For a data source providing exposure data (given in the form of a number $n$ of recorded failures over an exposure time $t$), the likelihood function is a Poisson distribution, expressing the probability that $n$ failures are observed when the expected number of failures is $x$ times $t$. Here also, the likelihood needs to be expressed as a function unconditional on the failure rate $x$, which is done by integrating $x$ out, in a similar manner as above:

$$b := 1..8 \qquad fd(b,x) := dpois(B_{b,1}, B_{b,2} \cdot x) \qquad \text{(Eq. C-5)}$$

$$LB(b,\nu,\tau) := \int_{10^{-8}}^{10^{-2}} fd(b,x) \cdot dlnorm(x,\nu,\tau)\, dx \qquad \text{(Eq. C-6)}$$

(In the above formulas, $b$ is an index used to particularize a likelihood function to a data source in the matrix $B$.)

The maximum likelihood method is used to calculate ν and τ. This involves maximizing the likelihood function for the entire set of data sources. This likelihood function is the product of the individual likelihood function for each data source (this is because the data sources are independent from each other). It is equivalent and computationally convenient to find the maximum likelihood estimators for ν and τ by using the sum of the log-likelihood (logarithm of the likelihood) of each data source.

Therefore, the log-likelihood function to be maximized is:

$$L(\nu,\tau) := \sum_{a=1}^{4} ln(LA(a,\nu,\tau)) + \sum_{b=1}^{8} ln(LB(b,\nu,\tau)) \qquad \text{(Eq. C-7)}$$

To maximize a function, Mathcad requires guess values and a range over which to search for maxima. The quantity ν represents the logarithm of a failure rate, which is expected to be in the $10^{-6}$/hr range. Therefore, a guess value for ν is:

$$\nu := ln(10^{-6}) \qquad \nu = -13.8$$

Based on a typical error factor value of 10, a guess value for τ is:

$$\tau := \frac{ln(10)}{1.645} \qquad \tau = 1.4$$

A reasonable range over which to perform the likelihood maximization is as follows:

*Given* $\nu > -20$ $\nu < -1$

$\tau > 0.01$ $\tau < 5$

The maximum likelihood estimators for ν and τ are:

$L := Maximize(L, \nu, \tau)$ $\quad \nu := L_1 \quad \nu = -11.478$

$\tau := L_2 \quad \tau = 1.874$

Therefore, the mean and error factors of the population-variability distribution for the failure rate are (based on the formula in NUREG/CR-6823 (Ref. C5.4, Section A.7.3)):

$m := exp\left(\nu + \frac{\tau^2}{2}\right) \quad m = 6.00 \times 10^{-5}$ per hour

$EF := exp(1.645 \cdot \tau) \quad EF = 21.8$

Notable percentiles of the population-variability distribution are as follows (expressed as hourly failure rates) and shown in Figure C2.1-1:

1st percentile: $qlnorm(0.01, \nu, \tau) = 1.32 \times 10^{-7}$

5th percentile: $qlnorm(0.05, \nu, \tau) = 4.75 \times 10^{-7}$

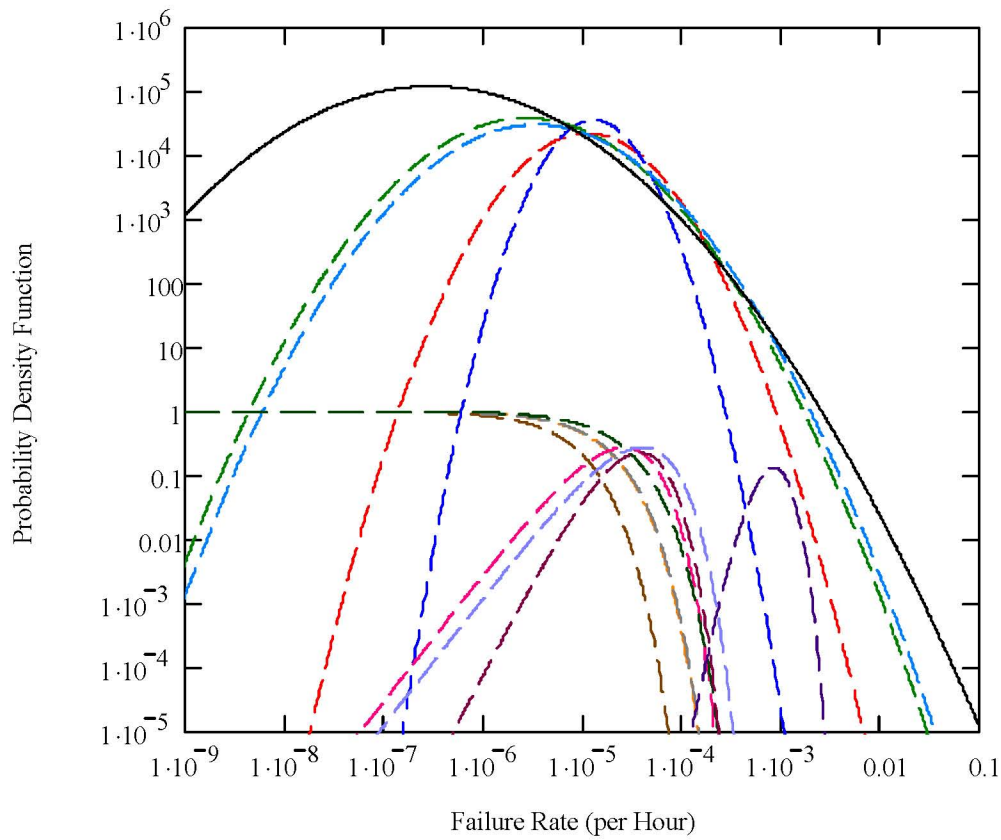
10th percentile: $qlnorm(0.10, \nu, \tau) = 9.38 \times 10^{-7}$

50th percentile: $qlnorm(0.50, \nu, \tau) = 1.04 \times 10^{-5}$

90th percentile: $qlnorm(0.90, \nu, \tau) = 1.14 \times 10^{-4}$

95th percentile: $qlnorm(0.95, \nu, \tau) = 2.26 \times 10^{-4}$

99th percentile: $qlnorm(0.99, \nu, \tau) = 8.10 \times 10^{-4}$




Source: Original

Figure C2.1-1. Likelihood Functions from Data Sources (Dashed Lines) and Population-Variability Probability Density Function (Solid Line)

## C2.2 PARAMETER ESTIMATION IN CASE ONLY ONE DATA SOURCE IS AVAILABLE

To be developed, a population-variability distribution requires at least two data sources, and therefore the previous method is not applicable when only one data source is available. In this case, the probability distribution for the reliability parameter of an active component is that yielded by the data source. For example, if the data source provides a mean and an error factor for the component reliability parameter, the probability distribution is modeled in SAPHIRE as a lognormal distribution with that mean and that error factor. If the data source does not readily provide a probability distribution, but instead exposure data (i.e., a number of recorded failures over an exposure time for failure rates, or over a number of demands for failure probabilities) the probability distribution for the reliability parameter is developed through a Bayesian update using Jeffreys' noninformative prior distribution. As indicated in NUREG/CR-6823 (Ref. C5.4, Section 6.2.2.5.2), this noninformative prior conveys little prior belief or information, thus allowing the data to speak for themselves.

As mentioned in "Bayesian Parameter Estimation in Probabilistic Risk Assessment" (Ref. C5.44, Section 4.2), the likelihood function associated with exposure data is either a Poisson distribution (in the case of failure rates), or a binomial distribution (in the case of failure probabilities).

Applying Bayes' theorem with Jeffreys' noninformative prior in conjunction with a Poisson likelihood function characterized by $r$ recorded failures over an exposure time $t$ results in a closed-form posterior distribution, namely a gamma distribution, characterized by a shape parameter equal to $0.5 + r$, and a scale parameter equal to $t$; the mean of this distribution is $(0.5 + r)/t$ (Ref. C5.4, Sections 6.2.2.5.2 and A7.6). In SAPHIRE, this distribution is characterized by its mean and by its shape parameter (i.e., $0.5 + r$).

Applying Bayes' theorem with Jeffreys' noninformative prior in conjunction with a binomial likelihood function characterized by $r$ recorded failures out of $n$ demands results in a closed-form posterior distribution, namely a beta distribution, characterized by a parameter "$a$" equal to $0.5 + r$, and a parameter "$b$" equal to $n - r + 0.5$; the mean of this distribution is $(0.5 + r)/(n + 1)$ (Ref. C5.4, Sections 6.3.2.3.2 and A7.8). In SAPHIRE, this distribution is characterized by its mean and by the parameter "b" (i.e., $n - r + 0.5$).

## C3 COMMON-CAUSE FAILURE DATA

Dependent failures are modeled in event tree and fault tree logic models, with potential dependent failures modeled explicitly via the logic models, whenever possible. For example, failure of the HVAC system is explicitly dependent upon failures in the electrical supply systems that are modeled in the fault trees. Similarly, the effects of erroneous calibration or other human failure events can be explicitly included in the system fault tree models and the basic event probabilities considered during the human reliability analysis. Otherwise, potential dependencies known as common-cause failures are included in fault tree logic, but their probabilities are quantified by an implicit, parametric method. Therefore, another subtask of the active component reliability data analysis is to estimate common-cause failure (CCF) probabilities.

Surveys of failure events in the nuclear industry have led to several parameter models. Of these, three are most commonly used: the Beta Factor method (Ref. C5.18), the Multiple Greek Letter method (Ref. C5.29) and (Ref. C5.30), and the Alpha Factor method (Ref. C5.31). These methods do not require an explicit knowledge of the dependence failure mode. For the YMP PCSA, CCF rates or probabilities were estimated using the Alpha Factor method described in NUREG/CR-5485 (Ref. C5.31).

The vast majority of the equipment types for which CCF basic events were modeled in the YMP PCSA are not covered by the detailed component-specific alpha factor sources based on commercial nuclear plant equipment. Therefore, it was necessary to use alpha factors to address the CCF estimates for crane hoist wire ropes, gear boxes, over-torque sensors and the like.

The Alpha Factor method provides a model to treat CCF probabilities of $k$-of-$m$ components. In addition, industry-wide alpha factors have been developed for the NRC from experience data collected at nuclear power plants. The data analysis reported in NUREG/CR-5485 (Ref. C5.31) consisted of:

1. Identifying the number of redundant components in each subsystem being reported (e.g., two, three, or four (this is termed the CCF group size, common-cause component group (CCCG) of size $m$)).

2. Partitioning the total number of reported failure events for a given component into the number of components that failed together, i.e., $k = 1$ for one component at a time, $k = 2$ for two components at a time, $k = 3$ for three components at a time, up to $m$ for failure of all components in a given CCF group.

3. Estimating the alpha factor for a given component type based on its definition as the fraction of total failure events that involve $k$ component failures due to common-cause, for a system of $m$ redundant components, using the alpha factor estimator from NUREG/CR-5485 (Ref, C5.31, Table 5-10), as shown below.

$$\alpha_k^m = \frac{n_k}{\sum_{j=1}^{m} n_j} \qquad k = 1, \ldots, m$$

   where $n_i$ is the number of basic events observed that involve failure of i similar components.

4. Performing statistical analysis and curve fitting to define the mean and uncertainty range for alpha factors for various CCF group sizes up to eight.

The data analysis also produced industry-wide prior distributions for the alpha factors for each CCCG size, based on all CCF events in their database. Events were mapped to a given CCCG size, the maximum likelihood estimator obtained and fit to a constrained noninformative prior distribution. The parameter $A_T$ of a Dirichlet distribution was then calculated for each alpha and the results combined using the geometric mean. The results are the industry-wide mean alpha factors and beta uncertainty distributions reported in of NUREG/CR-5485 (Ref. C5.31, Table 5-11) shown in Table C3-1:

