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Updates two earlier calculations: *Probability of PWR UCF WP Postclosure Criticality for Enhanced Design Alternatives* (BBA000000-01717-0210-00072 REV 00) and *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality* (BBA000000-01717-0210-000010).

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1. PURPOSE

The purpose of this calculation is to update the estimate of the probability of criticality for waste packages (WP) containing commercial pressurized water reactor (PWR) spent nuclear fuel (SNF). This update will reflect the degradation characteristics of the recently developed Enhanced Design Alternative II (EDA II) WP design (Ref. 1, pp. 5-37 through 5-40, 5-44, and 5-45). These characteristics include the distribution of time of first waste package breach and the probability of breach on the upper side before breach on the lower side (so that there can be standing water in the waste package). The calculation simulates the degradation of the entire projected inventory of PWR SNF up to 250,000 years after emplacement in the repository.

This calculation improves upon the most recent update of commercial PWR criticality probability (Ref. 2) by using a full Monte Carlo simulation of the waste package degradation processes. It updates the first Monte Carlo simulation (Ref. 3) by assuming the EDA II design. It improves upon both previous calculations by incorporating the incremental effect on criticality of assembly collapse and fission product loss. Significant loss of iron oxide is considered to test the sensitivity of the results to iron oxide loss because the possibility of iron oxide loss has been mentioned in response to presentations of the standard degradation scenarios. Consideration of iron oxide loss provides an extra measure of conservatism; there is no natural mechanism to produce such a loss.

This calculation is associated with disposal criticality analysis and has been prepared in accordance with procedure AP-3.12Q (Rev. 0, ICN 0, effective 06/30/1999).

2. METHOD

The likely internal degradation scenario for the commercial PWR SNF waste package is shown in six stages in Figure 2-1. The first stage (Figure 2-1A) is the intact configuration, which is assumed to exist just prior to breach of the waste package irrespective of the time to breach (Assumption 3.1). The water breaching the waste package will fill the waste package to the level of the breach. For several hundred years following the filling of the waste package, the dominant degradation process will be the corrosion of the carbon steel and aluminum components. The first structural components to fail will be the carbon steel side guides and corner guides (Figure 2-1B). Following those failures, the rest of the structural material and thermal shunts will fail, leading to the fully collapsed basket configuration (Figure 2-1C).

The Monte Carlo simulation process tracks the loss of borated stainless steel following the attainment of the fully collapsed basket configuration of Figure 2-1C. Of course, there will be some degradation of borated stainless steel before the basket fully collapses, so it is conservative to assume that the progression from the initial configuration to the fully collapsed basket (Figure 2-1A through Figure 2-1C) is instantaneous (Assumption 3.2). The remaining configurations (Figure 2-1D through Figure 2-1F) show the results of the degradation of the borated stainless steel, the Zircaloy assembly spacer grids, and the Zircaloy cladding, respectively. In actuality, these components will degrade simultaneously, but the borated stainless steel will degrade at a much faster rate than the Zircaloy, so the scenario is very likely to pass through a configuration resembling Figure 2-1D. Since the Zircaloy spacer grids (Ref. 4, Table 4.2-1) are thinner than

the Zircaloy fuel pin cladding (Ref. 5, p. 26), and since the spacer grids are exposed to corrosion from both sides while the cladding is only exposed to corrosion from one side, the assemblies are more likely to collapse (Figure 2-1E) before significant degradation of the fuel matrix itself (Figure 2-1F). However, the Monte Carlo simulation does consider the possibility of these processes occurring simultaneously, with appropriate probability weighting, to ensure that the final result represents a conservative estimate.

The degradation scenario illustrated in Figure 2-1 has been used as the basis for earlier estimates of criticality probability for the commercial SNF waste package (Ref. 2, Section 2 and Ref. 3, Section 2), and it is consistent with the degradation analysis methodology established in Ref. 6 (pp. 3-11 through 3-13).

The Monte Carlo technique is implemented by a software routine, "montecarlo.c" that builds the expected criticality statistics from a file of expected assembly receipts at the repository. In this file, the assemblies are grouped in batches of from 1 to 50 assemblies representing common reactor histories. Each batch is characterized by a set of parameters; the ones most important for criticality are burnup and initial enrichment. The first step in the processing of each batch is to screen for criticality potential; only those batches with criticality potential above a specified threshold are then subject to the large number of Monte Carlo realizations. The number of realizations used for this calculation is 500. Each Monte Carlo realization begins with a random selection of whether the package is dripped on and whether the package is breached on the top before it is breached on the bottom. For realizations that satisfy both conditions, the time before breach and the time between first top breach and first bottom breach (duration of waste package "bathtub" configuration) are randomly generated. Also generated at this time are the parameters for the distribution of rates of assembly collapse and fission product loss (which results from the degradation of the fuel matrix).

For each time step of the numerical integration of a Monte Carlo realization, the following parameters are also calculated or generated randomly from a specified distribution: decrement in thickness of borated stainless steel, quantity of boron lost from the waste package, degree of assembly collapse, and quantity of fission products lost from the fuel matrix. The k_{eff} of the remaining configuration is then calculated, using a regression as a function of: time since irradiation, burnup, initial enrichment, and parameters describing the degree of degradation of the borated stainless steel and the boron loss from the waste package. This regression is based on over 1000 criticality calculations using MCNP4A, as described in Ref. 7 (pp. 4, 5, and 24). The regression is extended to include a parameter characterizing the degree of assembly collapse and a parameter characterizing the loss of neutron absorbing fission products from the fuel matrix. This extension is based on an additional 400 criticality calculations, as described in Ref. 8 (Section 6).

If the calculated k_{eff} is less than the criticality limit (CL), which is set at 0.98 for this calculation, then the calculation moves to the next time step and the process is repeated. If the calculated k_{eff} exceeds the CL the realization is ended and the time of criticality is sorted into discrete increments or bins 1000 years wide for later processing. The simulation then moves to the next realization, and the process is repeated until the specified number of realizations has been

generated for this batch of assemblies, after which the process begins again with the next batch of assemblies. After all the batches have been processed, the summary statistics of the resulting probability distribution are generated: the frequency of criticality, the cumulative probability of criticality, and the expected number of criticalities, all as a function of time up to 250,000 years in discrete time steps of 1000 years.

