac{0.4536 \text{ kg}}{1 \text{ lbm}} \quad (11)$$

$$m_{H_2O} = 2.54 \text{ kg} \approx 2.5 \text{ kg} \quad (12)$$

Similarly, the maximum amount of water allowed to remain in the MCO that precludes actuation of the pressure relief valve at 117.7 psia is calculated to be 1.7 kg (3.7 lbs).

These values represent the amount of water that can be present within an MCO and not have the MCO pressure exceed the pressure relief valve and rupture disk design pressures during steady state CSB staging conditions.

5.2 MODEL DESCRIPTION

After calculating the limiting water masses that can remain in an MCO that preclude actuation of the pressure relief valve and rupture disk, an uncertainty analysis was performed to evaluate the likelihood of an MCO exceeding these water mass limits. The uncertainty analysis was based on a model developed to determine the amount of particulate in an MCO and the amount of hydrate water expected to be held in the particulate. The model was, in principle, identical to the models used to determine a bounding fuel particulate mass in an MCO (Pajunen et al. 1996) and a nominal fuel particulate mass (Pajunen et al. 1997).

The nominal fuel particulate model described in Pajunen et al., 1997, provided several improvements relative to the bounding fuel particulate model in terms of the loading and generation of fuel particulate in an MCO. First, the fuel particulate density distribution was modified to reflect results of fuel particulate density measurements obtained from fuel particulate samples taken from K Basins. Second, five of six fuel particulate cleaning efficiencies developed in the bounding model for removal of particulate from fuel and scrap were modified based on fuel element cleaning data to provide a better representation of the actual cleaning results. Third, the approach used to distribute fuel elements into fuel baskets and into MCOs was modified to better represent the process that will be used in retrieving fuel canisters from K Basins.

The nominal fuel particulate model represents fuel particulate loading and generation for a typical MCO and is more representative of what is anticipated from normal operations. Consequently, this analysis uses probability distributions taken from the nominal fuel particulate model to represent each variable that affects the fuel particulate quantity in the MCO up through completion of the CVD process step.

The total fuel particulate after CVD is equal to the fuel particulate loaded into an MCO during the loading process plus the fuel particulate generated through completion of the CVD process and is represented by the following equation.

$$P_T = P_L + P_G \quad (13)$$

where;

- P_T = total fuel particulate in an MCO (kg),
- P_L = total loaded fuel particulate in an MCO (kg), and
- P_G = total generated fuel particulate in an MCO (kg).

The total generated fuel particulate in an MCO can be written as,

$$P_G = P_B + P_{Tran} + P_{CVD} \quad (14)$$

where; P_B = fuel particulate generated during basket queue and loadout (kg),
 P_{Tran} = fuel particulate generated during MCO transfer to CVD (kg), and
 P_{CVD} = fuel particulate generated during CVD (kg).

The generated particulate following basket queue and loadout is less likely to contain as much water as the loaded particulate. Hydration of the uranium oxide particulate is generally a slow process considering the time required for loadout and transfer to the CVD, and the process conditions of CVD are not conducive to the formation of additional hydrates. However, for conservatism, this analysis will assume that generated particulate has the same amount of water as loaded particulate.

The residual water content in an MCO after CVD is given by:

$$W_R = W_W \times P_T \quad (15)$$

where; W_R = residual water content (kg), and
 W_W = weight percent water content of fuel particulate (wt%)

$$= \frac{\text{kg H}_2\text{O}}{\text{kg Fuel Particulate}}$$

A probability distribution was developed for the weight percent water content of fuel particulate based on the limited data currently available. The *Spent Nuclear Fuel Project Technical Databook* (DESH 1997) provides an upper bound of 10 wt% for the water content of fuel particulate after CVD, however, it does not include lower bound and nominal values needed to develop a probability distribution.