Table C3-1. Industry-Wide Alpha Factors

**Table 5-11. Generic prior distributions for various system sizes.**

| CCCG Size m | α-Factor | Distributions Parameters | | Percentiles | | | Mean |
|---|---|---|---|---|---|---|---|
| | | a | b | $P_{05}$ | $P_{50}$ | $P_{95}$ | |
| 2 | $\alpha_1$ | 9.5300 | 0.470 | 8.20E-01 | 9.78E-01 | 1.00E-00 | 0.95300 |
| | $\alpha_2$ | 0.4700 | 9.530 | 1.42E-04 | 2.16E-02 | 1.81E-01 | 0.04700 |
| 3 | $\alpha_1$ | 15.2000 | 0.800 | 8.42E-01 | 9.67E-01 | 9.99E-01 | 0.95000 |
| | $\alpha_2$ | 0.3872 | 15.613 | 2.10E-05 | 8.79E-03 | 1.01E-01 | 0.02420 |
| | $\alpha_3$ | 0.4128 | 15.587 | 3.45E-05 | 1.01E-02 | 1.05E-01 | 0.02580 |
| 4 | $\alpha_1$ | 24.7000 | 1.300 | 8.67E-01 | 9.61E-01 | 9.95E-01 | 0.95000 |
| | $\alpha_2$ | 0.5538 | 25.446 | 1.44E-04 | 1.08E-02 | 7.81E-02 | 0.02130 |
| | $\alpha_3$ | 0.2626 | 25.737 | 2.98E-07 | 1.99E-03 | 4.82E-02 | 0.01010 |
| | $\alpha_4$ | 0.4836 | 25.516 | 6.29E-05 | 8.42E-03 | 7.17E-02 | 0.01860 |
| 5 | $\alpha_1$ | 38.042 | 1.958 | 8.86E-01 | 9.58E-01 | 9.91E-01 | 0.95106 |
| | $\alpha_2$ | 0.7280 | 39.272 | 3.72E-04 | 1.10E-02 | 6.05E-02 | 0.01820 |
| | $\alpha_3$ | 0.4120 | 39.588 | 1.32E-05 | 3.93E-03 | 4.22E-02 | 0.01030 |
| | $\alpha_4$ | 0.2336 | 39.766 | 4.57E-08 | 8.97E-04 | 2.89E-02 | 0.00584 |
| | $\alpha_5$ | 0.5840 | 39.416 | 1.24E-04 | 7.66E-03 | 5.27E-02 | 0.01460 |
| 6 | $\alpha_1$ | 50.4724 | 2.528 | 8.97E-01 | 9.58E-01 | 9.89E-01 | 0.95231 |
| | $\alpha_2$ | 0.7791 | 52.221 | 3.76E-04 | 9.20E-03 | 4.78E-02 | 0.01470 |
| | $\alpha_3$ | 0.5406 | 52.459 | 6.04E-05 | 5.02E-03 | 3.79E-02 | 0.01020 |
| | $\alpha_4$ | 0.3127 | 52.687 | 9.28E-07 | 1.56E-03 | 2.66E-02 | 0.00590 |
| | $\alpha_5$ | 0.2433 | 52.757 | 5.77E-08 | 7.67E-04 | 2.24E-02 | 0.00459 |
| | $\alpha_6$ | 0.6519 | 52.348 | 1.66E-04 | 6.93E-03 | 4.27E-02 | 0.01230 |
| 7 | $\alpha_1$ | 74.5360 | 3.464 | 9.12E-01 | 9.59E-01 | 9.86E-01 | 0.95559 |
| | $\alpha_2$ | 0.9906 | 77.009 | 6.44E-04 | 8.84E-03 | 3.79E-02 | 0.01270 |
| | $\alpha_3$ | 0.6817 | 77.318 | 1.39E-04 | 5.05E-03 | 2.99E-02 | 0.00874 |
| | $\alpha_4$ | 0.4891 | 77.511 | 2.21E-05 | 2.82E-03 | 2.42E-02 | 0.00627 |
| | $\alpha_5$ | 0.2941 | 77.706 | 3.39E-07 | 8.97E-04 | 1.74E-02 | 0.00377 |
| | $\alpha_6$ | 0.2051 | 77.795 | 3.84E-09 | 2.94E-04 | 1.35E-02 | 0.00263 |
| | $\alpha_7$ | 0.8034 | 77.197 | 2.89E-04 | 6.52E-03 | 3.32E-02 | 0.01030 |
| 8 | $\alpha_1$ | 97.6507 | 4.349 | 9.20E-01 | 9.60E-01 | 9.84E-01 | 0.95736 |
| | $\alpha_2$ | 1.1118 | 100.888 | 7.25E-04 | 7.91E-03 | 3.13E-02 | 0.01090 |
| | $\alpha_3$ | 0.7915 | 101.209 | 2.07E-04 | 4.87E-03 | 2.52E-02 | 0.00776 |
| | $\alpha_4$ | 0.6253 | 101.375 | 6.92E-05 | 3.34E-03 | 2.17E-02 | 0.00613 |
| | $\alpha_5$ | 0.4417 | 101.558 | 8.51E-06 | 1.76E-03 | 1.74E-02 | 0.00433 |
| | $\alpha_6$ | 0.2581 | 101.742 | 6.09E-08 | 4.74E-04 | 1.21E-02 | 0.00253 |
| | $\alpha_7$ | 0.1969 | 101.803 | 1.59E-09 | 1.93E-04 | 1.00E-02 | 0.00193 |
| | $\alpha_8$ | 0.9241 | 101.076 | 3.82E-04 | 6.12E-03 | 2.78E-02 | 0.00906 |

Source: Ref. C5.31

Values from Table C3-1 are applied to the YMP PCSA using the CCF algorithms contained in the SAPHIRE code compound event library to combine the random failure probabilities of the events in the CCF group with the appropriate alpha factor for *k*-of-*m* components for failure-on-demand events (e.g., pump failure to start). For example, for a 2-out-of-2 failure-on-demand event, the mean alpha factors of 0.953 and 0.047 shown in the far right column of Table C3-1 associated with $\alpha_1$ and $\alpha_2$ are input into a compound event with the two component demand

failures and the 2-of-2 failure criteria. The CCF algorithm for the alpha-factor common-cause model with staggered testing is selected from the SAPHIRE code library of potential common-cause models to yield the common-cause failure probability.

For failure-to-operate events (e.g., pump fails to run), the mean alpha factor ($M$) for events with more than one failure from Table C3-1 is divided by 2 in accordance with NUREG/CR-5485 (Ref. C5.31). (The mean alpha factor for events with one failure is computed as 1 minus the sum of the remaining alpha factors.) In addition, the parameter b associated with the beta distribution function for the alpha factor is modified to reflect the change in the alpha factor mean value while preserving the coefficient of variation from the distribution described by the parameters presented in Table C3-1. To preserve the coefficient of variation, the variance ($V$) of each failure-to-operate alpha factor is set at one fourth that of the corresponding failure-on-demand alpha factor. The factor of 4 results from allowing the standard deviation to be reduced by a factor of 2, like the mean, but because the variance is the square of the standard deviation, the variance is reduced by a factor of 4. The following formulas give the mean and variance of a beta distribution in terms of the parameters $a$ and $b$ (Ref. C5.4, Section A.7.8). To derive an alpha factor for a failure-to-operate event, the mean alpha factor is taken from Table C3-1 (or computed from the following formula) and divided by 2.

$$M = \frac{a}{a+b}$$

Then, the variance is calculated from the following formula and divided by 4.

$$V = \frac{a \cdot b}{(a+b)^2 \cdot (a+b+1)}$$

Inserting the modified values of $M$ and $V$ into the following formula (which can be derived from the two formulas above) yields the parameter $b$.

$$b = \frac{\left(M - M^2 - V\right) \cdot (1 - M)}{V}.$$

Table C3-2 provides values taken or derived from Table C3-1 in the form required by SAPHIRE, that is, the mean alpha factor and the parameter $b$, which together completely specify the uncertainty distribution.

Table C3-2. Alpha Factor Inputs for SAPHIRE

| SAPHIRE Template Event Identifier[a] | Mean Alpha Factor | Uncertainty Parameter (*b*) |
|---|---|---|
| ALPHADEM-1OF2 | 0.95300 | 0.470 |
| ALPHADEM-2OF2 | 0.04700 | 9.530 |
| ALPHARUN-1OF2 | 0.97650 | 0.0506 |
| ALPHARUN-2OF2 | 0.02350 | 21.036 |
| ALPHADEM-1OF3 | 0.95000 | 0.800 |
| ALPHADEM-2OF3 | 0.02420 | 15.613 |
| ALPHADEM-3OF3 | 0.02580 | 15.587 |
| ALPHARUN-1OF3 | 0.97500 | 0.847 |
| ALPHARUN-2OF3 | 0.01210 | 33.018 |
| ALPHARUN-3OF3 | 0.01290 | 33.018 |
| ALPHADEM-1OF4 | 0.95000 | 1.300 |
| ALPHADEM-2OF4 | 0.02130 | 25.446 |
| ALPHADEM-3OF4 | 0.01010 | 25.737 |
| ALPHADEM-4OF4 | 0.01860 | 25.516 |
| ALPHARUN-1OF4 | 0.97500 | 1.361 |
| ALPHARUN-2OF4 | 0.01065 | 53.016 |
| ALPHARUN-3OF4 | 0.00505 | 53.005 |
| ALPHARUN-4OF4 | 0.00930 | 53.012 |
| ALPHADEM-2OF8 | 0.09812 | 28.600 |
| ALPHARUN-20F8 | 0.04906 | 64.646 |
| ALPHADEM-8OF8 | 0.00906 | 101.076 |
| ALPHARUN-8OF8 | 0.00453 | 205.014 |

NOTE: [a]The identifier follows the pattern ALPHAXXX-*k*OF*m*, where XXX = DEM for failures on demand, XXX = RUN for failures during operation, *m* represents the size of the CCF group, and *k* is the number of failed items within the CCF group.

Source: Original

For the 2-of-8 failure criterion listed in Table C3-2, the value given in each case is not actually a 2-of-8 alpha factor but is a weighted sum of all of the alpha factors for a CCCG of size 8 calculated in accordance with the summation term in the following equation given in NUREG/CR-6268 (Ref. B5.47) for a staggered testing scheme

$$BE_{CCF} = Q_T \sum_{i=k}^{m} C_i \frac{(m-i)!(i-1)!}{(m-1)!} \alpha_i^{(m)}$$

where:

$k$ = specific number failures out of a system of $m$ components

$Ci \equiv$ number of combinations of $k$ component failures that will fail the system.

The weighted sum is treated in the SAPHIRE model as if it were a 2-of-2 alpha factor, which results in multiplication of the component's random failure rate by the weighted sum. The multiplication within SAPHIRE completes the implementation of the equation, giving the CCF probability. This approach was taken because the SAPHIRE plug-in function for computing alpha factors is limited to CCCGs of size 6 or fewer (Ref. C5.47).

This approach was considered to provide conservative CCF data for all the component types for which common-causes were modeled. This was considered particularly important since the YMP has never operated and therefore the applicability of conventional nuclear plant alpha factors could not be justified.

The conservatism of this approach can be demonstrated by comparing the alpha factors used for the PCSA diesel generator CCF events to those posted on the NRC Web site for use in probabilistic risk assessment studies of commercial nuclear power plants in the U.S.

The alpha factor used for the PCSA for 2-of-2 diesel generators failing to start was the 0.047 value cited earlier, while the mean alpha factor for a CCCG=2 cited by the NRC (Ref. C5.36) is 0.0136.

Diesel generators are the only component types for which such a comparison can be made since the other YMP component types for which CCFs were modeled were not covered by the NRC equipment-specific alpha factors.

## C4 ACTIVE COMPONENT RELIABILITY ESTIMATES INPUT TO SAPHIRE

Since the primary active component reliability data task objective is to support the quantification of fault tree models developed in SAPHIRE by the system analysts, the output data had to conform to the format appropriate for input to the SAPHIRE code.

SAPHIRE provides template data to the fault tree models in the form of three input comma delimited files:

- .BEA – attributes to assign information to the proper SAPHIRE fields
- .BED – descriptions of the component type name and failure mode
- .BEI – information on the failure rate or probability estimates and distributions used.

Demonstration files for the .BEA, .BED and .BEI template data files provided with SAPHIRE were originally used to construct the PCSA template data files to ensure the proper formatting of the data for use by the fault tree models. In general, the .BEA file provides attribute designators for the code to implement such that the template data is properly assigned to the appropriate fields in SAPHIRE. The .BED file allows description information to be entered and linked to the template data name or designator (which in the YMP PCSA case was the TYP-FM coding). Examples of descriptions used for the PCSA template data were Clutch Failed to Operate, Relay Spurious Operation, Position Sensor Fails on Demand, and Wire Rope Breaks. The .BEI file contains the actual active component reliability parameters, namely the mean value and uncertainty parameter, either the Lognormal Error Factor, or the shape parameter of the beta or gamma distributions.

Geometric means of the input parameters from the industry-wide data sources were initially used as screening values for each TYP-FM and were entered into the .BEI file, along with a default Error Factor of 10. Once the Bayesian combination process was completed for all 275 TYP-FM combinations, mean and uncertainty parameter information was entered into the BEA files, and tested in SAPHIRE before being distributed to the systems analysts.

Failure probability per demand information was entered as SAPHIRE Calculation Type 1 for a simple probability and failure rate per hour information was entered as SAPHIRE Calculation Type 3 as a mean failure rate in the lambda field. Calc Type 3 uses the formula $P = 1 - \exp(-\lambda T_m)$, where $\lambda$ is the mean failure rate (or lambda) and $T_m$ is the mission time. Mission time is defined in the SAPHIRE Basics manual as "…the period of time that a component is required to operate in order to characterize the component operation as successful." Since the template data was to be used for all YMP facilities while the mission times would be system-specific, the mission time field in the three template data files was left blank and these times were instead input individually by the systems analysts.

The correlation class field was also used for the YMP template data files "to account for data dependencies among like events in the database" during the uncertainty analysis, as stated in the SAPHIRE Basics manual. This meant that all components in the same correlation class would be treated the same during the uncertainty analysis. This feature of SAPHIRE is based upon the observations documented (Ref. C5.2) that in the risk models, all components of the same type are quantified with the same failure rate or probability, therefore it is appropriate to group together the experience of all the nominally identified components in the same facility. Therefore, all components of the same type and failure mode are aggregated into a single number, meaning that the dependency between components of the same class must somehow be addressed. For example, if multiple motor-operated valves needed to open for success and all are assigned the same failure probability, then these basic events needed to be correlated via being assigned the same correlation class in the .BEI file. However, if different probabilities were to be used for different motor-operated valves based on the data, then the basic events would not be correlated. In all cases, a correlation class identifier, using the TYP-FM acronyms, was input to the .BEI file to indicate that all equipment with in the same TYP-FM should be correlated by the SAPHIRE model. SAPHIRE then would sample from one distribution and then use this sampled probability for all other basic events with the same correlation class.

The template data was also identified by TYP-FM combination and was utilized by the fault tree models by being imported into SAPHIRE using the MAR-D portion of the code, then by using the Modify Event feature to link the template data to each basic event in the fault tree. This permitted each active component of the same type and failure mode to utilize the same failure estimate and uncertainty information, based on the results of the industry-wide data investigation and Bayesian combination process.

Table C4-1 shows the active component reliability estimates that were input to SAPHIRE as template data for fault tree model quantification.