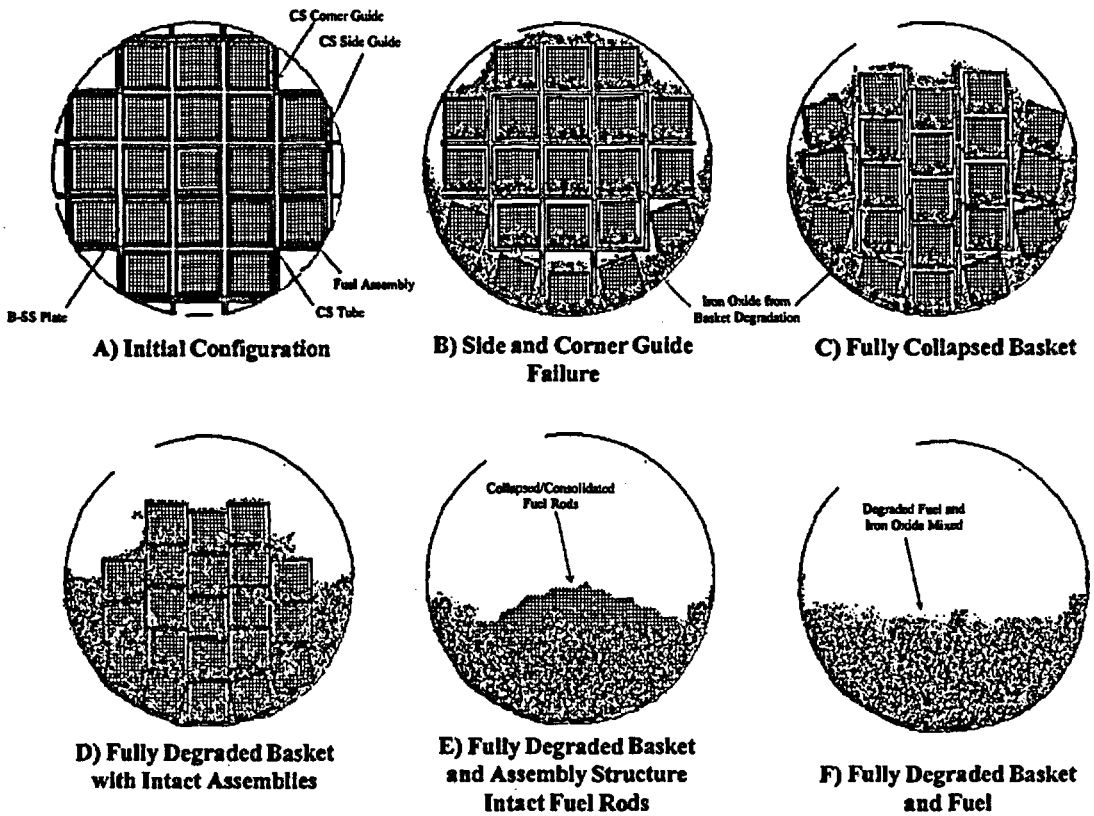

Figure 2-1. Degradation Sequence for the 21 PWR Absorber Plate Waste Package

3. ASSUMPTIONS

3.1 It is assumed that the spent fuel and other internal components of the waste package do not degrade before the breach of the waste package. The basis for this assumption is that the dry interior of the package is to be rendered inert with helium before sealing (Ref. 9, p. 4-23), so there are no agents for chemical reaction. This assumption is used throughout the calculation.

3.2 It is assumed that after the waste package is breached, water fills the package and corrodes the carbon steel and aluminum components instantaneously. The bases of this

assumption are that (a) it is conservative to assume that the WP fills instantaneously and (b) Ref. 6 (pp. C-17 through C-19) indicates that these components will degrade quickly in comparison to the borated stainless steel components. This assumption is used throughout the calculation.

3.3 It is assumed that Babcock & Wilcox (B&W) Mark B 15 x 15 fuel type, which was assumed in the criticality calculations (Ref. 7, p. 6) that were used to estimate the fraction of fuel exceeding the critical limit, is bounding for all PWR fuel types. The bases for this assumption are that (a) a previous evaluation performed for the BR-100 transportation cask established the B&W Mark B assembly as one of the most reactive PWR fuel designs in the 30 GWd/MTU burnup range under intact fuel assembly and fixed basket geometry conditions (Ref. 10, p. II.6-6) and (b) the most important parameters predicting whether a waste package will exceed the criticality limit are: time since irradiation, burnup, and enrichment of the fuel, rather than the specific fuel type. This assumption is used throughout the calculation.

3.4 It is assumed that only the 21 PWR WP design with 7-mm thick borated stainless steel absorber plates (Ref. 11, pp. 21, 29, and 30) is used for the entire PWR waste stream. The basis for this assumption is that it is conservative because a more robust (less soluble) absorber may ultimately be used. This assumption is used throughout the calculation.

3.5 Principal Isotope (PI) burnup credit is assumed to be an acceptable method to account for reduced reactivity of SNF in criticality evaluations. The basis for this assumption is Controlled Design Assumption Key 009 (Ref. 12, p. 3-22). In addition, this assumption was used in the criticality calculations (Ref. 7, p. 15, Assumption 4.3.1) used to develop the k_{eff} regressions discussed in Section 5.2. This assumption is used throughout the calculation.

3.6 It is assumed that a general corrosion rate for 304/316 stainless steel, when increased by a "boron factor" of 2.5 can be used to represent the bulk corrosion rate of Neutronit A978 borated stainless steel in the repository environment. The basis for this assumption is that Neutronit A978 is similar in composition to 316 stainless steel (Ref. 13, p. 96), and corrosion data in repository relevant environments is only available for 304/316 stainless steels. The boron factor of 2.5 is the mean of a uniform distribution ranging from 1 to 4. The basis for the upper bound of the boron factor distribution is that borated 304 stainless steel was found to have a corrosion rate up to 4 times that of unborated 304 stainless steel in a short-term corrosion test in a harsh environment (Ref. 7, pp. 11-13). The basis for the lower bound is the expectation that the presence of boron will not decrease the corrosion rate. The basis for assuming a uniform distribution of uncertainty between the lower and upper bounds is a lack of more specific information about the effect of boron in the less harsh repository environment. The basis for choosing the mean value and, therefore, not propagating the uncertainty of the boron factor, is that whether or not criticality is attained is expected to be more sensitive to other parameters, which are treated stochastically. This assumption is used throughout the calculation.