A recent analysis was completed to determine the post-CVD bounding water content of fuel particulate (Plys 1997). The analysis concludes that for the nominal CVD process the bounding water content would be when all of the fuel particulate consists initially of $\text{UO}_4 \cdot 4\text{H}_2\text{O}$. The $\text{UO}_4 \cdot 4\text{H}_2\text{O}$ decomposes to $\text{UO}_3 \cdot 2\text{H}_2\text{O}$ in this case, with a bounding water content of 10.7 wt%. If the CVD process allows vapor purging at 75 °C, the bounding water content would then be when all of the fuel particulate consists initially of $\text{UO}_3 \cdot 2\text{H}_2\text{O}$. The $\text{UO}_3 \cdot 2\text{H}_2\text{O}$ decomposes to UO_3 in this case, providing a bounding water content of 5.9 wt%. However, it is anticipated that $\text{UO}_3 \cdot 2\text{H}_2\text{O}$ could only decompose to $\text{UO}_3 \cdot 0.8\text{H}_2\text{O}$ during staging so that the actual water content available for reaction is 1.2 wt%.

In the absence of having lower bound and nominal values provided for the weight percent water content of fuel particulate, bounding values from Plys (1997) for the $\text{UO}_3 \cdot 2\text{H}_2\text{O}$ case were used to define lower bound (1.2 wt%) and nominal (5.9 wt%) values. The 10.7 wt% upper bound given in Plys (1997) was also used in this analysis as the maximum bounding value of water content. This upper bound is slightly greater than that provided in the Technical Databook and is acceptable since it provides greater conservatism. The water content of fuel particulate is the subject of ongoing study and analysis and these values may require further refinement pending new information.

The values discussed above were used to develop a probability density function for the weight percent water content of fuel particulate. First, it was assumed that the lower water content (1.2 wt%) represents a lower bound such that the probability that the actual water content would exceed 1.2 wt% is 0.99 (or, conversely, a probability of 0.01 that the water content would not exceed 1.2 wt%). Similarly it was assumed that the 50th percentile of the water content was 5.9 wt%. Further, it was assumed that the water content of 10.7 wt% represents an upper bound such that the probability that the actual water content would exceed 10.7 wt% is 0.01 (or, conversely, a probability of 0.99 that the water content would not exceed 10.7 wt%). This information is expressed as a cumulative distribution function (probability of not exceeding a specified value, $\text{Pr}[X \leq x]$) in Table 1.

Table 1. Probability That The Particulate Water Content Will Not Exceed Specified Values.

Particulate Water Content (wt%)	Probability, $\text{Pr}[X \leq x]$
10.7	0.99
5.9	0.50
1.2	0.01

The values in Table 1 were fit to a cumulative distribution function (CDF) by a least squares technique. The Weibull cumulative distribution function was chosen because of its flexibility. The Weibull distribution represents a family of distributions whose shape can characterize several other common distributions by changing the shape parameter. For example, depending on the shape parameter, the Weibull probability density function can represent a symmetric (Normal), skewed right (Lognormal), skewed left, or Exponential distribution. Figure 1 shows the resulting Weibull cumulative distribution function (defined by the three Weibull parameters γ , η , and β) that was fit to the data in Table 1 using a least square technique. Also shown in Figure 1 is the corresponding Weibull probability density function. The mean value of the Weibull probability density function is calculated to be 5.9 wt%, and the area under the right-hand tail of the Weibull probability density function beyond 10.7 wt% was determined to be 0.01. This represents a 0.99 probability of not exceeding

10.7 wt% water. The mean value of the fitted Weibull probability density function and the area under the right-hand tail beyond 10.7 wt% are in agreement with the data in Table 1.

Other sets of probability values (e.g., 0.90, 0.50, 0.10, and 0.80, 0.50, 0.20) for the fuel particulate water content were considered, but the curve fit was very sensitive to small variations in the probability values, particularly the lower end (i.e., 0.01 versus 0.10). The probability values presented in Table 1 and shown in Figure 1 represent the best fit.

Figure 1. Weibull Cumulative Distribution Function and Probability Density Function for Weight Percent Water in the Fuel Particulate per MCO.

5.3 RESULTS

In terms of probability density functions, the residual water content is a convolution of the probability density function for the total fuel particulate and the probability density function for the weight percent water (see Equation 15). The probability density function used for the weight percent water in the fuel particulate is given in Figure 1. Rather than developing an appropriate probability density function for the total fuel particulate and then mathematically convoluting the two probability density functions, the same results are obtained by a Monte Carlo analysis.