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| AHU-FTR | Air Handling Unit Failure to Run | G | 5.00E-01 | — | 3.80E-06 | 1 source; N/D | NUREG/CR-6928 (Ref. C5.16) |
| ALM-SPO | Alarm/Annunciator Spurious Operation | L | 1.30E+01 | — | 4.74E-07 | 5 sources N/D; 1 source mean | IEEE-500 (Ref. C5.23), NPRD-95 (Ref. C5.40) |
| AT-FOH | Actuator (Electrical) Failure | L | 1.24E+01 | — | 7.54E-05 | 3 sources; N/D | NPRD-95 (Ref. C5.40) |
| ATH-FOH | Actuator (Hydraulic) Failure | L | 3.81E+01 | — | 8.91E-04 | 4 sources; N/D | NPRD-95 (Ref. C5.40) |
| ATP-SPO | Actuator (Pneumatic Piston) Spurious Operation | L | 5.00E+00 | — | 1.34E-06 | 1 source; mean + EF | NPRD-95 (Ref. C5.40) |
| AXL-FOH | Axle Failure | G | 5.00E-01 | — | 1.60E-08 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| B38-FOH | Bearing Failure | L | 1.13E+01 | — | 2.50E-06 | 8 sources; N/D | NPRD-95 (Ref. C5.40) |
| BEA-BRK | Lifting Beam/Boom Breaks | G | 1.50E+00 | — | 2.40E-08 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| BLD-RUP | Air Bag Ruptures | B | 1.10E+04 | 1.36E-04 | — | 1 source; N/D | BSC 2007 (Ref. C5.7) |
| BLK-FOD | Block or Sheaves Failure on Demand | B | 1.30E+06 | 1.15E-06 | — | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| BRH-FOD | Brake (Hydraulic) Failure on Demand | L | 5.50E+01 | 8.96E-06 | — | 3 sources N/D; 1 source mean + EF | NPRD-95 (Ref. C5.40) |
| BRK-FOD | Brake Failure on Demand | L | 6.30E+00 | 1.46E-06 | — | 3 sources; mean + EF | EPRI PRA (Ref. C5.8) |
| BRK-FOH | Brake (Electric) Failure | G | 2.50E+00 | — | 4.40E-06 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| BRP-FOD | Brake (Pneumatic) Failure on Demand | L | 2.55E+00 | 5.02E-05 | — | 4 sources; N/D | NPRD-95 (Ref. C5.40) |
| BRP-FOH | Brake (Pneumatic) Failure | L | 2.55E+00 | — | 8.38E-06 | 4 sources; N/D | NPRD-95 (Ref. C5.40) |
| BTR-FOD | Battery No Output Given Challenge | B | 6.05E+01 | 8.20E-03 | — | 1 source; N/D | NUREG/CR-4639 (Ref. C5.39) |
| BTR-FOH | Battery Failure | L | 4.30E+00 | — | 4.29E-06 | 12 sources N/D; 8 sources mean + EF | CCPS (Ref. C5.1), N-Reactor (Ref. C5.46), NPRD-95 (Ref. C5.40), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16), SAIC Umatilla (Ref. C5.41) |
| BUA-FOH | AC Bus Failure | L | 3.08E+00 | — | 6.10E-07 | 3 sources; N/D | IEEE 493 (Ref. C5.22), NUREG/CR-6928 (Ref. C5.16) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| BUD-FOH | DC Bus Failure | L | 8.70E+01 | — | 2.40E-07 | 1 source mean + EF | IEEE-500 (Ref. C5.23) |
| BYC-FOH | Battery Charger Failure | L | 1.00E+01 | — | 7.60E-06 | 1 source mean + EF | CCPS (Ref. C5.1) |
| C52-FOD | Circuit Breaker (AC) Fails on Demand | L | 9.80E+00 | 2.24E-03 | — | 19 sources N/D; 1 source mean + EF | CCPS (Ref. C5.1), NUREG/CR-4639 (Ref. C5.39), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| C52-SPO | Circuit Breaker (AC) Spurious Operation | L | 2.29E+01 | — | 5.31E-06 | 12 sources N/D; 1 source mean + EF | CCPS (Ref. C5.1), MIL-HDBK-217F (Ref. C5.12), NUREG/CR-6928 (Ref. C5.16), NUREG/CR-4639 (Ref. C5.39), SAIC Umatilla (Ref. C5.41) |
| C72-SPO | Circuit Breaker (DC) Spurious Operation | L | 1.20E+00 | — | 1.07E-06 | 3 sources N/D; 1 source mean + EF | CCPS (Ref. C5.1), MIL-HDBK-217F (Ref. C5.12), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16) |
| CAM-FOH | Cam Lock Fails | L | 8.30E+01 | — | 3.19E-06 | 4 sources N/D; 1 source mean + EF | NPRD-95 (Ref. C5.40) |
| CBP-OPC | Cables (Electrical Power) Open Circuit | G | 5.00E-01 | — | 9.13E-08 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| CBP-SHC | Cables (Electrical Power) Short Circuit | G | 5.00E-01 | — | 1.88E-08 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| CKV-FOD | Check Valve Fails on Demand | L | 1.36E+01 | 6.62E-04 | — | 4 sources N/D; 7 sources mean + EF | CCPS (Ref. C5.1), N-Reactor (Ref. C5.46), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16), SRS Reactors (Ref. C5.5) |
| CKV-FTX | Check Valve Fails to Check | L | 1.50E+01 | 2.20E-03 | — | 1 source; mean + EF | CCPS (Ref. C5.1) |
| CON-FOH | Electrical Connector (Site Transporter) Failure | G | 5.00E-01 | — | 7.14E-05 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| CPL-FOH | Coupling (Automatic) Failure | L | 5.00E+00 | — | 1.91E-06 | 1 source mean + EF | AIAA (Ref. C5.11) |
| CPO-FOH | Control System Onboard (TEV or Trolley) Failure | G | 9.85E+01 | — | 2.10E-08 | 1 source; N/D | NPRD-95 (Ref. C5.40) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| CRD-FOH | Card Reader Failure | L | 5.00E+00 | — | 4.55E-05 | 1 source mean + EF | HID (Ref. C5.21) |
| CRN-DRP | 200 Ton Crane Drop | L | 4.32E+01 | 3.16E-05 | — | 2 sources N/D;<br>4 sources mean + EF | NUREG-0612 (Ref. C5.35),<br>NUREG-1774 (Ref. C5.26),<br>EPRI PRA (Ref. C5.8) |
| CRN-TBK | 200 Ton Crane Two Block Drop | L | 1.15E+01 | 4.41E-07 | — | 1 source N/D;<br>3 sources mean + EF | NUREG-0612 (Ref. C5.35),<br>NUREG-1774 (Ref. C5.26) |
| CRS-DRP | 200 Ton Crane Sling Drop | B | 2.13E+04 | 1.17E-04 | — | 1 source; N/D | NUREG-1774 (Ref. C5.26) |
| CRW-DRP | WP (Non-Single Failure Proof) Crane Drop | B | 3.27E+04 | 1.07E-04 | — | 1 source; N/D | NUREG-1774 (Ref. C5.26) |
| CRW-TBK | WP (Non-Single Failure Proof) Crane Two Block Drop | B | 3.27E+04 | 4.59E-05 | — | 1 source; N/D | NUREG-1774 (Ref. C5.26) |
| CSC-FOH | Cask Cradle Failure | G | 1.50E+00 | — | 4.81E-08 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| CT-FOD | Controller Mechanical Jamming | L | 5.00E+00 | 4.00E-06 | — | 1 source; mean + EF | EPRI PRA (Ref. C5.8) |
| CT-FOH | Controller Failure | L | 1.00E+01 | — | 6.88E-05 | 1 source mean + EF | CCPS (Ref. C5.1) |
| CT-SPO | Controller Spurious Operation | L | 1.00E+01 | — | 2.27E-05 | 1 source mean + EF | CCPS (Ref. C5.1) |
| CTL-FOD | Logic Controller Fails on Demand | L | 1.10E+01 | 2.03E-03 | — | 3 sources; N/D | NUREG/CR-6928 (Ref. C5.16) |
| DER-FOM | Derailment Failure per Mile | G | 3.97E+03 | — | 1.18E-05 | 1 source; N/D | Federal Railroad Administration (Ref. C5.17) |
| DG-FTR | Diesel Generator Fails to Run | L | 1.51E+01 | — | 4.08E-03 | 8 sources N/D;<br>1 source mean + EF | CCPS (Ref. C5.1),<br>IEEE 493 (Ref. C5.22),<br>NUREG/CR-4639 (Ref. C5.39),<br>NUREG/CR-3831 (Ref. C5.24),<br>NUREG/CR-6890 (Ref. C5.15),<br>NUREG/CR-6928 (Ref. C5.16),<br>SAIC Umatilla (Ref. C5.41),<br>SRS Reactors (Ref. C5.5) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| DG-FTS | Diesel Generator Fails to Start | L | 3.50E+00 | 8.38E-03 | — | 9 sources N/D; 1 source mean + EF | CCPS (Ref. C5.1), IEEE 493 (Ref. C5.22), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-3831 (Ref. C5.24), NUREG/CR-6890 (Ref. C5.15), NUREG/CR-6928 (Ref. C5.16), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| DGS-FTR | Diesel Generator - Seismic - Fails to Run for 29 Days | G | 5.05E+01 | — | 8.27E-04 | 1 source, N/D | NUREG/CR-6890 (Ref. C5.15) |
| DM-FOD | Drum Failure on Demand | L | 1.00E+01 | 4.00E-08 | — | 2 sources mean + EF | EPRI PRA (Ref. C5.8) |
| DM-MSP | Drum Misspooling (Hourly) | G | 5.00E-01 | — | 6.86E-07 | 1 source, N/D | NPRD-95 (Ref. C5.40) |
| DMP-FOH | Damper (Manual) Fails to Operate | L | 4.30E+00 | — | 5.94E-06 | 3 sources mean + EF | IEEE-500 (Ref. C5.23), N-Reactor (Ref. C5.46), Moss (Ref. C5.32) |
| DMP-FRO | Damper (Manual) Fails to Remain Open (Transfers Closed) | L | 3.20E+00 | — | 8.38E-08 | 2 sources N/D; 2 sources mean + EF | NUREG/CR-3154 (Ref. C5.6), NUREG/CR-1363 (Ref. C5.28), NUREG/CR-4639 (Ref. C5.39), SAIC Umatilla (Ref. C5.41) |
| DMS-FOH | Demister (Moisture Separator) Failure | L | 5.00E+00 | — | 9.12E-06 | 1 source mean + EF | EPRI Pipe Failure Study (Ref. C5.10) |
| DRV-FOH | Drive (Adjustable Speed) Failure | G | 5.0E-01 | — | 2.5E-04 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| DRV-FSO | Drive (Adjustable Speed) Failure to Stop on Demand | B | 2.5E+02 | — | 3.4E-05 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| DTC-RUP | Duct Ruptures | L | 2.6E+01 | — | 3.7E-06 | 9 sources N/D; 1 source mean + EF | NPRD-95 (Ref. C5.40), SRS Reactors (Ref. C5.5), SAIC Umatilla (Ref. C5.41) |
| DTM-FOD | Damper (Tornado) Failure on Demand | L | 5.0E+00 | 8.7E-04 | — | 1 source; mean + EF | IEEE-500 (Ref. C5.23) |
| DTM-FOH | Damper (Tornado) Failure | L | 7.9E+00 | — | 2.3E-05 | 2 sources N/D; 1 source mean + EF | IEEE-500 (Ref. C5.23), Moss (Ref. C5.32) |
| ECP-FOH | Position Encoder Failure | G | 5.0E-01 | — | 1.8E-06 | 2 sources; N/D | NPRD-95 (Ref. C5.40) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| ESC-FOD | Emergency Stop Button Controller Failure to Stop (on Demand) | L | 5.0E+00 | 2.5E-04 | — | 1 source; mean + EF | EPRI PRA (Ref. C5.8) |
| FAN-FTR | Fan (Motor-Driven) Fails to Run | L | 4.6E+01 | — | 7.21E-05 | 11 sources N/D; 6 sources mean + EF | CCPS (Ref. C5.1), N-Reactor (Ref. C5.46), NPRD-95 (Ref. C5.40), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| FAN-FTS | Fan (Motor-Driven) Fails to Start on Demand | L | 1.0E+01 | 2.0E-03 | — | 7 sources N/D; 5 sources mean + EF | CCPS (Ref. C5.1), N-Reactor (Ref. C5.46), NPRD-95 (Ref. C5.40), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| FRK-PUN | Forklift Puncture | L | 1.06E+01 | — | 1.20E-05 | 1 source mean + EF | SAIC Umatilla (Ref. C5.41) |
| G65-FOH | Governor Failure | G | 1.82E+02 | — | 1.16E-05 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| GPL-FOD | Grapple Failure on Demand | B | 1.30E+06 | 1.15E-06 | — | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| GRB-FOH | Gear Box Failure | L | 1.40E+01 | — | 2.21E-04 | 1 source N/D; 1 source mean + EF | NPRD-95 (Ref. C5.40) |
| GRB-SHH | Gear box Shaft/Coupling Shears | L | 5.00E+00 | — | 2.40E-06 | 1 source; mean + EF | EPRI PRA (Ref. C5.8) |
| GRB-STH | Gear Box Stripped | L | 5.00E+00 | — | 7.86E-08 | 1 source; mean + EF | NPRD-95 (Ref. C5.40) |
| HC-FOD | Hand Held Radio Remote Controller Failure to Stop (on Demand) | L | 8.39E+01 | 1.74E-03 | — | 1 source N/D; 3 sources mean + EF | EPRI PRA (Ref. C5.8), NPRD-95 (Ref. C5.40) |
| HC-SPO | Hand Held Radio Remote Controller Spurious Operation | G | 5.00E-01 | — | 5.23E-07 | 1 source N/D | NPRD-95 (Ref. C5.40) |
| HEP-LEK | Filter (HEPA) Leaks (Bypassed) | L | 1.00E+01 | — | 3.00E-06 | 1 source; mean + EF | SRS Reactors (Ref. C5.5) |
| HEP-PLG | Filter (HEPA) Plugs | L | 9.5E+00 | — | 4.3E-06 | 3 sources N/D; 2 sources mean + EF | IEEE-500 (Ref. C5.23), NUREG/CR-4639 (Ref. C5.39), SAIC Umatilla (Ref. C5.41) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| HOS-LEK | Hose Leaking | L | 2.47E+01 | — | 1.48E-05 | same as HOS-RUP with factor of 10 | CCPS (Ref. C5.1), NPRD-95 (Ref. C5.40), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| HOS-RUP | Hose Ruptures | L | 2.47E+01 | — | 1.48E-06 | 2 sources N/D; 3 sources mean + EF | CCPS (Ref. C5.1), NPRD-95 (Ref. C5.40), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| IEL-FOD | Interlock Failure on Demand | L | 5.0E+00 | 2.8E-05 | — | 1 source; mean + EF | NPRD-95 (Ref. C5.40) |