3.7 It is assumed that the boron will immediately enter solution and be available for removal from the waste package (the effect of potential adsorption on iron oxide is ignored) once it has been released from the borated stainless steel matrix. The basis of this assumption is that it is conservative in light of (a) the discussion in (Ref. 7, pp. 11-13) of the corrosion of borated stainless steel, which indicates that the boride particles would corrode relatively quickly because they have a large surface-to-volume ratio. A further basis is that neglecting the effects of boron adsorption on iron oxides is also conservative in light of indications in (Ref. 7, p. 48) that adsorption on Fe_2O_3 may provide up to a 1.4% reduction in k_{eff} (greater reductions may occur if adsorption on Al oxides or other types of iron oxides is considered). This assumption is used throughout the calculation.

3.8 It is assumed that the waste package is horizontally emplaced and floods instantaneously upon breach on the upper side, and drains instantaneously upon breach on the bottom. The basis for this assumption is the evaluation of waste package filling and draining times performed in Ref. 14 (pp. 38-41) which indicated that the filling and draining times are relatively short (a few tens to hundreds of years) in comparison to the potential duration of flooding discussed in Section 5.1.3 of this calculation and the 1000 year time step typically used in the mass-balance calculations. This assumption is used throughout the calculation.

3.9 It is assumed that the duration of waste package flooding is independent of waste package breach time. The TSPA results discussed in Ref. 3 (pp. 16-17) show that there is a positive correlation of flood duration and waste package breach time. This assumption is conservative in the early years because assuming independence implies longer flood duration at early breach times than would occur if flood duration and breach time were positively correlated. On the other hand, assuming independence implies shorter flood duration in later years, which is not conservative in the later years. Flooding during the earlier years is of greater concern due to the expectation that the peak post-closure k_{eff} (Ref. 7, p. 48) will occur in the early years between 10,000 and 35,000 years after closure. Therefore, the basis of this assumption is that it is conservative because it allows for longer flood duration during the more important early years. This assumption is used throughout the calculation.

3.10 It is assumed that the subcritical limit for all configurations evaluated in this calculation is 0.98. The basis for this assumption is a statistical estimate of bias for benchmark calculations that was developed using the same software systems (MCNP and SAS2H) as those used to estimate the fraction of fuel that could exceed a given k_{eff} value (Ref. 15, pp. 22 and 23). The cited calculation yielded a subcritical limit of 0.98 if no trending parameters are used, and no administrative bias is applied. This assumption is used throughout the calculation.

3.11 It is assumed that water entering the WP after dripping onto the WP replaces boron-saturated water inside the WP with a transfer efficiency drawn from a uniform probability distribution between 5 and 15 percent. The transfer efficiency is, in effect, the ratio of

the volume of boron-saturated water leaving the WP to the volume of water entering the WP, with the rest of the water that enters the WP leaving unchanged in boron concentration. The basis for this assumption is that it is approximately consistent with, and slightly more conservative than, the range of transfer efficiency used in Assumption 4.3.4 of Ref. 14 (0.1 to 10 percent). Greater transfer efficiency implies greater conservatism due to more rapid removal of boron from the WP. This assumption is used throughout the calculation.

3.12 It is assumed that estimated numbers of SNF assemblies by burnup and initial enrichment from Reference 16 are appropriate for this calculation. Although a revised set of waste stream data has recently become available (Ref. 17), the earlier set is used. The data used may predict fewer low-burnup assemblies than will actually be present in the future waste stream. However, any concern about the criticality of WPs with low-burnup assemblies will likely be handled by "derating" that is, disposing of the low-burnup assemblies in WPs with fewer assemblies. Because this calculation assumes that all assemblies, including low-burnup ones, are disposed of at a rate of 21 assemblies per WP, this calculation exaggerates the probability of criticality and is therefore conservative. The basis of this assumption is that it is conservative and maintains consistency with previous work (Ref. 3). This assumption is used throughout the calculation.

4. USE OF COMPUTER SOFTWARE AND MODELS

4.1 SOFTWARE APPROVED FOR QA WORK

None used.

4.2 SOFTWARE ROUTINES

The Monte Carlo mass balance calculation was performed using a C software routine named "montecarlo.c", Version 1. The function of "montecarlo.c" is to (a) select a set of inputs by randomly sampling the probability distributions that describe the repository environment and waste package degradation (Section 5.1) and (b) using the selected inputs, perform a deterministic mass balance to determine whether a waste package exceeds the subcritical limit for the selected inputs. This sampling and calculating process is repeated a specified number of times, resulting in a number of possible outcomes or realizations. Further discussion on the operation of "montecarlo.c" is provided in Section 5.2.

The implementation of the Monte Carlo process is independently verified as part of the technical check of this calculation. The source code for "montecarlo.c" is provided in Attachment II. The input and output files for the "montecarlo.c" scenarios that were run for this calculation are included as Attachments III and IV.

4.3 MODELS

None used.

5. CALCULATION

5.1 CALCULATION INPUT

5.1.1 Probability that a WP Is Located Under a Dripping Fracture

The probability that a waste package was located under a dripping fracture is taken to be 0.26 for all cases. This is consistent with the mean seepage fraction used for Total System Performance Assessment-Viability Assessment for the long-term average climate.

5.1.2 Time of Waste Package Breach

The parameters of two estimated Weibull cumulative distribution functions (CDFs) of waste package breach times for EDA II and VA waste packages under dripping fractures were obtained from Ref. 2 (Section 5.1). The data used to estimate the CDF was developed using the WAPDEG software (Ref. 18, pp. 5 through 9, 24). The WAPDEG output for each case estimates the times that first penetrations will occur on the top and bottom of the package (above and below the centerline) both for parts of the package under the drip and parts not under the drip. The WAPDEG output contains this information for a sample of 400 waste packages. Under the convention adopted here, breaches on the top of the package are required to allow dripping water to enter. Therefore, the earliest time of *any* top penetration was used as the waste package breach time. This is conservative because only top breaches directly under a drip would be expected to allow significant amounts of water to enter the waste package.