Appropriate probability distributions are used to represent each of the variables that affect the total fuel particulate mass (loaded and generated) up through completion of the CVD process. The fuel particulate mass model used was consistent with the nominal fuel particulate model (Pajunen et al. 1997). For each random selection of a value from each variable distribution in the fuel particulate model, a random selection was also chosen for the weight percent water using as an input the probability density function in Figure 1. This process amounts to a random determination of the value P_T multiplied by a random selection of a value W_w to develop a point value for W_R in Equation 15. Randomly sampling many times from each variable in the fuel particulate model and from the weight percent water distribution, determines a corresponding distribution for the value of W_R , the residual water content.

Figure 2 shows the probability distribution developed in the analysis for the total mass of fuel particulate in an MCO (loaded and generated up through CVD). It should be noted that, as expected, the loaded fuel particulate mass per MCO developed in this analysis for the nominal fuel particulate model was the same as the loaded fuel particulate mass per MCO as presented in Pajunen, et al. 1997. However, the generated fuel particulate mass per MCO was different (distribution shifted to lower values) because in the present analysis the fuel particulate generation was only considered up through the CVD process.

Figure 3 shows the probability distribution for the residual water content in an MCO. Also shown in the figure is the probability of the residual water content in an MCO exceeding the values of 1.7 kg and 2.5 kg ($\Pr[X \geq 1.7 \text{ kg}] = 0.08$, and $\Pr[X \geq 2.5 \text{ kg}] = 0.01$, respectively).

Figure 2. Total Fuel Particulate Mass per MCO after CVD for the Nominal Fuel Particulate Model.

Figure 3. Residual Water Content of Fuel Particulate per MCO for the Nominal Fuel Particulate Model.

The probability of exceeding the water limit of 1.7 kg and 2.5 kg was determined from the complimentary cumulative distribution function (CCDF) of the actual data shown in Figure 3. Note that the CCDF gives the probability of exceeding the residual water content in an MCO. The CCDF for the residual water content using the nominal fuel particulate model is presented in Figure 4 together with the residual water content limits. From this data the probability of exceeding 1.7 kg of water and 2.5 kg of water in an MCO for the nominal fuel particulate model is calculated to be 0.08 and 0.01, respectively.

Figure 4. Complementary Cumulative Distribution Function for the Residual Water Content in the Fuel Particulate per MCO for the Nominal Fuel Particulate Model.

5.4 SENSITIVITY ANALYSIS

A sensitivity analysis was performed during the calculations to determine the model parameters that have the greatest influence on the uncertainty in the residual water content of the fuel particulate. Table 2 lists the model parameters with the greatest influence in terms of the percent contribution to the variance in the residual water content.

Table 2. Sensitivity Analysis Results for Residual Water Content Using the Nominal Fuel Particulate Model.

Model input Parameter	Percent Contribution to Variance
Wt% Water Content in Fuel Particulate	45 %
Particulate Density	18 %
Fuel Particulate Pockets Under Clad	17 %

The weight percent water contained in the fuel particulate and the particulate density are the two model parameters with the greatest influence in the variance of the residual water content in the fuel particulate. As noted above, the particulate density for the nominal fuel particulate model (Pajunen et al. 1997) was developed from fuel particulate density measurements from the K Basins. Unless further fuel particulate density measurements are made, the probability density function for the fuel particulate density is the best representation of the available data and, without additional data, further refinements are not possible.

As presented earlier, the probability density distribution for the weight percent water in the fuel particulate was developed using the information provided in Plys 1997. Also as noted, the probability values presented in Table 1 represented the best fit to the data, although other sets of probability values (e.g., 0.90, 0.50, 0.10, and 0.80, 0.50, 0.20) for the fuel particulate water content were considered. The sensitivity of the probability of the residual water content exceeding the 1.7 kg and 2.5 kg limits was evaluated using two other weight percent water probability density functions. The first was a Weibull distribution fit to the data presented in Table 3, and the second was a triangular distribution with the minimum value equal to 1.2 wt% water, the likely value equal to 5.9 wt% water, and the maximum value equal to 10.7 wt% water. It should be emphasized that the original weight percent water probability density function is considered to be the most representative of the available data. These other two probability density functions for the weight percent water were considered in order to evaluate the sensitivity of the probability of exceeding the residual water content of 1.7 kg and 2.5 kg in an MCO to the probability density function for the weight percent water.

Table 3. Consideration of Other Probability Values That The Particulate Water Content Will Not Exceed the Specified Values.