| IEL-FOH | Interlock Failure | L | 5.50E+01 | — | 3.43E-05 | 4 sources; N/D | NPRD-95 (Ref. C5.40) |
| LC-FOD | Level Controller Failure on Demand | B | 6.07E+03 | 6.25E-04 | — | 1 source; N/D | NUREG/CR-6928 (Ref. C5.16) |
| LRG-FOH | Lifting Rig or Hook Failure | G | 4.65E+01 | — | 7.45E-07 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| LVR-FOH | Lever (two position; up-down) Failure | G | 9.85E+01 | — | 2.10E-06 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| MCC-FOH | Motor Control Centers (MCCs) Failure | L | 1.00E+01 | — | 7.49E-06 | composite of Relay (RLY-FTP) + Motor Starter (MST FOH) + Limit Switch (ZS-FOH) | |
| MOE-FOD | Motor (Electric) Fails on Demand | L | 5.00E+00 | 6.00E-05 | — | 1 source; mean + EF | EPRI PRA (Ref. C5.8) |
| MOE-FSO | Motor (Electric) Fails to Shut Off | L | 1.07E+01 | — | 1.35E-08 | 1 source N/D; 1 source mean + EF | CCPS (Ref. C5.1), MIL-HDBK-217F (Ref. C5.12) |
| MOE-FTR | Motor (Electric) Fails to Run | L | 9.50E+00 | — | 6.50E-06 | 8 sources N/D; 2 sources mean + EF | NPRD-95 (Ref. C5.40), NSWC-98-LE1 (Ref. C5.37), NUREG/CR-4639 (Ref. C5.39), OREDA-2002 (Ref. C5.43) |
| MOE-FTS | Motor (Electric) Fails to Start (Hourly) | L | 1.90E+01 | — | 7.14E-06 | 5 sources N/D; 2 sources mean + EF | NPRD-95 (Ref. C5.40) |
| MOE-SPO | Motor (Electric) Spurious Operation | L | 1.07E+01 | — | 6.74E-07 | 1 source N/D; 1 source mean + EF | CCPS (Ref. C5.1), MIL-HDBK-217F (Ref. C5.12) |
| MOH-FOH | Motor (Hydraulic) Failure | G | 5.00E-01 | — | 2.50E-04 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| MSC-FOH | Motor Speed Control Module Failure | G | 5.00E-01 | — | 1.28E-04 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| MST-FOH | Motor Starter Failure | L | 1.33E+00 | — | 1.43E-07 | 2 sources; N/D | IEEE 493 (Ref. C5.22) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| NZL-FOH | Nozzle Failure | L | 7.50E+00 | — | 2.85E-06 | 5 sources N/D; 1 source mean + EF | IEEE-500 (Ref. C5.23), NPRD-95 (Ref. C5.40), SAIC Umatilla (Ref. C5.41) |
| PIN-BRK | Pin (Locking or Stabilization) Breaks | L | 1.46E+00 | — | 2.12E-09 | 4 sources; N/D | NPRD-95 (Ref. C5.40) |
| PLC-FOD | Programmable Logic Controller Fails on Demand | B | 1.35E+03 | 3.69E-04 | — | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| PLC-FOH | Programmable Logic Controller Fails to Operate | L | 1.00E+01 | — | 3.26E-06 | 5 sources N/D; 1 source mean + EF | MIL-HDBK-217F (Ref. C5.12), NPRD-95 (Ref. C5.40), SAIC Umatilla (Ref. C5.41) |
| PLC-SPO | Programmable Logic Controller Spurious Operation | L | 1.00E+01 | — | 3.65E-07 | 5 sources N/D; 1 source mean + EF | MIL-HDBK-217F (Ref. C5.12), NPRD-95 (Ref. C5.40), SAIC Umatilla (Ref. C5.41) |
| PMD-FTR | Pump (Motor Driven) Fails to Run | L | 9.9E+00 | — | 3.5E-05 | 6 sources N/D; 87 sources mean + EF | CCPS (Ref. C5.1), N-Reactor (Ref. C5.46), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-1205 (Ref. C5.45), NUREG/CR-2886 (Ref. C5.13), NUREG/CR-6928 (Ref. C5.16), OREDA-2002 (Ref. C5.43), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| PMD-FTS | Pump (Motor Driven) Fails to Start on Demand | L | 3.80E+00 | 2.50E-03 | — | 7 sources N/D; 80 sources mean + EF | N-Reactor (Ref. C5.46), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-1205 (Ref. C5.45), NUREG/CR-2886 (Ref. C5.13), NUREG/CR-6928 (Ref. C5.16), OREDA-2002 (Ref. C5.43), SAIC Umatilla (Ref. C5.41), SRS Reactors (Ref. C5.5) |
| PPL-RUP | Piping (Lined) Catastrophic | L | 1.50E+01 | — | 4.42E-07 | 1 source; mean + EF | CCPS (Ref. C5.1) |
| PPM-PLG | Piping (Water) Plugs | L | 1.35E+01 | — | 7.26E-07 | 1 source N/D; 2 sources mean + EF | DuPont (Ref. C5.14), EPRI Pipe Failure Study (Ref. C5.10), SAIC Umatilla (Ref. C5.41) |
| PPM-RUP | Piping (Water) Ruptures | L | 2.00E+01 | — | 8.75E-10 | 1 source; mean + EF | NUREG/CR-6928 (Ref. C5.16) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| PR-FOH | Passive restraint (bumper) Failure | G | 2.09E+02 | — | 4.45E-10 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| PRM-FOH | EPROM (HVAC Speed Control) Failure | G | 5.00E-01 | — | 5.38E-07 | 1 source; N/D | MIL-HDBK-217F (Ref. C5.12) |
| PRV-FOD | Pressure Relief Valve Fails on Demand | L | 2.72E+01 | 6.54E-03 | — | 6 sources N/D; 2 sources mean + EF | CCPS (Ref. C5.1), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16) |
| PV-SPO | Pneumatic Valve Spurious Operation | G | 5.00E-01 | — | 2.92E-05 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| QDV-FOH | Quick Disconnect Valve Failure | L | 3.56E+00 | — | 4.26E-06 | 4 sources N/D | NPRD-95 (Ref. C5.40) |
| RCV-FOH | Air Receiver Fails to Supply Air | L | 1.00E+01 | — | 6.00E-07 | 1 source; mean + EF | IEEE-500 (Ref. C5.23) |
| RLY-FTP | Relay (Power) Fails to Close/Open | G | 5.00E-01 | — | 8.77E-06 | 1 source N/D | NPRD-95 (Ref. C5.40) |
| SC-FOH | Speed Control Failure | G | 5.00E-01 | — | 1.28E-04 | 1 source N/D | NPRD-95 (Ref. C5.40) |
| SC-SPO | Speed Control Spurious Operation | G | 5.00E-01 | — | 3.20E-05 | 1 source N/D | NPRD-95 (Ref. C5.40) |
| SEL-FOH | Speed Selector Fails | L | 5.34E+00 | — | 4.16E-06 | 3 sources N/D | NPRD-95 (Ref. C5.40) |
| SEQ-FOD | Sequencer Fails on Demand | B | 7.49E+02 | 3.33E-03 | — | 1 source N/D | NUREG/CR-6928 (Ref. C5.16) |
| SFT-COL | Spent Fuel Transfer Machine (SFTM) Collision or Impact | L | 4.00E+00 | 2.94E-06 | — | 2 sources N/D | NUREG-1774 (Ref. C5.26), McKenna (Ref. C5.20) |
| SFT-DRP | Spent Fuel Transfer Machine (SFTM) Drop | L | 3.00E+00 | 5.15E-06 | — | 2 sources N/D | NUREG-1774 (Ref. C5.26), McKenna (Ref. C5.20) |
| SFT-RTH | Spent Fuel Transfer Machine (SFTM) Raised Fuel Too High | L | 7.00E+00 | 7.36E-07 | — | 2 sources N/D | NUREG-1774 (Ref. C5.26), McKenna (Ref. C5.20) |
| SJK-FOH | Screw Jack (TEV) Failure | G | 5.00E-01 | — | 8.14E-06 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| SRF-FOH | Flow Sensor Failure | G | 5.00E-01 | — | 1.07E-06 | 1 source; N/D | NUREG/CR-4639 (Ref. C5.39) |
| SRP-FOD | Pressure Sensor Fails on Demand | B | 1.25E+02 | 3.99E-03 | — | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| SRP-FOH | Pressure Sensor Fails | L | 1.21E+01 | — | 2.95E-06 | 8 sources N/D | NPRD-95 (Ref. C5.40), NUREG/CR-6928 (Ref. C5.16) |
| SRR-FOH | Radiation Sensor Fails | L | 5.00E+00 | — | 2.00E-05 | 1 source; mean + EF | Laurus (Ref. C5.25) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| SRS-FOH | OverSpeed Sensor Fails | G | 1.28E+02 | — | 2.14E-05 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| SRT-FOD | Temperature Sensor/Transmitter Fails on Demand | L | 2.10E+00 | 7.33E-04 | — | 2 sources N/D | NUREG/CR-6928 (Ref. C5.16), OREDA-92 (Ref. C5.42) |
| SRT-FOH | Temperature Sensor/Transmitter Fails | L | 1.41E+01 | — | 7.05E-07 | 4 sources N/D; 2 sources mean + EF | NPRD-95 (Ref. C5.40), NUREG/CR-6928 (Ref. C5.16), OREDA-2002 (Ref. C5.43) |
| SRT-SPO | Temperature Sensor Spurious Operation | L | 2.80E+01 | — | 2.23E-06 | 1 source; mean + EF | OREDA-2002 (Ref. C5.43) |
| SRU-FOH | Ultrasonic Sensor Fails | G | 5.00E-01 | — | 9.62E-05 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| SRV-FOH | Vibration Sensor (Accelerometer) Fails | L | 1.07E+01 | — | 9.40E-05 | 4 sources N/D | NPRD-95 (Ref. C5.40) |
| SRX-FOD | Optical Position Sensor Fails on Demand | B | 3.18E+03 | 1.10E-03 | — | 1 source; N/D | SAIC Umatilla (Ref. C5.41) |
| SRX-FOH | Optical Position Sensor Fails | L | 5.00E+00 | — | 4.70E-06 | 1 source; mean + EF | NPRD-95 (Ref. C5.40) |
| STR-FOH | Steering (tractor or trailer) Fails | L | 4.63E+01 | — | 1.84E-05 | 4 sources N/D | NPRD-95 (Ref. C5.40) |
| STU-FOH | Structure (truck or railcar) Failure | G | 1.50E+00 | — | 4.81E-08 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| SV-FOD | Solenoid Valve Fails on Demand | L | 1.17E+01 | 6.28E-04 | — | 4 sources N/D; 5 sources mean + EF | CCPS (Ref. C5.1), N-Reactor (Ref. C5.46), NSWC-98-LE1 (Ref. C5.37), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16), SRS Reactors (Ref. C5.5) |
| SV-FOH | Solenoid Valve Fails | L | 1.70E+01 | — | 4.87E-05 | 1 source; mean + EF | CCPS (Ref. C5.1) |
| SV-SPO | Solenoid Valve Spurious Operation | L | 3.00E+00 | — | 4.09E-07 | 1 source; mean + EF | CCPS (Ref. C5.1) |
| SWA-FOH | Auto-Stop Switch (CTT hose travel) Fails | G | 6.50E+00 | — | 3.12E-06 | 1 source; N/D | NPRD-95 (Ref. C5.40) |
| SWG-FOH | 13.8kV Switchgear Fails | G | 2.85E+01 | — | 1.31E-07 | 1 source; N/D | IEEE 493 (Ref. C5.22) |
| SWP-FTX | Electric Power Switch Fails to Transfer | G | 6.50E+00 | — | 3.59E-07 | 1 source; N/D | IEEE 493 (Ref. C5.22) |
| SWP-SPO | Electric Power Switch Spurious Transfer | G | 6.50E+00 | — | 1.55E-07 | 1 source; N/D | IEEE 493 (Ref. C5.22) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| TD-FOH | Transducer Failure | L | 4.70E+00 | — | 9.84E-05 | 3 sources N/D; 1 source mean + EF | NPRD-95 (Ref. C5.40) |
| TDA-FOH | Transducer (Air Flow) Failure | L | 6.21E+00 | — | 1.65E-04 | 2 sources N/D | NPRD-95 (Ref. C5.40), NSWC-98-LE1 (Ref. C5.37) |
| TDP-FOH | Transducer (Pressure) Fails | L | 5.35E+01 | — | 2.20E-04 | 23 sources N/D; 2 sources mean + EF | NPRD-95 (Ref. C5.40), NSWC-98-LE1 (Ref. C5.37) |
| TDT-FOH | Transducer (Temperature) Fails | L | 2.95E+01 | — | 1.04E-04 | 12 sources N/D; 1 source mean + EF | NPRD-95 (Ref. C5.40) |
| THR-BRK | Third Rail Breaks | L | 1.00E+01 | — | 1.01E-08 | 1 source; mean + EF | NPRD-95 TRK-BRK adjusted with failure information from Federal Railroad Administration Safety Data Web site (Ref. C5.17) |
| TKF-FOH | Fuel Tank Fails | L | 1.11E+01 | — | 4.40E-07 | 15 sources; N/D | NPRD-95 (Ref. C5.40), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16) |
| TL-FOH | Torque Limiter Failure | G | 8.05E+01 | — | 8.05E-05 | 1 source N/D | NPRD-95 (Ref. C5.40) |
| TRD-FOH | Tread (Site Transporter) | L | 3.40E+00 | — | 5.89E-07 | 1 source N/D; 1 source mean + EF | NPRD-95 (Ref. C5.40), Rand (Ref. C5.38) |
| UDM-FOH | Damper (Backdraft) Failure | L | 7.90E+00 | — | 2.26E-05 | 2 sources N/D; 1 source mean + EF | IEEE-500 (Ref. C5.23), Moss (Ref. C5.32) |
| UPS-FOH | Uninterruptible Power Supply (UPS) Failure | L | 5.08E+00 | — | 2.02E-06 | 10 sources; N/D | NPRD-95 (Ref. C5.40) |
| WNE-BRK | Wire Rope Breaks | L | 5.00E+00 | 2.00E-06 | — | 1 source; mean + EF | EPRI PRA (Ref. C5.8) |
| XMR-FOH | Transformer Failure | L | 1.53E+01 | — | 2.91E-07 | 13 sources N/D; 2 sources mean + EF | CCPS (Ref. C5.1), MIL-HDBK-217F (Ref. C5.12), NPRD-95 (Ref. C5.40), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16) |
| XV-FOD | Manual Valve Failure on Demand | L | 1.00E+01 | 6.48E-04 | — | 3 sources N/D; 12 sources mean + EF | CCPS (Ref. C5.1), N-Reactor (Ref. C5.46), NUREG/CR-4639 (Ref. C5.39), NUREG/CR-6928 (Ref. C5.16), SRS Reactors (Ref. C5.5) |