The Weibull distribution was chosen because of its ability to fit a wide variety of distribution shapes. The probability density function (pdf) of the Weibull distribution is given by:

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\theta}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{t-\theta}{\alpha}\right)^{\beta}\right] \quad \text{for } t \geq \theta \qquad \text{Eq. 5-1}$$

where α, β, and θ represent the scale, shape, and location parameters (Ref. 19, p. 77). The location parameter gives the lower end of the range over which the equation defines the distribution. For $t < \theta$, the probability density is defined to be zero. Thus, the location parameter shifts the time of earliest possible failure. All of the Weibull parameters are defined to be non-negative. The associated Weibull CDF is given by:

$$F(t) = 1 - \exp\left[-\left(\frac{t-\theta}{\alpha}\right)^{\beta}\right] \quad \text{for } t \geq \theta. \qquad \text{Eq. 5-2}$$

For $t < \theta$, the cumulative failure probability is defined to be zero.

The estimated Weibull parameters for EDA II waste package breach time are given in Table 5-1. Figure 5-1 (Ref. 2, Figure 5.1.2-2) shows the fitted Weibull CDF for the waste package breach time for the EDA II WP design along with the WAPDEG data that was used to estimate the Weibull parameters.

Table 5-1. Weibull Parameters for WP Breach Time and Flood Duration

Characteristic	α	β	θ	Flood Probability
Breach Time, VA	12.099	16.425	0.000	Not applicable
Flood Duration, VA	10.849	8.228	0.000	0.4775
Breach Time, EDA II	2.347	4.810	10.820	Not applicable
Flood Duration, EDA II	11.881	10.218	0.000	0.4125

Source: Section 5.1 of Ref. 2.

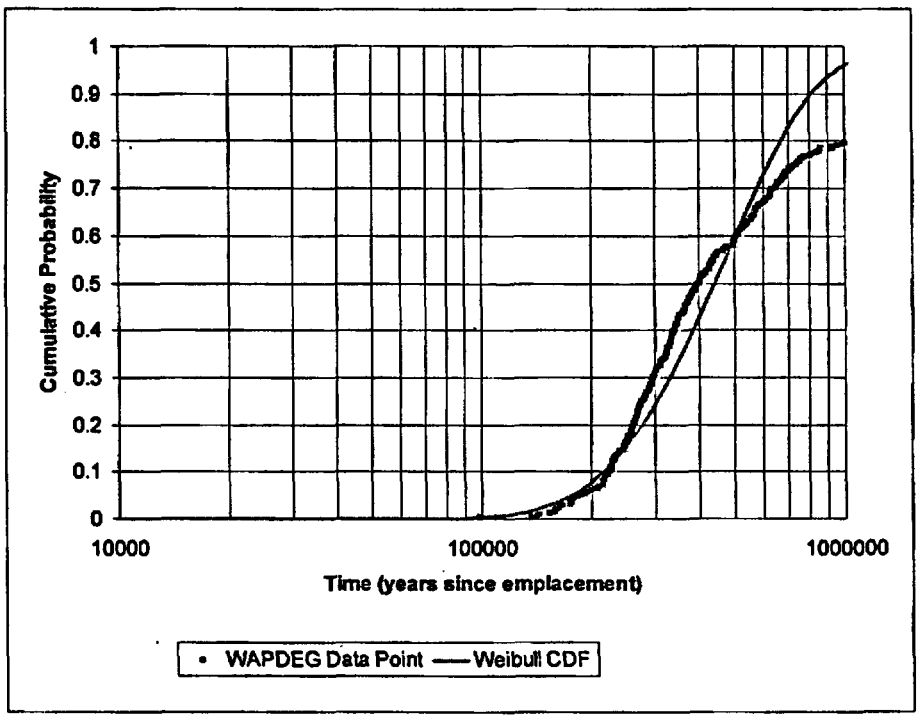

Figure 5-1. Cumulative Distribution for EDA II WP Breach Time

5.1.3 Probability And Duration Of Waste Package Flooding

The parameters of two estimated Weibull CDFs of the duration of waste package flooding for EDA II and VA waste packages under dripping fractures (Table 5-1) were obtained from Ref. 2 (Section 5.1). As indicated in Section 5.1.2, the WAPDEG output on which the CDFs are based estimates the time of penetration of both the top and bottom surfaces of the waste package. If the waste package is to accumulate water, it must be penetrated on the top surface, and not on the bottom surface. To obtain a distribution for the possible duration of this condition, the time

difference, Δt, between the earliest top penetration, and the earliest bottom penetration, was calculated (Ref. 2, Section 5.1) for each of the 400 waste packages modeled in the WAPDEG output files. A little over half the EDA II waste packages had a negative Δt, indicating that they were penetrated on the bottom first. Thus, at the time of top breach, the waste packages that had been penetrated at the bottom first would be unable to accumulate water. The fraction of waste packages with positive Δt is indicated as "flood probability" in Table 5-1.
Figure 5-2 shows the data used in the fit along with the fitted Weibull CDF for the duration of flooding for waste packages that are capable of accumulating water according to the assumptions stated (Ref. 2, Section 5.1).