Particulate Water Content (wt%)	Probability, $\Pr[X \leq x]$
10.7	0.90
5.9	0.50
1.2	0.10

The second Weibull distribution (fit to the data in Table 3) has a longer right-hand tail in the probability density function for the weight percent water, and, hence, will result in a longer right-hand tail in the residual water probability density function. The triangular probability density function has no tails (i.e., by definition the probability density is zero for water content larger than 10.7 wt%). Consequently, the triangular probability density function for the weight percent water will result in a shorter right-hand tail in the residual water probability density function. The combined

results are presented in Table 4. The corresponding complimentary cumulative distribution functions are presented in Figure 5.

The results for the best fit for the weight percent water in fuel particulate (Table 1 and Figure 1) and the results for the triangular probability density function are nearly identical (see Table 4). As expected, the results for the second Weibull distribution (fit to the data in Table 3) has a longer right-hand tail in the residual water probability density function. However, the probability that the residual water content will exceed 2.5 kg in an MCO is not that much different (i.e., 0.04 compared to 0.01). Thus, within the uncertainty of the available data, there is a small probability (i.e., the order of 0.01 to 0.04) that the residual water content will exceed 2.5 kg in an MCO (or, conversely, a reasonably large probability, 0.96 to 0.99, that the residual water content will not exceed 2.5 kg in an MCO).

Table 4. Comparison of the Probability of Exceeding a Residual Water Content of 1.7 kg and 2.5 kg in an MCO for Three Weight Percent Water Probability Density Functions.

Weight Percent Water Probability Density Function	Probability of Residual Water Content Exceeding x kg in an MCO	
	x = 1.7 kg	x = 2.5 kg
Original pdf (best fit to data)	0.08	0.01
Triangular pdf	0.08	0.01
Second Weibull pdf (fit to data in Table 3)	0.14	0.04

Figure 5. Comparison of the Complimentary Cumulative Distribution Functions for the Residual Water Content in the Fuel Particulate per MCO.

A comparison of the results is further presented in Table 5 where the probability of not exceeding a specific value for the residual water in the fuel particulate is presented for the three results. For example, from Table 5 there is a probability of 0.99 of not exceeding 2.57 kg, 3.42 kg, and 2.49 kg of water in an MCO using the original Weibull pdf, the 2nd Weibull pdf, and the Triangular pdf, respectively, for the weight percent water in the fuel particulate. Again the original Weibull pdf is considered to be the best representation of the available data for the weight percent water in the fuel particulate.

Table 5. Comparison of the Probability of Not Exceeding a Specific Value of the Residual Water in the Fuel Particulate per MCO.

Probability of Not Exceeding a Specific Value	Residual Water in Fuel Particulate (kg H ₂ O per MCO)		
	Original Weibull pdf	2nd Weibull pdf	Triangular pdf
0.10	0.37	0.30	0.38
0.50	0.79	0.84	0.79
0.80	1.21	1.45	1.26
0.90	1.62	1.90	1.55
0.95	1.92	2.32	1.90
0.96	1.97	2.48	2.02
0.98	2.30	2.86	2.30
0.99	2.57	3.42	2.49
0.999	3.76	4.65	3.28

5.5 CONCLUSIONS

The probability density function for the residual water content in the fuel particulate in an MCO is as presented in Figure 3. A summary of the probability density function for the residual water content in the fuel particulate is presented in Table 6 using the best available representation for the weight percent water. Based on the available data and information developed in this analysis, there is a probability of 0.08 that the hydrate water in an MCO will exceed 1.7 kg. This implies that approximately 32 of the 400 MCOs staged at the CSB may experience pressure relief. There is a probability of 0.01 that the residual water content in the fuel particulate in an MCO will exceed 2.5 kg. This implies that in the event that a pressure relief valve fails to open, there is a probability of 1 in 100 that MCO's rupture disk would be actuated.

Table 6. Summary of the Residual Water in the Fuel Particulate for the Best Representation of the Weight Percent Water Data.