Table C4-1. Active Component Reliability Estimates Entered into SAPHIRE Models (Continued)

| TYP-FM | Component Name and Failure Mode | Dist Type | Uncert Value | Demand Proba-bility | Hourly Failure Rate | Number of Inputs | Input Data Sources[a] |
|---|---|---|---|---|---|---|---|
| ZS-FOD | Limit Switch Failure on Demand | L | 5.7E+00 | 2.9E-04 | — | 3 sources N/D | MIL-HDBK-217F (Ref. C5.12), NPRD-95 (Ref. C5.40), SRS Reactors (Ref. C5.5) |
| ZS-FOH | Limit Switch Fails | L | 6.03E+00 | — | 7.23E-06 | 3 sources N/D | MIL-HDBK-217F (Ref. C5.12), NPRD-95 (Ref. C5.40), NUREG/CR-4639 (Ref. C5.39) |
| ZS-SPO | Limit Switch Spurious Operation | L | 5.56E+00 | — | 1.28E-06 | 3 sources N/D | MIL-HDBK-217F (Ref. C5.12), NPRD-95 (Ref. C5.40), NUREG/CR-4639 (Ref. C5.39) |

NOTE: [a]Refer to Section C1.2 for specific citation to data sources.

B = beta distribution; Dist Type = Distribution Type; EF = Lognormal Error Factor; G = gamma distribution; L = lognormal distribution; N/D = Numerator/Denominator; TYP-FM = Component Type and Failure Mode.

Source: Original

## C5 REFERENCES; DESIGN INPUTS

The PCSA is based on a snapshot of the design. The reference design documents are appropriately documented as design inputs in this section. Since the safety analysis is based on a snapshot of the design, referencing subsequent revisions to the design documents (as described in EG-PRO-3DP-G04B-00037, *Calculations and Analyses* (Ref. 2.1.1, Section 3.2.2.F)) that implement PCSA requirements flowing from the safety analysis would not be appropriate for the purpose of the PCSA.

The inputs in this Section noted with an (*) indicate that they fall into one of the designated categories described in Section 4.1, relative to suitability for intended use.

C5.1 *AIChE (American Institute of Chemical Engineers) 1989. *Guidelines for Process Equipment Reliability Data with Data Tables*. G-07. New York, New York: American Institute of Chemical Engineers, Center for Chemical Process Safety. TIC: 259872. ISBN: 978-0-8169-0422-8.

C5.2 *Apostolakis, G. and Kaplan, S. 1981. "Pitfalls in Risk Calculations." *Reliability Engineering, 2,* 135-145. Barking, England: Applied Science Publishers. TIC: 253648.

C5.3 ASME NOG-1-2004. 2005. *Rules for Construction of Overhead and Gantry Cranes (Top Running Bridge, Multiple Girder)*. New York, New York: American Society of Mechanical Engineers. TIC: 257672. ISBN: 0-7918-2939-1.

C5.4 *Atwood, C.L.; LaChance, J.L.; Martz, H.F.; Anderson, D.J.; Englehardt, M.; Whitehead, D.; and Wheeler, T. 2003. *Handbook of Parameter Estimation for Probabilistic Risk Assessment*. NUREG/CR-6823. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20060126.0121.

C5.5 *Blanton, C.H. and Eide, S.A. 1993. *Savannah River Site, Generic Data Base Development (U)*. WSRC-TR-93-262. Aiken, South Carolina: Westinghouse Savannah River Company. TIC: 246444.

C5.6 *Borkowski, R.J.; Kahl, W.K.; Hebble, T.L.; Fragola, J.R.; Johnson, J.W. 1983. *The In-Plant Reliability Data Base for Nuclear Plant Components: Interim Report-The Valve-Component*. NUREG/CR-3154. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20071129.0315.

C5.7 BSC 2007 (Bechtel SAIC Company). *Waste Form Throughputs for Preclosure Safety Analysis*. 000-PSA-MGR0-01800-000-00A. Las Vegas, Nevada: Bechtel SAIC Company. ACC: ENG.20071106.0001.

C5.8 *Canavan, K.; Gregg, B.; Karimi, R.; Mirsky, S.; and Stokley, J. 2004. *Probabilistic Risk Assessment (PRA) of Bolted Storage Casks, Updated Quantification and Analysis Report*. 1009691. Palo Alto, California: Electric Power Research Institute. TIC: 257542.

C5.9 *Crutchfield, D.M. 1996. "Movement of Heavy Loads Over Spent Fuel, Over Fuel in the Reactor Core, or Over Safety-Related Equipment." NRC Bulletin 96-02. Washington, D.C.: U.S. Nuclear Regulatory Commission. Accessed February 12, 2008. ACC: MOL.20080213.0021. URL: http://www.nrc.gov/reading-rm/doc-collections /gen-comm/bulletins/1996/bl96002.html.

C5.10 *Derdiger, J.A.;Bhatt, K.M.;Siegfriedt, W.E. 1981. *Component Failure and Repair Data for Coal-Fired Power Units*. AP-2071. Palo Alto, California: Electric Power Research Institute. TIC: 260070.

C5.11 *Dhillon, B.S. 1988. *Mechanical Reliability: Theory, Models and Applications*. AIAA Education Series. Washington, D.C.: American Institute of Aeronautics & Astronautics. TIC: 259878.

C5.12 *DOD (U.S. Department of Defense) 1991. *Military Handbook, Reliability Prediction of Electronic Equipment*. MIL-HDBK-217F. Washington, D.C.: U.S. Department of Defense. TIC: 232828.

C5.13 *Drago, J.P.; Borkowski, R.J.; Fragola, J.R.; and Johnson, J.W. 1982. *The In-Plant Reliability Data Base for Nuclear Plant Components: Interim Data Report — The Pump Component*. NUREG/CR-2886. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20071219.0222.

C5.14 *E.I. du Pont de Nemours & Company 1981. *Some Published and Estimated Failure Rates for Use in Fault Tree Analysis*. Wilmington, Delaware: E.I. du Pont de Nemours & Company. TIC: 260092.

C5.15 *Eide, S.A.; Gentillon, C.D.; Wierman, T.E.; and Rasmuson, D.M. 2005. *Analysis of Station Blackout Risk*. Volume 2 of *Reevaluation of Station Blackout Risk at Nuclear Power Plants*. NUREG/CR-6890. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20071114.0165.

C5.16 *Eide, S.A.; Wierman, T.E.; Gentillon, C.D.; Rasmuson, D.M.; and Atwood, C.T. 2007. *Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants*. NUREG/CR-6928. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20071211.0229.

C5.17 *Federal Railroad Administration. 2004. "Train Accidents by Cause from Form FRA F 6180.54." Washington, D.C.: U.S. Department of Transportation, Federal Railroad Administration. Accessed 03/12/2004. ACC: MOL.20040311.0211. URL: http://safetydata.fra.dot.gov/OfficeofSafety/Query/Default.asp.

C5.18 *Fleming, K.N. 1975. *A Reliability Model for Common Mode Failures in Redundant Safety Systems*. GA-A13284. San Diego, California: General Atomic Company. ACC: MOL.20071219.0221.

C5.19 *Fragola, J.R. and McFadden, R.H. 1995. "External Maintenance Rate Prediction and Design Concepts for High Reliability and Availability on Space Station Freedom." *Reliability Engineering and System Safety, 47,* 255-273. New York, New York: Elsevier. TIC: 259675.

C5.20 *Framatome ANP (Advanced Nuclear Power) 2001. *Summary, Commercial Nuclear Fuel Assembly Damage/Misload Study – 1985-1999.* Lynchburg, Virginia: Framatome Advanced Nuclear Power. ACC: MOL.20011018.0158.

C5.21 *HID Corporation [n.d.]. Ruggedized Card Reader/Ruggedized Keypad Card Reader. Dorado 740 and 780. Irvine, California: HID Corporation. TIC: 260007.

C5.22 *IEEE Std 493-1997. 1998. *IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems.* New York, New York: Institute of Electrical and Electronics Engineers. TIC: 243205. ISBN: 1-55937-969-3.

C5.23 *IEEE Std 500-1984 (Reaffirmed 1991). 1991. *IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations.* New York, New York: Institute of Electrical and Electronics Engineers. TIC: 256281.

C5.24 *Kahl, W.K. and Borkowski, R.J. 1985. *The In-Plant Reliability Data Base for Nuclear Plant Components: Interim Report - Diesel Generators, Batteries, Chargers, and Inverters.* NUREG/CR-3831. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20071212.0181.

C5.25 *Laurus Systems [n.d.]. Instruments and Software Solutions for Emergency Response and Health Physics. Ellicott City, Maryland: Laurus Systems. TIC: 259965.

C5.26 Lloyd, R.L. 2003. *A Survey of Crane Operating Experience at U.S. Nuclear Power Plants from 1968 through 2002.* NUREG-1774. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20050802.0185.

C5.27 *Lopez Droguett, E.; Groen, F.; and Mosleh, A. 2004. "The Combined Use of Data and Expert Estimates in Population Variability Analysis." *Reliability Engineering and System Safety, 83,* 311-321. New York, New York: Elsevier. TIC: 259380.

C5.28 *Miller, C.F.; Hubble, W.H.; Trojovsky, M.; and Brown, S.R. 1982. *Data Summaries of Licensee Event Reports of Valves at U.S. Commercial Nuclear Power Plants from January 1, 1976 to December 31, 1980.* NUREG/CR-1363, Rev. 1. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20071219.0223.

C5.29 *Mosleh, A.; Fleming, K.N.; Parry, G.W.; Paula, H.M.; Worledge, D.H.; and Rasmuson, D.M. 1988. *Analytical Background and Techniques.* Volume 2 of *Procedures for Treating Common Cause Failures in Safety and Reliability Studies.* NUREG/CR-4780. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 221775.

C5.30 *Mosleh, A.; Fleming, K.N.; Parry, G.W.; Paula, H.M.; Worledge, D.H.; and Rasmuson, D.M. 1988. *Procedural Framework and Examples*. Volume 1 of *Procedures for Treating Common Cause Failures in Safety and Reliability Studies*. NUREG/CR-4780. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 221775.

C5.31 *Mosleh, A.; Rasmuson, D.M.; and Marshall, F.M. 1998. *Guidelines on Modeling Common-Cause Failures in Probabilistic Risk Assessment*. NUREG/CR-5485. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20040220.0106.

C5.32 *Moss, T.R. 2005. *The Reliability Data Handbook*. 1st Edition. New York, New York: American Society of Mechanical Engineers Press. TIC: 259912. ISBN: 0-7918-0233-7.

C5.33 Not used.

C5.34 NRC (U.S. Nuclear Regulatory Commission) 1979. *Single-Failure-Proof Cranes for Nuclear Power Plants*. NUREG-0554. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 232978.

C5.35 NRC 1980. *Control of Heavy Loads at Nuclear Power Plants*. NUREG-0612. Washington, D.C.: U.S. Nuclear Regulatory Commission. TIC: 209017.

C5.36 NRC 2005. *CCF Parameter Estimations 2005*. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20080213.0022.

C5.37 *NSWC (Naval Surface Warfare Center) 1998. *Handbook of Reliability Prediction Procedures for Mechanical Equipment*. NSWC-98/LE1. West Bethesda, Maryland: Naval Surface Warfare Center, Carderock Division. TIC: 245703.

C5.38 *Peltz, E.; Robbins, M.; Boren, P.; Wolff, M. 2002. *Diagnosing the Army's Equipment Readiness, The Equipment Downtime Analyzer*. Santa Monica, California: RAND. TIC: 259917. ISBN: 0-8330-3115-5.