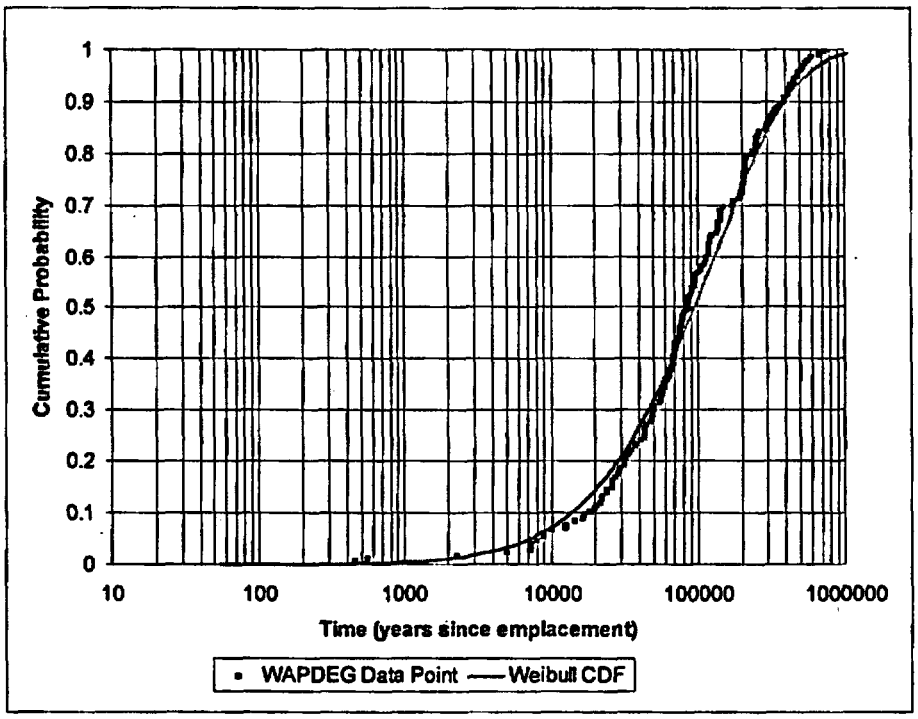

Figure 5-2. Cumulative Distribution for EDA II WP Bathtub Duration

5.1.4 Borated Stainless Steel Corrosion Rate

Ref. 3 (pp. 18 and 19) provides a fit of the negative natural logarithm of 304/316 stainless steel corrosion rates to a Weibull distribution. The estimated Weibull parameters are: $\alpha = 4.852$, $\beta = 4.041$, and $\theta = 4.605$. Figure 5-4 shows the resulting Weibull CDF for the stainless steel corrosion rate. In addition, Ref. 3 (pp. 19 and 20) assumed an increased corrosion rate for borated stainless to account for the presence of boron in the alloy. The author of Ref. 3 implemented the assumption by multiplying the corrosion rate by a "boron factor" between 1 and 4. For this calculation, the midpoint of the range from 1 to 4, that is, 2.5, was used as the boron factor (Assumption 3.6).

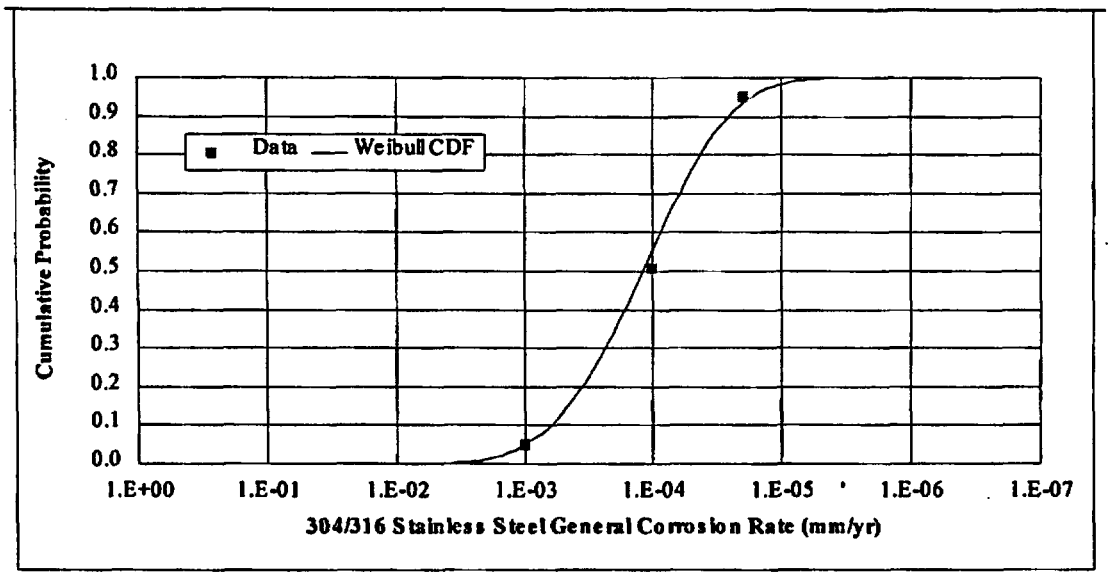

Figure 5-3. 304/316 Stainless Steel Corrosion Rate Weibull CDF

5.1.5 Waste Stream Data

Estimated numbers of SNF assemblies by burnup and initial enrichment were taken from Reference 16. The specific electronic data file used is the uncompressed C1_WSM.ZIP, with only the information on the historic and projected PWR population used for this analysis. Although a revised set of waste stream data has recently become available (Ref.17), the earlier set is used to maintain consistency with previous work (Ref. 3).

5.2 PROCEDURE

As mentioned in Section 2, the procedure for estimating the probability of criticality for the commercial SNF waste stream is to use the software routine "montecarlo.c", which is listed in Attachment II. This software routine implements a Monte Carlo technique for generating parameter values to use for inputs to a simple numerical integration of a set of mass balance equations over a discrete set of time steps up to 250,000 years.

The input data used by the software routine are of two types: specific waste package design parameter values (e.g., dimensions, volumes, and masses) and parameters specifying distributions from which random values are sampled for the Monte Carlo realizations. Nominal values of these parameter values are hard coded into the software routine, but they can be overridden by values entered in the input file "parameters.in" which thereby serves as a record of values used for sensitivity exercises. Examples of this file are given in Attachment III. In this file there is one line for each override. The override line begins with the name of the parameter to be overridden preceded by the '$' character and followed by an equal sign which is then followed by the numerical value to be assigned as override. The value may be followed by one,

or more, blank spaces, which can then be followed by a comment indicating the purpose of the override. This override technique is similar to the namelist input of FORTRAN. This input file can also contain comment lines, which are indicated by an '*' in the first column.

The characteristics of the commercial PWR SNF waste stream arriving at the repository are provided by the file "data.in" (Assumption 3-12). This file contains approximately 20,000 records, one for each batch of assemblies in the order in which they have been, or are expected to be, discharged from a commercial reactor. The batch records are processed one at a time. The burnup and enrichment values from "data.in" are used to compute a k_{eff} for a basket degradation condition which is, or is close to, the worst case with respect to criticality; that is, stainless steel fully degraded so that all the boron is lost from the waste package. This value of k_{eff} is then compared with a specified threshold, set well below (typically 5%) the criticality limit (0.98). If the k_{eff} is found to be below this value, the batch is assumed incapable of criticality; the number of assemblies is incremented according to the number in the batch, and the program moves to the next batch record.