Percentiles	Probability of Not Exceeding	Residual Water in Fuel Particulate (kg / MCO)
50th	0.50	0.79
90th	0.90	1.62
99th	0.99	2.57
999th	0.999	3.76

6.0 REFERENCES

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APPENDIX A
POINT VALUE MODEL RESULTS

POINT VALUE MODEL RESULTS

A.1 INTRODUCTION

The model used in this analysis with associated point value results is presented in Tables A-1, A-2, and A-3. Table A-1 provides the initial MCO canister loading information. Table A-2 provides the MCO fuel particulate loading model, and Table A-3 provides the MCO fuel particulate generation model. In these tables the variables that were represented by probability density functions are in lightly shaded cells, while the forecast values, or results for which probability density functions were determined, are in darker shaded cells.

The model is developed in Microsoft ExcelTM ⁽¹⁾ as a workbook. The Monte Carlo analysis was completed using Crystal BallTM ⁽²⁾. The number of iterations was 1,000, with an initial seed value of 0 (zero). The data obtained from the Monte Carlo analysis was also placed in an ExcelTM workbook for further data reduction. The figures were developed in OriginTM ⁽³⁾, and some further data reduction and calculations were completed using MathcadTM ⁽⁴⁾.

The point value results were each checked using hand calculations to be sure that the model was producing the correct results. In some cases the results of a Monte Carlo single iteration were also checked using hand calculations.

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- (1) Microsoft Excel is a registered trademark of Microsoft Corporation.
 - (2) Crystal Ball is a registered trademark of Decisioneering, Inc.
 - (3) Origin is a registered trademark of Microcal Software, Inc.
 - (4) Mathcad is a registered trademark of MathSoft Inc.

Table A-1. Initial MCO Loading Information.

New Model of Fuel Elements Loaded in an MCO						
Date: 12/2/96						
	Original	Visible to				
	Loading	Survey	Intact	Breached	Defected	Bad
Original Survey	50,683	36,105	25,302	1,816	8,045	942
			70.08%	5.03%	22.28%	2.61%
Assumed Defected Bottoms				3.52%	15.62%	1.83%
Total defected elements			49.11%	8.55%	37.90%	4.44%
Percent Badly Defected Elements	Minimum	0.0%				
	Likely	5.0%	5.0%			1.89%
	Maximum	10.0%				
			49.11%	8.55%	36.00%	6.33%
Fuel Elements per Canister	14		7	1	5	1
Number Elements/Basket	54		6.88	1.20	5.04	0.89
Number Baskets/MCO	4					
Number Elements/MCO	216					
Scrap Baskets/MCO	1					
No. Canister Elements placed in Basket	13	13.11				
No. Canister Elements placed in Scrap	1	0.89				
No. Canisters per basket	4	4.118				
No. Canisters per MCO	16	16.47				
No. Elements per scrap Basket	16	14.6				
Volume bad/good elements	29.6%	27.0%				
Number of MCOs	200					
Loading Per MCO						
Distribution of Defective Elements	Distribution of Defected Fuel Elements per MCO					
	Log Mean	Log Dev		Value		
Number 1	4.43	0.08		84		
	Intact	Breached	Defected			
	112	20	84	216		
MCO Totals						
	Intact	Breached	Defected			
	112	20	84	216		

Table A-2. MCO Fuel Particulate Loading Model.

Particulate Loading Model Elements								
1. Particulate density	Eta =	1.185						
	Beta =	1.537		2.08				
	Gamma =	1						
			Volume	Mass	Effectiveness of the cleaning process			
Defected Assembly Particulate	Initial Values		(kg)	(kg/assembly)	Percent of material removed in cleaning			
2. Fuel particulate in assembly ends								
End volume (two) (cm ²)	44.4							
Particulate depth (cm) - min	0				min	80.0%		
likely	0.25	0.25			likely	95.0%	0.95	
max	1				max	99.0%		
Fuel particulate volume (cm ³)	11.1		23.0621	0.0231	Remaining particulate (cm ³)	0.001		
3. Fuel Particulate Layer on Ext. Sur.								
Surface area (cm ²)	3112							
Layer thickness (cm) - min	5.00E-04				min	80.0%		
likely	5.00E-03	5.00E-03			likely	95.0%	0.95	
max	5.00E-02				max	99.0%		
Fuel particulate volume (cm ³)	15.6		32.3629	0.0324	Remaining particulate (cm ³)	0.0016		
4. Fuel particulate pockets under clad								
Surface area (cm ²)	3112							

Table A-2. MCO Fuel Particulate Loading Model.