C5.39 *Reece, W.J.; Gilbert, B.G.; and Richards, R.E. 1994. *Nuclear Computerized Library for Assessing Reactor Reliability (NUCLARR), Volume 5: Data Manual, Part 3: Hardware Component Failure Data*. NUREG/CR-4639, Vol. 5, Rev. 4. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20071220.0209.

C5.40 *Denson, W.; Chandler, G.; Crowell, W.; Clark, A.; and Jaworski, P. 1994. *Nonelectronic Parts Reliability Data 1995*. NPRD-95. Rome, New York: Reliability Analysis Center. TIC: 259757.

C5.41 *SAIC (Science Applications International Corporation) 2002. *Umatilla Chemical Agent Disposal Facility Quantitative Risk Assessment*. Report No. SAIC-00/2641. Volume I. Abingdon, Maryland: Science Applications International Corporation. ACC: MOL.20071220.0210.

C5.42 *SINTEF Industrial Management 1992. *OREDA, Offshore Reliability Data Handbook.* 2nd Edition. Trondheim, Norway: OREDA. ISBN: 825150188.1.

C5.43 *SINTEF Industrial Management 2002. *OREDA, Offshore Reliability Data Handbook.* 4th Edition. Trondheim, Norway: OREDA. TIC: 257402. ISBN: 8214027055.

C5.44 *Siu, N.O. and Kelly, D.L. 1998. "Bayesian Parameter Estimation in Probabilistic Risk Assessment." *Reliability Engineering and System Safety, 62,* 89-116. New York, New York: Elsevier. TIC: 258633.

C5.45 *Trojovsky, M. 1982. *Data Summaries of Licensee Event Reports of Pumps at U.S. Commercial Nuclear Power Plants, January 1, 1972 to September 30, 1980.* NUREG/CR-1205, Rev. 1. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.20080207.0024.

C5.46 *Zentner, M.D.; Atkinson, J.K.; Carlson, P.A.; Coles, G.A.; Leitz, E.E.; Lindberg, S.E.; Powers, T.B.; and Kelly, J.E. 1988. *N Reactor Level 1 Probabilistic Risk Assessment: Final Report.* WHC-SP-0087. Richland, Washington: Westinghouse Hanford Company. ACC: MOL.20080207.0021.

C5.47 Wieman, T.E; Rasmuson, D.M.; Molesh, A. 2007. *Common-Cause Failure Database and Analysis System: Event Data Collection, Classification, and Coding.* NUREG/CR-6268. Rev. 1. Idaho Falls, ID: Idaho National Laboratory. ACC: MOL.20080930.0050.

# ATTACHMENT D
# PASSIVE EQUIPMENT FAILURE ANALYSIS

# ATTACHMENT D
# PASSIVE EQUIPMENT FAILURE ANALYSIS

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# ACRONYMS AND ABBREVIATIONS

## Acronyms

| | |
|---|---|
| CDF | cumulative distribution function |
| COV | coefficient of variation |
| CRCF | Canister Receipt and Closure Facility |
| CTM | canister transfer machine |
| DOE | U.S. Department of Energy |
| DPC | dual-purpose canister |
| EPS | equivalent (or effective) plastic strain |
| ETF | expended toughness fraction |
| FEA | finite element analysis |
| GROA | geologic repository operations area |
| HLW | high-level radioactive waste |
| INL | Idaho National Laboratory |
| LLNL | Lawrence Livermore National Laboratory |
| LOS | loss of shielding |
| LS-DYNA | Livermore Software–Dynamic Finite Element Program |
| MCO | multicanister overpack |
| OCB | outer corrosion barrier |
| PCSA | preclosure safety analysis |
| PDF | probability density function |
| SAR | Safety Analysis Report |
| SLS | steel/lead/steel |
| SNF | spent nuclear fuel |
| STC | shielded transfer cask |
| TAD | transportation, aging, and disposal |
| TEV | transport and emplacement vehicle |
| WPTT | waste package transfer trolley |
| YMP | Yucca Mountain Project |

## ACRONYMS AND ABBREVIATIONS (Continued)

### Abbreviations

| | |
|---|---|
| °C | degrees Celsius |
| cm | centimeter |
| °F | degrees Fahrenheit |
| ft | foot |
| g | gram |
| hr | hour, hours |
| in. | inch |
| J | joule |
| K | degrees Kelvin |
| kg | kilogram |
| kj | kilojoule |
| kW | kilowatt |
| m | meter |
| min | minute |
| MJ | megajoule |
| MPa | megapascal |
| mph | miles per hour |
| mrem | millirem |
| psig | pounds per square inch gauge |
| rem | roentgen equivalent man |
| sec | second |
| W | watt |

# ATTACHMENT D
# PASSIVE EQUIPMENT FAILURE ANALYSIS

Many event sequences described in Section 6.1 include pivotal events that arise from loss of integrity of a passive component, namely one of the aging overpacks, casks, or canisters that contain a radioactive waste form. Such pivotal events involve (1) loss of containment of radioactive material that may result in airborne releases, or (2) loss of shielding effectiveness. Both types of pivotal events may be failure modes caused by either physical impact to the container or by thermal energy transferred to the container. This attachment presents the results of passive failure analyses that provide conditional probability of loss of containment or loss of shielding. Many scenarios were selected for analysis as representative or bounding for anticipated scenarios in the risk assessment. Results of some scenarios may not have been used in the final event sequence quantification.

## D1 LOSS OF CONTAINMENT DUE TO DROPS AND IMPACTS

The category of passive equipment includes canisters and casks used during transport, aging, and disposal of spent nuclear fuel. The canisters and casks contain the spent fuel and provide containment of radioactive material. During transport and handling, the canisters and casks could be subjected to drops, impacts, or fires, which may result in loss of containment. The probabilities of loss of containment due to various physical or thermal challenges are evaluated primarily through structural and thermal analysis and drop test data.

Passive equipment (e.g., transportation casks, storage canisters, and waste packages) may fail from abnormal use such as defined by the event sequences. Studies were performed and passive equipment failure probabilities were determined using the methodologies summarized in Section 4.3.2.2. The probability of loss of containment (breach) was determined for several types of containers, including transportation casks (analyzed without impact limiters), shielded transfer casks, waste packages, transportation, aging, and disposal (TAD) canisters, dual-purpose canisters (DPCs), DOE standardized canisters, multicanister overpacks (MCOs), high-level radioactive waste (HLW) canisters, and naval spent nuclear fuel (SNF) canisters. The mechanical breach of TAD canisters, DPCs and naval SNF canisters were analyzed as representative canisters as described in Section D1.1. The structural analysis of DOE standardized canisters and MCOs for breaches is described in Section D1.2 and then the probabilistic methodology of Section D1.1 was applied. Transportation casks, shielded transfer casks (STCs) and horizontal STCs were analyzed as representative transportation casks as describe in Section D1.1. The probabilistic estimation of breach from mechanical loads of all other waste containers is described in Sections D1.3 through D1.6. The analysis of loss or degradation of shielding of casks and overpacks against mechanical loads is described in Section D3. The probabilistic analysis of fire severity and the associated effects on casks, canisters, and overpacks with respect to both containment breach and shielding degradation or loss is described in Section D2. The analysis of mechanical failures and thermal failures included the specific configuration defined by the event sequences. For example, if the event sequence occurred during a process in which the canister is within a transportation casks or aging overpack, the analysis is performed in that configuration.

## D1.1 LAWRENCE LIVERMORE NATIONAL LABORATORY ANALYSIS OF CANISTERS AND CASKS

Lawrence Livermore National Laboratory (LLNL) performed the finite element analysis (FEA) using Livermore Software–Dynamic Finite Element Program (LS-DYNA) to model drops and impacts for casks and canisters with selected properties for use as representative containers expected to be delivered to Yucca Mountain (Ref. D4.1.27). LS-DYNA, which has been used in nuclear facility and non-nuclear industrial applications, is appropriate to model nonlinear, transient responses of a passive component to a structural challenge such as a drop or an impact. Existing commercial casks and canisters that would likely be used on the Yucca Mountain Project (YMP) were identified and characterized. The cases analyzed are listed in Table D1.2-1.

Appropriate finite element models were developed for the representative cask, selected container types, configurations, and drop types. The level of detail for each model was selected to understand deformation and damage patterns, possible failure mode(s) in each structural element, and failure-related response. Special attention was required to properly model the bottom-weld and closure regions to ensure that coarser mesh of the simplified model would capture failure-related response with acceptable accuracy. A consistent failure criterion for each case was identified as part of the detailed analyses. The effective plastic strain in each element, in combination with material ductility data, was used to predict failure measures.

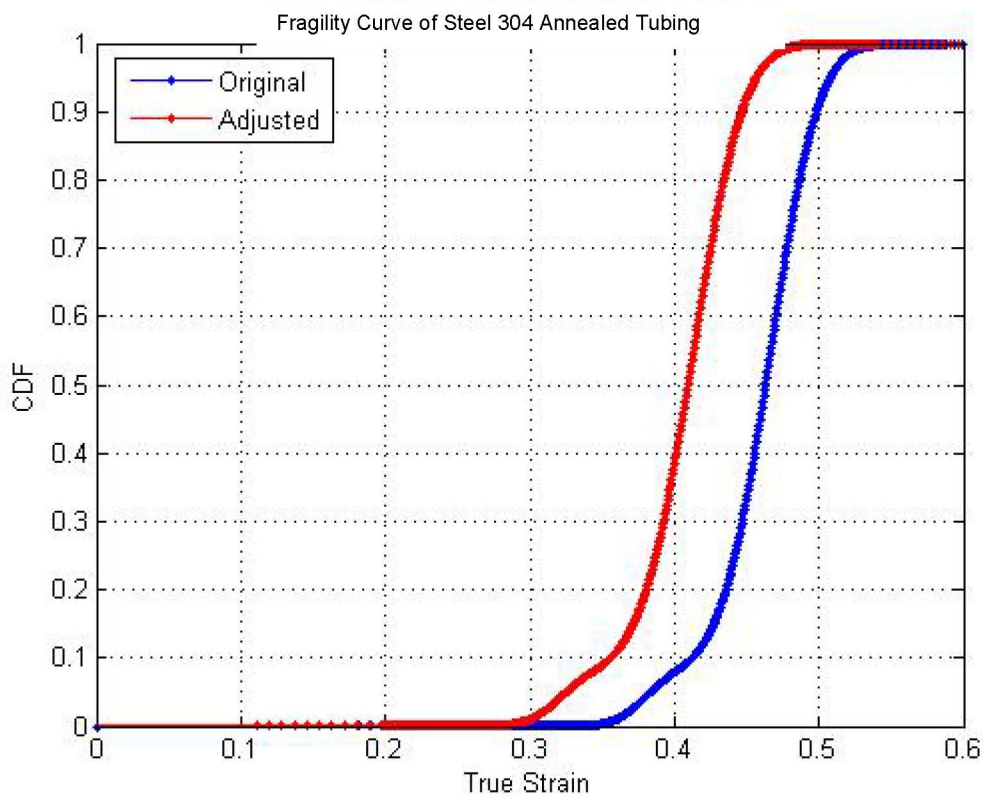
The maximum strain for each scenario was compared with the capacity distribution based on material properties to obtain containment failure probabilities using the methodology described in Section 4.3.2.2. For simplicity and consistency in interpreting results, the impact-surface conditions, including both the ground and the falling 10-ton load for the analyses, were considered infinitely stiff and unyielding, which is conservative.

The results of these cases are summarized in Tables D1.2-2 through D1.2-4. The bases for these results are summarized in the following paragraphs. If a probability for the event sequence is less than $1.0 \times 10^{-8}$, additional conservatism is incorporated in the preclosure safety analysis (PCSA) by using a failure probability of $1.0 \times 10^{-5}$, which are termed "LLNL, adjusted." This additional conservatism is added to account for a) future evolutions of cask and canister designs, and b) uncertainties, such as undetected material defects, undetected manufacturing deviations, and undetected damage associated with handling before the container reaches the repository, which are not included in the tensile elongation data.

LLNL developed a fragility curve for the base metal by fitting a mixture of two normal probability density functions (PDFs) to the engineering (tensile) strain data (Ref. D4.1.4). Both the data and their corresponding log-transforms were found to be non-normally distributed ($p < 10^{-4}$) by the Shapiro-Wilk test (Ref. D4.1.62). These data, collected at 100°F, were determined to be reasonably well modeled as a sample from a weighted mixture of two normal distributions, one with a mean of 46% and a standard deviation of 2.24% (weight = 7.84%), and the other with a mean of 59.3% and a standard deviation of 4.22% (weight = 92.16%), with the goodness of fit ($p = 0.939$) assessed by the Kolmogorov-Smirnov 1 sample test (Ref. D4.1.33).

The stainless steel used in the LLNL (Ref. D4.1.27) analysis is Alloy 304L. The un-annealed alloys have relatively shorter elongations at failure than annealed 304L. Therefore, the base

fragility cumulative distribution function (CDF) model was adjusted to different steels used in a typical design and to meet the code specification of the material model used in LS-DYNA. The adjustment consisted of shifting the distribution by -8.3% (Ref. D4.1.27, p. 93). Thus the initial fragility curve was shifted by 8.3% to a lower value of minimum elongation. The fragility curves before and after the shift are shown in Figure D1.1-1 and tabulated in Table D1.1-1. 316L stainless steel might be used for construction of some canisters and casks, but the stress-strain curves would be similar.