For each batch that passes the screening criterion, there are a specified number of Monte Carlo realizations (500 for this calculation). Each realization begins with two random selections, which are based on the probabilities of their respective events. The first selection is for whether the waste package is dripped on. If the waste package is not dripped on another realization is tried. If the waste package is dripped on, the next selection is for whether the waste package breaches first from the top (which means it can form a bathtub). If not, the next realization is tried.

For those realizations that pass this further screening, the degradation scenario parameters are generated according to their respective probability distribution. The principal parameters generated in this manner are breach time, bathtub duration, and start and finish times for both assembly collapse and fission product loss. Then the parameters for each successive time step are generated. These include the transfer efficiency of the water entering the waste package bathtub (Assumption 11) and the corrosion rate of borated stainless steel, which are drawn from probability distributions. The uncertainty implied by these two distributions could be applied once for each realization or once for each time step of each realization. The uncertainty is applied each time step because there could be significant changes in the transfer efficiency and the nature of the passivation layer that limits corrosion of the borated stainless steel in a 1000-year time step. After these parameters are generated, the remaining boron and iron oxide are calculated (by the numerical integration of the mass balance equations), and a new value of k_{eff} is calculated from a regression dependent on burnup, initial enrichment, amount of oxide, and thickness of remaining borated stainless steel. The first two of these are characteristic of the assembly batch; the other two are calculated from the mass balance equations, as indicated in the previous sentences.

There are four forms of the regression equation, for the four combinations of the two boolean parameters: whether or not there remains any borated stainless steel and whether or not the oxide is uniformly distributed or settled to the bottom of the waste package (in which case it is less effective in controlling criticality by moderator displacement). These forms of the regression

equation were developed in Ref. 3 (pp. 19-23) using over 1000 MCNP cases. Subsequent waste package design changes incorporated aluminum thermal shunts to minimize the peak fuel temperature. Since the aluminum is expected to corrode before the stainless steel, and occupy the lower portion of the waste package, it is also expected to limit the amount of iron oxide that could settle to the bottom of the waste package. It was therefore decided that the most likely distribution would be the uniform oxide. The uniform oxide distribution is the one used in this calculation.

After the nominal k_{eff} calculation, the k_{eff} is adjusted for (1) boron remaining in solution, (2) collapse of the assembly, and (3) the loss of fission product neutron absorbers from degradation of the fuel matrix. These supplementary regressions are given in Ref. 8 (Section 6). As mentioned above, the start and finish times of these two processes are generated randomly according to specified uniform distributions, and measured from the time of breach of the waste package. For each time step between these start and finish times, the value of the two parameters (measuring degree of collapse and fission product loss) are determined by linear interpolation, as a function of the time between the respective start and stop times.

If the adjusted k_{eff} equals or exceeds the CL, then a criticality will be recorded. For this purpose, the total number of criticalities is incremented by the number of assemblies in the batch. The total number of criticalities is also apportioned according to the time of occurrence of the criticality using an array of bins, with one bin for each time step. For this purpose, the bin corresponding to this time step is also incremented by the number of assemblies in the batch. The simulation then moves to the next realization. If, on the other hand, the $k_{eff} < CL$, then the simulation moves to the next time step. If the time steps reach to the duration of the bathtub, the realization is considered to have had no criticality, and the next realization will begin all over.

After all the realizations have been processed for each batch that passes the screening threshold, the summary statistics can be generated over the time period covered, 250,000 years. The fraction of assemblies participating in a criticality is determined by dividing the total number of criticalities by the number of chances for criticality. This number of chances is the product of two factors: the total number of assemblies, and the number of Monte Carlo realizations. This considers the assemblies that did not pass the k_{eff} screening threshold on the same basis as those that did. The probability density function (pdf, more properly called a frequency function, ff, since the distribution is characterized by discrete time steps) is similarly computed by dividing the number of criticalities in each bin by the same number of chances for criticality. The CDF as a function of time is then calculated by summing the pdf's (or ff's) to that point in time. Although this fraction has been calculated as a fraction of assemblies that could be critical, it is equally valid as a fraction of waste packages since x% of assemblies would also be x% of waste packages. The expected number of waste packages that will experience criticality is then the fraction of waste packages that become critical (which is the probability of criticality) multiplied by the total number of waste packages (which is the total number of assemblies divided by the number of assemblies per waste package, 21).

The summary output file, "montecarlo.out" contains the date of the run, a descriptive title, and the expected number of criticalities for each 1000-year time step. The output summary also

reports the number of batches screened into Monte Carlo processing and the number of waste packages calculated for the observed number of assemblies. The number of waste packages is the same for all cases, so it is used as a check on each run. The detailed time-step data is only used for the four cases in Figure 6-1. For the other cases, this calculation only reports the data for the time steps at 10,000 years, 100,000 years, and 249,000 years, so only the summary parts of "montecarlo.out" (which give this information) are given in Attachment IV.

As with all Monte Carlo programs, the random numbers are generated by a pseudo-random sequence generated by an algorithm in the code. By default, this algorithm will generate the same sequence each time it is run; furthermore, since the sequence is only pseudo-random, it will repeat after some large number of steps. With this default, the program will produce the same statistics every time it is run with a specific set of input parameters in "params.in". The C compiler has capability to start this sequence at an arbitrary point, which is called seeding. The program "montecarlo.c" can select the seed randomly by using the computer's internal clock time as the argument of the seeding function (srand). In order to ensure reproducibility, the nominal cases do not use random seeding. However, to demonstrate the accuracy of the Monte Carlo simulation process, four randomly seeded repetitions of the nominal VA waste package design run were executed; the standard deviations of the expected numbers of criticalities at 100,000 and 250,000 years were computed for the five runs.