Pocket thickness (cm) - min	0							
likely	0.2	0.2						
max	0.5							
Fraction of surface area covered %- min	0				min	0.0%		
likely	0.02	0.02			likely	10.0%	0.1	
max	0.05				max	50.0%		
Fuel particulate volume (cm ³)	12.4		25.8903	0.0259	Remaining particulate (cm ³)	0.0233		
5. Particulate Cladding Split								
Split width (cm)	2							
Split length (cm) - min	5							
likely	20	20			min	10.0%		
max	35				likely	30.0%	0.3	
Split thickness (cm)	1				max	90.0%		
Split volume (cm ³)	40		83.2000	0.0832	Remaining particulate (cm ³)	0.05824		
6. Plugged flow channels								
Particulate plug (cm) ²	7.53							
Plug length - min	0.635				min	80.0%		
likely	2.54	2.54			likely	95.0%	0.95	
max	6.858				max	99.0%		
Particulate plug volume (cm ³)	19.13		39.7858	0.0398	Remaining particulate (cm ³)	0.0020		
7. Scrap for scrap basket								
Scrap basket volume (cm ³)	167213							
Void volume	60.0%							

Table A-2. MCO Fuel Particulate Loading Model.

Volume of scrape (cm ³)	66885							
Fraction of Vol. as particulate - min	5.0%				min	80.0%		
likely	20.0%	0.2			likely	95.0%	0.95	
max	50.0%				max	99.0%		
Volume of particulate in Scrap basket	13377		27824.32	27.82	Remaining particulate (cm ³)	1.39		
	Part. Mass	Number			Effectiveness of Cleaning	Part. Mass	Number	
Defected Fuel Element	(kg/assembly)	80			Remaining particulate	(kg/assembly)	80	
1. Fuel particulate in assembly ends	0.0231				1. Fuel particulate in assembly ends	0.001		
2. Fuel Particulate Layer on Ext. Sur.	0.0324				2. Fuel Particulate Layer on Ext. Sur.	0.0016		
3. Fuel particulate pockets under clad	0.0259				3. Fuel particulate pockets under clad	0.0233		
5. Plugged flow channels	0.0398				5. Plugged flow channels	0.0020		
subtotal	0.1211	9.7 kg			subtotal	0.0281	2.2 kg	
	Part. Mass	Number				Part. Mass		
Badly Defected Fuel Element	(kg/assembly)	4			Badly Defected Fuel Element	(kg/assembly)	4	
1. Fuel particulate in assembly ends	0.0231				1. Fuel particulate in assembly ends	0.001		
2. Fuel Particulate Layer on Ext. Sur.	0.0324				2. Fuel Particulate Layer on Ext. Sur.	0.0016		
3. Fuel particulate pockets under clad	0.0259				3. Fuel particulate pockets under clad	0.0233		
4. Particulate Cladding Split	0.0832				4. Particulate Cladding Split	0.0582		
5. Plugged flow channels	0.0398				5. Plugged flow channels	0.0020		
subtotal	0.2043	0.8 kg			subtotal	0.0863	0.3 kg	
	Part. Mass	Number				Part. Mass		

Table A-2. MCO Fuel Particulate Loading Model.

Breached Fuel Element	(kg/assembly)	20		Breached Fuel Element	(kg/assembly)	20	
3. Fuel particulate pockets under clad	0.0259			3. Fuel particulate pockets under clad	0.0233		
5. Plugged flow channels	0.0398			5. Plugged flow channels	0.0020		
subtotal	0.0657	1.3 kg		subtotal	0.0253	0.5 kg	
	Part. Mass	Number			Part. Mass	Number	
Intact Fuel Elements	(kg/assembly)	112		Intact Fuel Elements	(kg/assembly)	112	
3. Fuel particulate pockets under clad	0.0259			3. Fuel particulate pockets under clad	0.0233		
5. Plugged flow channels	0.0398			5. Plugged flow channels	0.0020		
subtotal	0.0657	7.4 kg		subtotal	0.0253	2.8 kg	
Scrap Basket		1		Scrap Basket		1	
Volume of particulate in Scrap basket	27.82			Volume of particulate in Scrap basket	1.39		
subtotal		27.8 kg		subtotal		1.4 kg	
Total Particulate Mass/MCO	Uncleaned	47.0 kg		Total Particulate Mass/MCO	Cleaned	7.3 kg	
From Loading Operation				From Loading Operation			
Scrap Basket	Part. Mass	Number		Scrap Basket	Part. Mass	Number	
	(kg/assembly)	15			(kg/assembly)	15	
All Badly Defected Fuel Elements	0.2043	2.98 kg		All Badly Defected Fuel Elements	0.0863	1.3 kg	

Table A-3. MCO Fuel Particulate Generation Model.