Source: Ref. D4.1.27, Figure 6.3.7-3

Figure D1.1-1. Original and Shifted Cumulative Distribution Functions (CDF) for Capacity (or Fragility) Plotted as a Function of True Strain

Table D1.1-1. Probability of Failure versus True Strain Tabulated for Figure D1.1-1

| True Strain (*TS*) | $\frac{TS - TS_{mean}}{TS_{std}}$ | Probability of Failure Original | Probability of Failure Adjusted (-8.3% shift) | True Strain (*TS*) | $\frac{TS - TS_{mean}}{TS_{std}}$ | Probability of Failure Original | Probability of Failure Adjusted (-8.3% shift) |
|---|---|---|---|---|---|---|---|
| 0.00 | -1.70 | 0.0000E+00 | 1.6754E-15 | 0.36 | 0.05 | 1.0506E-02 | 1.0973E-01 |
| 0.01 | -1.65 | 2.0924E-16 | 1.8688E-15 | 0.37 | 0.10 | 2.3978E-02 | 1.4282E-01 |
| 0.02 | -1.60 | 4.1848E-16 | 2.0622E-15 | 0.38 | 0.15 | 4.3259E-02 | 1.9679E-01 |
| 0.03 | -1.55 | 6.2772E-16 | 2.2555E-15 | 0.39 | 0.19 | 6.2863E-02 | 2.7687E-01 |
| 0.04 | -1.50 | 8.3696E-16 | 2.4489E-15 | 0.40 | 0.24 | 7.9100E-02 | 3.8310E-01 |
| 0.05 | -1.45 | 1.0462E-15 | 2.6422E-15 | 0.41 | 0.29 | 9.5539E-02 | 5.0814E-01 |
| 0.06 | -1.41 | 1.2554E-15 | 2.8356E-15 | 0.42 | 0.34 | 1.2068E-01 | 6.3823E-01 |
| 0.07 | -1.36 | 1.4647E-15 | 3.0290E-15 | 0.43 | 0.39 | 1.6410E-01 | 7.5736E-01 |
| 0.08 | -1.31 | 1.6739E-15 | 3.2223E-15 | 0.44 | 0.44 | 2.3393E-01 | 8.5309E-01 |
| 0.09 | -1.26 | 1.8832E-15 | 3.4157E-15 | 0.45 | 0.48 | 3.3371E-01 | 9.2036E-01 |
| 0.10 | -1.21 | 2.0924E-15 | 3.6090E-15 | 0.46 | 0.53 | 4.5893E-01 | 9.6161E-01 |
| 0.11 | -1.16 | 2.3016E-15 | 3.8024E-15 | 0.47 | 0.58 | 5.9615E-01 | 9.8363E-01 |
| 0.12 | -1.11 | 2.5109E-15 | 2.8601E-14 | 0.48 | 0.63 | 7.2682E-01 | 9.9385E-01 |
| 0.13 | -1.07 | 2.7201E-15 | 2.3645E-13 | 0.49 | 0.68 | 8.3454E-01 | 9.9797E-01 |
| 0.14 | -1.02 | 2.9294E-15 | 1.6225E-12 | 0.50 | 0.73 | 9.1117E-01 | 9.9941E-01 |
| 0.15 | -0.97 | 3.1386E-15 | 9.7686E-12 | 0.51 | 0.78 | 9.5806E-01 | 9.9985E-01 |
| 0.16 | -0.92 | 3.3478E-15 | 5.2952E-11 | 0.52 | 0.82 | 9.8270E-01 | 9.9997E-01 |
| 0.17 | -0.87 | 3.5571E-15 | 2.6233E-10 | 0.53 | 0.87 | 9.9379E-01 | 9.9999E-01 |
| 0.18 | -0.82 | 3.7663E-15 | 1.2513E-09 | 0.54 | 0.92 | 9.9807E-01 | 1.0000E+00 |
| 0.19 | -0.78 | 2.1733E-14 | 6.9107E-09 | 0.55 | 0.97 | 9.9948E-01 | 1.0000E+00 |
| 0.20 | -0.73 | 2.1209E-13 | 2.6769E-08 | 0.56 | 1.02 | 9.9988E-01 | 1.0000E+00 |
| 0.21 | -0.68 | 1.7358E-12 | 1.1600E-07 | 0.57 | 1.07 | 9.9998E-01 | 1.0000E+00 |
| 0.22 | -0.63 | 1.1373E-11 | 4.8126E-07 | 0.58 | 1.11 | 1.0000E+00 | 1.0000E+00 |
| 0.23 | -0.58 | 6.4625E-11 | 1.9316E-06 | 0.59 | 1.16 | 1.0000E+00 | 1.0000E+00 |
| 0.24 | -0.53 | 4.1126E-10 | 7.5246E-06 | 0.60 | 1.21 | 1.0000E+00 | 1.0000E+00 |
| 0.25 | -0.48 | 2.4773E-09 | 2.8566E-05 | 0.61 | 1.26 | 1.0000E+00 | 1.0000E+00 |
| 0.26 | -0.44 | 1.2132E-08 | 1.0566E-04 | 0.62 | 1.31 | 1.0000E+00 | 1.0000E+00 |
| 0.27 | -0.39 | 5.2343E-08 | 3.7635E-04 | 0.63 | 1.36 | 1.0000E+00 | 1.0000E+00 |
| 0.28 | -0.34 | 2.4478E-07 | 1.2625E-03 | 0.64 | 1.41 | 1.0000E+00 | 1.0000E+00 |
| 0.29 | -0.29 | 1.0945E-06 | 3.8474E-03 | 0.65 | 1.45 | 1.0000E+00 | 1.0000E+00 |
| 0.30 | -0.24 | 4.7123E-06 | 1.0185E-02 | 0.66 | 1.50 | 1.0000E+00 | 1.0000E+00 |
| 0.31 | -0.19 | 1.9709E-05 | 2.2466E-02 | 0.67 | 1.55 | 1.0000E+00 | 1.0000E+00 |
| 0.32 | -0.15 | 7.9860E-05 | 4.0237E-02 | 0.68 | 1.60 | 1.0000E+00 | 1.0000E+00 |
| 0.33 | -0.10 | 3.1104E-04 | 5.9110E-02 | 0.69 | 1.65 | 1.0000E+00 | 1.0000E+00 |

Table D1.1-1. Probability of Failure versus True Strain Tabulated for Figure D1.1-1 (Continued)

| True Strain (*TS*) | $\frac{TS - TS_{mean}}{TS_{std}}$ | Probability of Failure Original | Probability of Failure Adjusted (-8.3% shift) | True Strain (*TS*) | $\frac{TS - TS_{mean}}{TS_{std}}$ | Probability of Failure Original | Probability of Failure Adjusted (-8.3% shift) |
|---|---|---|---|---|---|---|---|
| 0.34 | -0.05 | 1.1366E-03 | 7.5125E-02 | 0.70 | 1.70 | 1.0000E+00 | 1.0000E+00 |
| 0.35 | 0.00 | 3.7379E-03 | 8.9858E-02 | | | | |

NOTE: The mean for true strain is 0.35, shown in bold. The standard deviation (std) of true strain is 0.21.

Source: Ref. D4.1.27, Table 6.3.7.3-1

The weldment at best can have the same mechanical properties as the hosting metal (native metal), but it is usually more brittle than the hosting metal. The failure likelihood of the weldment substructure was considered, reflecting weighting factors of both 1.0 and 0.75 applied to estimated true strain at failure.

The capacity function is based on coupon tensile strength tests in uniaxial tension. However, cracking of a stainless steel may not be determined simply by comparing the calculated plastic strain to the true strain of failure, because the equivalent (or effective) plastic strain (EPS) is calculated from a complex 3-D state of stress, while the true strain at failure was based on data from a 1-D state of stress. A 3-D state of stress may constrain plastic flow in the material and lower the EPS at which failure occurs. This loss of ductility is accounted for by the use of a triaxiality factor, which is the ratio of normal stress to shear stress on the octahedral plane, normalized to unity for simple tension. For the purpose of determining the probability of structural failure, LLNL (Ref. D4.1.27) set the ductility ratio to 0.5. This is equivalent to a triaxiality factor of 2, which corresponds to a state of biaxial tension.

Failure of containment can occur when strain in a component is of sufficient magnitude that it results in breakage or puncture of the container. The probability of failure is calculated based on the maximum strain for a single finite element brick obtained from LS-DYNA simulations. Fracture propagation takes place on the milliseconds time-scale and thus propagates across the canister wall thickness very quickly, compared to the time-frame of the LS-DYNA simulations. Furthermore, the fragility curve is obtained on the basis of a maximum average strain over the thickness of the respective specimens, which are 2 in. long stainless steel 304L specimens. Although LS-DYNA results provide multiple values of the strain through the thickness of the canister wall (the wall thickness being represented by multiple finite element layers), it is more conservative to use the maximum strain value at a single finite element brick than the average of the multiple values across the thickness of the wall.

The probability of failure for each impact scenario is evaluated by finding the maximum strain at a location in which a through-wall crack would constitute a radionuclide release. A probability of failure is determined from the CDF of capacity or fragility curve (as discussed below) from the global maximum strain.

A conservative approach and aid to computational efficiency is achieved by performing calculations focusing on the regions of the container having high strain (and deformation) after a drop ("hot zones"). An importance sampling strategy was used which places greater-than-

random emphasis on ranges of input-variable values, and/or on combinations of such value ranges, that are more likely to affect output. This approach is an alternative to Monte Carlo methods with the important advantage that possible combinations of upper-bound variable values are in fact incorporated into each probabilistic estimate of expected model output (which is not always guaranteed by uniform sampling).

Using the general probabilistic approach summarized here, LLNL (Ref. D4.1.27) calculated failure probabilities for representative canisters in an aging overpack, and in a transportation cask, and for the representative canister itself, as presented in Tables D1.2-2 through D1.2-5. For the drop of a 10-metric-ton load onto a cask, the falling mass is modeled as a rigid (unyielding) wall, oriented normal to longitudinal axis of the cask.

## D1.2 IDAHO NATIONAL LABORATORY ANALYSIS OF SPENT NUCLEAR FUEL CANISTERS AND MULTICANISTER OVERPACKS

Drop tests of prototype canisters conducted by the Idaho National Laboratory (INL) confirmed that the stainless steel shell material can undergo significant strains without material failure leading to loss of containment. These drop tests also validated analytical models used to predict strains under various drop scenarios. Table D1.2-6 shows scenarios selected to address potential drop scenarios at YMP facilities and the predicted strains.

INL performed FEA (using ABAQUS/Explicit, which, like LS-DYNA, has been used in nuclear facility and non-nuclear industrial applications, and is appropriate to model nonlinear, transient responses of a passive component to a structural challenge such as a drop or an impact) of 23-foot drops, three degrees off vertical, to determine the extent of strain at various positions in the bottom head, cylindrical shell, and joining weld. The strain was evaluated and reported for the inside, outside, and middle layers (Ref. D4.1.64). The U.S. Department of Energy (DOE) standardized spent nuclear fuel (SNF) canisters were modeled at 300°F, the maximum skin temperature expected due to the heat evolved by the fuel (based on review of thermal analyses performed by transportation casks vendors), resulting in diminished casing material strength. It was found that greater strains would be expected in the MCOs at ambient temperatures than at elevated temperatures.

During a canister drop event, the majority of the kinetic energy at impact performs work on the material, which causes the worst locations to exhibit plastic strain. A good measure of this work is equivalent plastic strain, which is a cumulative strain measure that takes into account the deformation history starting at impact. From the peak equivalent plastic strain, LLNL (Ref. D4.1.27) developed failure probabilities using the method described in Section D1.1 for an 18 in. and 24 in. DOE standard canister and an MCO. Results are summarized in Table D1.2-7.

Table D1.2-1. Container Configurations and Loading Conditions

| Container | Configuration | Drop Type/Impact Condition[a] | Drop Height |
|---|---|---|---|
| AO (aging overpack) cell with canister inside | Representative canister inside AO | A IC 1: End with vertical orientation | 3-ft vertical |
| | | A IC 2: Slapdown from a vertical orientation and 2.5 mph horizontal velocity | 0-ft vertical |
| Transportation cask with spent nuclear fuel (SNF) canister inside | Representative canister inside representative cask | T IC 1a: End, with 4 degree off-vertical orientation | 12-ft vertical |
| | | T.IC 1b: Same as T.IC 1a | 13.1-ft vertical |
| | | T.IC 1c: Same as T.IC 1a | 30-ft vertical |
| | | T IC 2a: End, with 4 degree off-vertical orientation, and approximated slapdown | 13.1-ft vertical |
| | | T.IC 2b: Same as T.IC 2a, with no free fall | 0-ft vertical |
| | | T IC 3: Side, with 3 degree off-horizontal orientation | 6-ft vertical |
| | | T IC 4: Drop of 10-metric-ton load onto top of cask | 10-ft vertical |
| DPC (dual-purpose canister)<br>TAD (transportation, aging, and disposal) canister | Representative canister | D IC 1a: End, with vertical orientation | 32.5-ft vertical |
| | | D IC 1b: Same as D.IC 1a | 40-ft vertical |
| | | D IC 2a: End, with 4 degree off-vertical orientation | 23-ft vertical |
| | | D IC 2b: Same as D.IC 2a | 10-ft vertical |
| | | D IC 2c: Same as D.IC 2a | 5-ft vertical |
| | | D IC 3: 40 ft/min horizontal collision inside the CTM bell | No drop |
| | | D IC 4: Drop of 10-metric-ton load onto top of canister | 10-ft vertical |
| | | D.IC 2a: Hourglass-control study for end drop, with 4 degree off-vertical orientation | 23-ft vertical |
| | | D.IC 2a: Friction coefficient sensitivity study for end drop, with 4 degree off-vertical orientation | 23-ft vertical |
| | | D.IC 2a: Mesh density study for end drop, with 4 degree off-vertical orientation | 23-ft vertical |
| | | D.IC 2a: Shell- and bottom-lid-thickness sensitivity study for end drop, with 4 degree off-vertical orientation | 23-ft vertical |
| DSNF (DOE spent nuclear fuel) canister | INL-analyzed case | O.IC 1: End, with 3-degree-off vertical orientation | 23-ft vertical |

NOTE: A = aging overpack; (AO) CTM = canister transfer machine; ft = foot; D = dual purpose canister; IC = impact condition; min = minute; mph = miles per hour; O = DOE SNF canister; SNF = spent nuclear fuel; T = transportation cask.