6. RESULTS

With a screening CL=0.93, there were typically between 1000 and 2000 potentially critical batches (out of somewhat more than 18,000 PWR batches in the receipt scenario of the file DATA.IN) for the cases considered in this calculation. With each of the potentially critical batches given 500 Monte Carlo realizations of waste package degradation, six representative cases are summarized in Table 6-1. Half of these cases are for the VA waste package design, which is expected to have a minimum time to breach somewhat less than 10,000 years. The other half are for the EDA II waste package design which is expected to have a breach time of more than 100,000 years.

Table 6-1. Comparison of Representative Cases

Case	Expected Number of Criticalities	
	At 100,000 years	At 249,000 years
1. VA Design, nominal	2.39 (0.055)*	6.51 (0.15)*
2. VA Design, delayed collapse of assembly	2.83	7.59
3. VA Design, drastic loss of iron oxide	28.7	78.8
4. EDA II Design, nominal	0.00276	1.32
5. EDA II Design, delayed collapse of assembly	0.00924	1.62
6. EDA II Design, drastic loss of iron oxide	0.0384	15.6

*Standard deviations (in parentheses) are calculated for the nominal VA design (Case 1) from a sample consisting of the nominal unrandomized run of "montecarlo.c", and of four randomized additional runs with the same input conditions (specified in PARAMS.IN).

There are two conservative variations on each of the nominal cases (Cases 1 and 4). The delayed-collapse variations (Cases 2 and 5) have the assembly collapse delayed until most of the fission products have been dissolved and removed from the waste package. In this way much of the neutron absorber material is removed from the waste package, while the assemblies are still in their nearly optimum spacing; therefore, the k_{eff} for these variations would be expected to be larger than for the nominal case, as is observed in Table 6-1.

The other comparison cases consider the loss of 50% of the iron oxide that had originally resulted from the steel corrosion. These cases are, which are presented here for comparison only, are unrealistically conservative because there is no physical mechanism for such a drastic loss and because the loss happens as the basket is degrading. A more realistic model would have the distribution of the iron oxide loss stretched out in time so that the loss is not as likely to happen during the bathtub period. By comparison, fission product loss is stretched out in time, so that it has a much weaker effect.

It should be noted that the EDA II cases show no expectation of criticality at 10,000 years and much less than one expected criticality even at 100,000 years. The ratio between expected number of criticalities for 249,000 and 100,000 years is much larger for EDA II than for VA because 100,000 years is just below the threshold of waste package breach time for the EDA II alternative. Therefore, the expected number of criticalities at 100,000 years is exceptionally low. By contrast, for the VA design, both the 100,000-year and the 249,000-year time steps are well

within the time range of criticality. A more detailed comparison of the expected numbers of criticalities as a function of time is given in Figure 6-1.

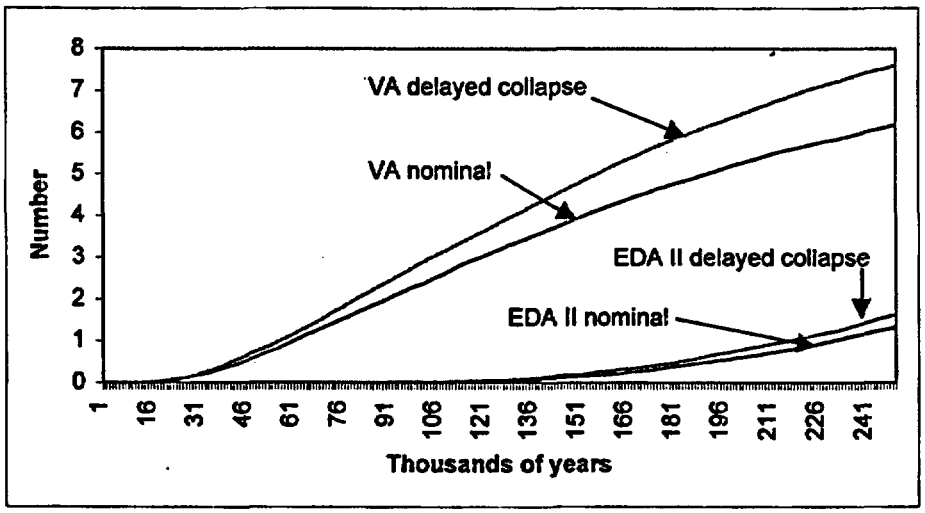

Figure 6-1. Conservative Estimate of the Expected Number of Criticalities for the Nominal and Alternative Scenarios

The comparison of the VA and EDA II cases in Figure 6-1 shows not only that the onset of the possibility of criticality for the EDA II case is delayed 100,000 years (because there is only a very small probability of waste package breach before 100,000 years) but also that the EDA II curves have a much smaller slope (as a function of time, and by comparison with the VA curves) once they do begin to climb. This is because the CDF for EDA II breach time shown in Figure 5-1 shows a much slower rise with time, once it does begin to rise beyond 100,000 years, than does the corresponding curve for the VA design (Ref. 6, Appendix C, Figure C-31).

This calculation also tested the sensitivity to drip rate. For this purpose the best estimate of the current drip rate, 0.05 m^3/yr is used. All the other cases used a uniform distribution of drip rates ranging from 0.05 m^3/yr to 0.5 m^3/yr, which is the conservative assumption of the Controlled Design Assumptions document (Ref. 12, TDSS 026, p. 10-19). The VA design was used for this comparison because it has more expected criticalities. The lower drip rate would be expected to give a lower number of criticalities because it would have a longer retention of boron in solution. The results for the lower drip rate are 2.33 and 6.16 for the 100,000-year and 249,000-year expectations, respectively. Comparison with the first line of Table 6-1 show that the 100,000-year expectation is only 0.06 lower than the nominal; this is only slightly larger than the standard deviation (0.055), so the difference cannot be considered to be statistically significant. The difference between the nominal and the 249,000-year expectation is 0.35, which is somewhat more than twice the standard deviation (0.15), so the difference can be considered to be marginally significant.

7. ATTACHMENTS

Table 7-1 provides a list of attachments.

Table 7-1. List of Attachments

Attachment Number	Description of Contents	Extent of Attachment
I	Document Input Reference Sheets (DIRS)	5 pages
II	Source code listing for "montecarlo.c"	7 pages
III	Input files "params.in" used for all the cases in this calculation	2 pages
IV	Output files "montecarlo.out" summarizing expected criticalities at the representative time steps 10,000 yr, 100,000 yr, and 249,000 yr	19 pages

8. REFERENCES

1. CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 1999. *License Application Design Selection Report.* B00000000-01717-4600-00123 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990528.0303.