Particulate Generation Model Elements						
Particulate Generation Activities						
Molecular wt. U	238.03	g/gmole				
Molecular wt UO ₂	270.03	g/gmole				
Molecular wt H ₂ O	18	g/gmole				
1. Oxidation Observed in K East Basin						
Oxidation observed under ideal conditions	200	gU/day at 9°C				
low (gU/day at 9oC)	150					
likely (gU/day at 9oC)	200	200				
max (gU/day at 9oC)	900					
Reaction rate factor to account for increased surface area						
min	1					
likely	10	10				
max	25					
Oxidation of total basin fuel						
gU /day in basin	2000					
gU /hr in basin	83.3					
Number of MCOs per basin	200					
gU/day/MCO	10					
gU/hr/MCO	0.42					
2. Basket Queuing and Loadout						
Queuing/loadout times						
min (day)	2					
likely (day)	7	7				
max (day)	30					
gU per basin contents (g)	14000					
gU per average MCO (g)	70					
kg UO ₂ per average MCO (kg)	0.08	kg				
3. Transfer to Cold Vacuum Drying						
Transfer time to cold vacuum drying (hr)						
min (hr)	1					
likely (hr)	4	4				
max (hr)	8					
gU/day/MCO	1.67					
kg UO ₂ per average MCO (kg)	0.002	kg				
4. Cold Vacuum Drying						
			Reaction	Fuel		

Table A-3. MCO Fuel Particulate Generation Model.

	Time	Relative	Rate	Reacted		
Drying Time vs Temp.	(hr)	Rate	(gU/hr)	(g)		
Time at 10 °C	17.3	1	0.42	7.21		
Time at 50 °C	25.6	21	8.75	224.00		
Time at 75 °C	14.5	98	40.83	592.08		
Time at 25 °C	4.5	3.5	1.46	6.56		
				829.85		
gU reacted (g)	829.85					
g UO ₂ generated (g)	941.42					
Number of cycles processed						
min	1					
max	2	1	1			
Total kg UO ₂ generated (kg)	0.9 kg					
6. Weight Percent Water in Fuel Particulate						
Total Particulate up to Cold Vacuum Drying						
Particulate in MCO after loading (kg)	7.32					
Basket Queuing and Loadout (kg)	0.08					
Transfer to Cold Vacuum Drying	0.002					
Cold Vacuum Drying	0.9					
Particulate Generated to CVD	1.023 kg					
Total Particulate to CVD	8.342 kg					
Weight % Water in Particulate	Weibull 1	5.0	Triangular	5.0	Weibull 2	5.0
	gamma	0.00	Min	1.2	gamma	0.00
	eta	6.63	Likely	5.9	eta	7.00
	beta	3.13	Max	10.7	beta	2.00
Residual Water Content	0.417 kg H ₂ O		0.417 kg H ₂ O		0.417 kg H ₂ O	

APPENDIX B

Probability Analysis of MCO Over-Pressurization During Staging

Signatures:

Analysis Performed By:

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M. J. Thurgood*

5/27/97
Date

M. R. Allen
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5/18/97
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T. D. Merkling	X3-79	X			
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R. W. Rasmussen	R3-86	X			
D. A. Reny	R3-11	X			
E. J. Shen	X3-75	X			
K. E. Smith	R3-86	X			
D. W. Smith	R3-11	X			
J. A. Swenson	R3-11	X			
C. A. Thompson	R3-85	X			
M. J. Wiemers	X3-85	X			

Fluor Daniel Hanford

E. W. Gerber	R3-11	X			
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Fluor Daniel Northwest

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L. J. Garvin	R3-15	X			
M. Kummerer	A3-34	X			
D. L. Scott	A3-34	X			
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