Source: [a]Modified from Ref. D4.1.27, Table 4.3.3-1a

Table D1.2-2. Failure Probabilities with and without Triaxiality Factor, with and without the Fragility Curve Adjustment, for Representative Canister within an Aging Overpack

| Container Type/ Impact Condition[a] | Impact Condition Description | Max EPS[b] | Failure Probability[b] | | | |
|---|---|---|---|---|---|---|
| | | | Original CDF Fragility Curve w/o Adjustment | | CDF Fragility Curve Adjusted for Minimum Elongation (-8.3% Shift) | |
| | | | w/o Triaxiality | with Triaxiality | w/o Triaxiality | with Triaxiality |
| A.IC 1 | 3-ft end drop, with vertical orientation | 0.16% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| A.IC 2 | Slapdown from a vertical orientation and 2.5-mph horizontal velocity | 0.82% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |

NOTE: [a]"A" stands for aging overpack. "IC" stands for impact condition, which are defined in Table D1.2-1.
[b]Values of Max EPS and failure probability are applicable to the SNF canister.

Source: Ref. D4.1.27, Table 6.3.7.6-1

Table D1.2-3. Failure Probabilities with and without Triaxiality Factor, with and without Fragility Curve Adjustment, for Representative Canister

| Container Type/ Impact Condition[a] | Impact Condition Description | Max EPS[b] | Failure Probability[b] | | | |
|---|---|---|---|---|---|---|
| | | | Original CDF Fragility Curve w/o Adjustment | | CDF Fragility Curve Adjusted for Minimum Elongation (-8.3% Shift) | |
| | | | w/o Triaxiality | with Triaxiality | w/o Triaxiality | with Triaxiality |
| D.IC 1a | 32.5-ft end drop, with vertical orientation | 2.13% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| D.IC 1b | 40-ft end drop, with vertical orientation | 2.65% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| D.IC 2a | 23-ft end drop, with 4-degree off-vertical orientation | 24.19% | $<1 \times 10^{-8}$ | **$7.71 \times 10^{-1}$** | **$9.72 \times 10^{-6}$** | **$9.96 \times 10^{-1}$** |
| D.IC 2b | 10-ft end drop, with 4-degree off-vertical orientation | 19.71% | $<1 \times 10^{-8}$ | **$7.01 \times 10^{-2}$** | **$1.73 \times 10^{-8}$** | **$3.19 \times 10^{-1}$** |
| D.IC 2c | 5-ft end drop, with 4-degree off-vertical orientation | 15.76% | $<1 \times 10^{-8}$ | **$4.10 \times 10^{-5}$** | $<1 \times 10^{-8}$ | **$3.12 \times 10^{-2}$** |
| D.IC 3 | 40-ft/min horizontal side collision | 0.16% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| D.IC 4 | 10-ft drop of 10-metric-ton load onto top of canister | 0.75% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| D.IC 2a S1-L1 | Same as D.IC 2a | 24.19% | $<1 \times 10^{-8}$ | **$7.71 \times 10^{-1}$** | **$9.72 \times 10^{-6}$** | **$9.96 \times 10^{-1}$** |
| D.IC 2a S2-L1 | Same as D.IC 2a | 21.52% | $<1 \times 10^{-8}$ | **$1.66 \times 10^{-1}$** | **$2.44 \times 10^{-7}$** | **$7.62 \times 10^{-1}$** |
| D.IC 2a S3-L1 | Same as D.IC 2a | 16.53% | $<1 \times 10^{-8}$ | **$3.37 \times 10^{-4}$** | $<1 \times 10^{-8}$ | **$6.02 \times 10^{-2}$** |
| D.IC 2a S1-L2 | Same as D.IC 2a | 23.34% | $<1 \times 10^{-8}$ | **$5.52 \times 10^{-1}$** | **$3.07 \times 10^{-6}$** | **$9.78 \times 10^{-1}$** |
| D.IC 2a S1-L3 | Same as D.IC 2a | 25.15% | $<1 \times 10^{-8}$ | **$9.28 \times 10^{-1}$** | **$3.48 \times 10^{-5}$** | **1.00** |
| D.IC 2a S2-L3 | Same as D.IC 2a | 22.57% | $<1 \times 10^{-8}$ | **$3.50 \times 10^{-1}$** | **$1.07 \times 10^{-6}$** | **$9.28 \times 10^{-1}$** |
| D.IC 2a S3-L3 | Same as D.IC 2a | 18.08% | $<1 \times 10^{-8}$ | **$1.22 \times 10^{-2}$** | $<1 \times 10^{-8}$ | **$1.14 \times 10^{-1}$** |
| D.IC 2a S2-L4 | Same as D.IC 2a | 24.07% | $<1 \times 10^{-8}$ | **$7.44 \times 10^{-1}$** | **$8.27 \times 10^{-6}$** | **$9.95 \times 10^{-1}$** |
| D.IC 2a S3-L4 | Same as D.IC 2a | 19.50% | $<1 \times 10^{-8}$ | **$6.29 \times 10^{-2}$** | **$1.37 \times 10^{-8}$** | **$2.77 \times 10^{-1}$** |

NOTE: [a]"D" stands for dual-purpose canister. "IC" stands for impact condition, which are defined in Table D1.2-1.
See Table 6.3.3.5-1 of Ref. D4.1.27 for definitions of H1, F1, M1, etc. See Table 6.3.3.6-1 of Ref. D4.1.27 for definitions of S1, L1, etc.
[b]Values of Max EPS and failure probability are applicable to the SNF canister. A range of canister shell and bottom plate thicknesses were evaluated. The values shown are for the configuration that yielded the highest strains (0.5-inch shell thickness and 2.313 inch bottom plate thickness)

Source: Ref. D4.1.27, Table 6.3.7.6-3

Table D1.2-4. Failure Probabilities with and without Triaxiality Factor, with and without the Fragility Curve Adjustment, for the Representative Canister inside the Transportation Cask

| Container Type/ Impact Condition[a] | Impact Condition Description | Max EPS[b] | Failure Probability[b] | | | |
|---|---|---|---|---|---|---|
| | | | Original CDF Fragility Curve w/o Adjustment | | CDF Fragility Curve Adjusted for Minimum Elongation (-8.3% Shift) | |
| | | | w/o Triaxiality | with Triaxiality | w/o Triaxiality | with Triaxiality |
| T.IC 1a | 12-ft end drop, with 4-degree off-vertical orientation | 3.53% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 1b | 13.1-ft end drop, with 4-degree off-vertical orientation | 4.06% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 1c | 30-ft end drop, with 4-degree off-vertical orientation | 5.77% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 2a | 13.1-ft end drop, with 4-degree off-vertical orientation, and approximated slapdown | 4.35% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 2b | Approximated slapdown from vertical orientation | 1.25% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 3 | 6-ft side drop, with 3-degree off-horizontal orientation | 2.07% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 4 | 10-ft drop of 10-metric-ton load onto top of cask | 0.96% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 5a | 30-ft end drop, with vertical orientation | 3.55% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 5b | 30-ft end drop, with 4-degree off-vertical orientation | 5.77% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 5c | 30-ft end drop, with 45-degree off-vertical orientation | 6.41% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 5d | 30-ft end drop, with center of gravity over corner (i.e., point of impact) | 6.63% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |

NOTE: [a]"T" stands for transportation cask. "IC" stands for impact condition, which are defined in Table D1.2-1.
[b]Values of Max EPS and failure probability are applicable to the SNF canister.

Source: Ref. D4.1.27, Table 6.3.7.6-2

Table D1.2-5. Failure Probabilities with and without Triaxiality Factor, with and without the Fragility Curve Adjustment, for the Transportation Cask

| Container Type/ Impact Condition[a] | Impact Condition Description | Max EPS[b] | Failure Probability: CDF Fragility Curve Adjusted for Minimum Elongation (-8.3% Shift) | |
|---|---|---|---|---|
| | | | w/o Triaxiality | with Triaxiality |
| T.IC 1a | 12-ft end drop, with 4-degree off-vertical orientation | 9.20% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 1b | 13.1-ft end drop, with 4-degree off-vertical orientation | 9.37% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 1c | 30-ft end drop, with 4-degree off-vertical orientation | 11.25% | $<1 \times 10^{-8}$ | $9 \times 10^{-7}$ |
| T.IC 2a | 13.1-ft end drop, with 4-degree off-vertical orientation, and approximated slapdown | 9.94% | $<1 \times 10^{-8}$ | $3 \times 10^{-8}$ |
| T.IC 2b | Approximated slapdown from vertical orientation | 5.30% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 3 | 6-ft side drop, with 3-degree off-horizontal orientation | 7.42% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 4 | 10-ft drop of 10-metric-ton load onto top of cask | 1.76% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 5a | 30-ft end drop, with vertical orientation | 3.17% | $<1 \times 10^{-8}$ | $<1 \times 10^{-8}$ |
| T.IC 5b | 30-ft end drop, with 4-degree off-vertical orientation | 11.25% | $<1 \times 10^{-8}$ | $9 \times 10^{-7}$ |
| T.IC 5c | 30-ft end drop, with 45-degree off-vertical orientation | 70.56% | 1 | 1 |
| T.IC 5d | 30-ft end drop, with center of gravity over corner (i.e., point of impact) | 44.88% | 0.9 | 1 |

NOTE: [a]"T" stands for transportation cask. "IC" stands for impact condition, which are defined in Table D1.2-1.
[b]Values of Max EPS and failure probability are applicable to the structural body of the transportation cask, which excludes the shield and shield shell.

Source: Probabilities calculated using Table D1.1-1 based on strains reported in Ref. D4.1.27, Table 6.3.7.6-2

Table D1.2-6. Strains at Various Canister Locations Due to Drops

| Canister | Component | Maximum PEEQ Strains (%) | | | Load Case/ Conditions |
|---|---|---|---|---|---|
| | | Outside Surface | Mid-Surface | Inside Surface | |
| 18-inch DOE STD canister | Lower head | 8 | 3 | 6 | 300°F, 23-ft drop, 3 degrees off-vertical<br>Material: ASME Code minimum strengths |
| | Lower head-to-main shell weld | 2 | 2 | 3 | |
| | Main shell | 2 | 2 | 3 | |
| | Upper head-to-main shell weld | 0 | 0 | 0 | |
| | Upper head | 1 | 0.2 | 2 | |
| 24-inch DOE STD canister | Lower head | 2 | 0.7 | 1 | 300°F, 23-ft drop, 3 degrees off-vertical<br>Material: ASME Code minimum strengths |
| | Lower head-to-main shell weld | 0.2 | 0.3 | 0.5 | |
| | Main shell | 0.2 | 0.3 | 0.5 | |
| | Upper head-to-main shell weld | 0 | 0 | 0 | |
| | Upper Head | 0 | 0 | 0 | |
| MCO | Lower head | 35 | 16 | 14 | 70°F, 23-ft drop, 3 degrees off-vertical<br>Material: Actual material properties (significantly higher than ASME Code minimums) |
| | Lower head-to-main shell weld | 21 | 11 | 11 | |
| | Main shell | 13 | 15 | 29 | |
| | Upper head-to-main shell weld | 0 | 0 | 0 | |
| | Upper head | 0 | 0 | 0 | |

NOTE: ASME = The American Society of Mechanical Engineers; DOE STD = U.S. Department of Energy standard; MCO = multicanister overpack; PEEQ = peak equivalent.

Source: Ref. D4.1.64, Tables 13, 14, and 16

Table D1.2-7. Failure Probabilities for the DOE Spent Nuclear Fuel (DSNF) Canisters and Multicanister Overpack (MCO)

| Component | Peak Equivalent Plastic Strain (%) | | | Probability of Failure | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Original CDF | | | CDF adjusted to min elongation | | |
| | Outside Surface | Middle | Inside Surface | Outside Surface | Middle | Inside Surface | Outside Surface | Middle | Inside Surface |
| **18-inch standard canister containment PEEQ strains, 3 degrees off vertical drop, 300°F** | | | | | | | | | |
| Lower head | 8 | 3 | 6 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Lower head-to-main shell weld | 2 | 2 | 3 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Main shell | 2 | 2 | 3 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Upper head-to-main shell weld | 0 | 0 | 0 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Upper head | 1 | 0.2 | 2 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| **24-inch standard canister containment PEEQ strains, 3 degrees off vertical drop, 300°F** | | | | | | | | | |
| Lower head | 2 | 0.7 | 1 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Lower head-to-main shell weld | 0.2 | 0.3 | 0.5 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Main shell | 0.2 | 0.3 | 0.5 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Upper head-to-main shell weld | 0 | 0 | 0 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Upper head | 0 | 0 | 0 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| **4 MCO containment PEEQ strains, 3 degrees off vertical drop, 70°F** | | | | | | | | | |
| Bottom | 35 | 16 | 14 | 3.74E-03 | <1E-08 | <1E-08 | 8.99E-02 | <1E-08 | <1E-08 |
| Bottom-to-main shell | 21 | 11 | 11 | <1E-08 | <1E-08 | <1E-08 | 1.16E-07 | <1E-08 | <1E-08 |
| Main shell | 13 | 15 | 29 | <1E-08 | <1E-08 | 1.09E-06 | <1E-08 | <1E-08 | 3.85E-03 |
| Collar | 0 | 0 | 0 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |
| Cover | 0 | 0 | 0 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 | <1E-08 |

NOTE: ASME = The American Society of Mechanical Engineers; CDF = cumulative distribution function; DOE STD = U.S. Department of Energy standard; MCO = multicanister overpack; PEEQ = peak equivalent.

Source: Ref. D4.1.27, Tables 6.3.7.6-4 and 6.3.7.6-5