2. CRWMS M&O 1999. *Probability of PWR UCF WP Postclosure Criticality for Enhanced Design Alternatives.* BBA000000-01717-0210-00072 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990927.0365.

3. CRWMS M&O 1998. *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality.* BBA000000-01717-0210-00010 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980806.0607.

4. Toledo Edison 1998. Table 4.2-1 Fuel Assembly Dimensions and Materials and Table 4-1 Fuel Design Parameters and Addendum 1, Unit 1, Cycle 12-Reload report from *Davis-Besse Nuclear Power Station No. 1: Updated Safety Analysis Report.* Vol. 6. Rev. 21. Toledo, Ohio: Toledo Edison. TIC: 245410.

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11. CRWMS M&O 1997. *Determination of Waste Package Design Configurations.* BBAA00000-01717-0200-00017 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19970805.0310.

12. CRWMS M&O 1998. *Controlled Design Assumptions Document.* B00000000-01717-4600-00032 REV 05. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980804.0481.

13. CRWMS M&O 1997. *Waste Package Materials Selection Analysis.* BBA000000-01717-0200-00020 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980324.0242.

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16. CRWMS M&O 1997. *Input Files and Models Used in the Waste Quantity, Mix and Throughtput Study.* VA.SAI.MF.03/97.007. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19970811.1264.

17. CRWMS M&O 1999. *Transmittal of Site Recommendation Waste Streams.* WP-SEV-9923.Ta. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990824.0138.

18. CRWMS M&O 1998. *Software Routine Report for WAPDEG (Version 3.09).* 30048-2999 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981012.0224.

19. Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis.* New York, New York: Marcel Dekker, Inc. TIC: 238168.

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DOCUMENT INPUT REFERENCE SHEET

1. Document Identifier No./Rev.:	Change:	Title:
CAL-UDC-MD-000001 REV 00B	N/A	Updated Calculation of Probability of Criticality for the EDA II Waste Package Design

Input Document							8. TBV Due To		
	2. Technical Product Input Source Title and Identifier(s) with Version	3. Section	4. Input Status	5. Section Used In	6. Input Description	7. TBV/TBD Priority	Unqual.	From Uncontrolled Source	Un-confirmed
2a 1	CRWMS M&O (Civilian Radioactive Waste Management System Management and Operating Contractor) 1999. *License Application Design Selection Report.* B00000000-01717-4600-00123 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990528.0303.	pp. 5-37 thru 5-40, 5-44, 5-45	TBV-3202	1	EDA II WP design	3	X	N/A	N/A
2	CRWMS M&O 1999. *Probability of PWR UCF WP Postclosure Criticality for Enhanced Design Alternatives.* BBA000000-01717-0210-00072 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990927.0365.	Entire	N/A	1	Passing reference to a previous calculation of probability of criticality	N/A	N/A	N/A	N/A
		Section 2	N/A	2	Evidence of earlier use of the same degradation scenario	N/A	N/A	N/A	N/A
		Section 5.1, Table 5.1.2.2	TBV-3203	5.1.2 Table 5-1	Estimated Weibull distributions for breach times of EDA II and VA WPs	3	X	N/A	N/A
		Section 5.1, Table 5.1.2-2	TBV-3203	5.1.3 Table 5-1	Estimated Weibull distributions for flood duration in EDA II and VA WPs	3	X	N/A	N/A
3	CRWMS M&O 1998. *Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality.* BBA000000-01717-0210-00010 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980806.0607.	Entire	N/A	1	Passing reference to a previous calculation of probability of criticality	N/A	N/A	N/A	N/A
		Section 2	N/A	2	Evidence of earlier use of the same degradation scenario	N/A	N/A	N/A	N/A
		pp. 16-17	TBV-3206	3	Evidence that flooding duration and waste package breach time are positively correlated	3	X	N/A	N/A
		pp. 18, 19	TBV-3207	5	A fit of the negative natural logarithm of 304/316 stainless steel corrosion rates to a Weibull distribution	3	X	N/A	N/A
		pp. 19, 20	TBV-3208	5	Magnitude of "boron factor" for corrosion rate of borated stainless steel	3	X	N/A	N/A
		pp. 19-23	TBV-3205	5.2	Linear regressions giving k_{eff} as a function of various variables	3	X	N/A	N/A

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4	Toledo Edison 1998. Table 4.2-1 Fuel Assembly Dimensions and Materials and Table 4-1 Fuel Design Parameters and Addendum 1, Unit 1, Cycle 12-Reload report from *Davis-Besse Nuclear Power Station No. 1: Updated Safety Analysis Report*, Vol. 6. Rev. 21. Toledo, Ohio: Toledo Edison. TIC: 245410.	Table 4.2-1	TBV-3209	2	Thickness of the Zircaloy spacer grids	3	X	N/A	N/A
5	CRWMS M&O 1998. *Summary Report of Commercial Reactor Criticality Data for Crystal River Unit 3*. B00000000-01717-5705-00060 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980728.0189.	p. 26	TBV-3210	2	Thickness of the Zircaloy fuel pin cladding	3	X	N/A	N/A
6	DOE (Department of Energy) 1998. *Disposal Criticality Analysis Methodology Topical Report*. YMP/TR-004Q REV 00. Las Vegas, Nevada: DOE. ACC: MOL.19990210.0236.	pp. 3-11 thru 3-13	N/A	2	Evidence of consistency with established degradation analysis methods	N/A	N/A	N/A	N/A
		Appendix C, pp. C-17 thru C-19	TBV-3272	3	Support for assumption that carbon steel and aluminum components will degrade quickly in comparison to the borated stainless steel components	3	X	N/A	N/A
		App. C, Fig. C-12	N/A	6	Passing reference to the CDF for VA breach time	N/A	N/A	N/A	N/A

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7	CRWMS M&O 1997. *Criticality Evaluation of Degraded Internal Configurations for the PWR AUCF WP Designs.* BBA000000-01717-0200-00056 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19971231.0251.	pp. 4, 5,24	TBV-3212	2	Results of criticality calculations using MCNP4A	3	X	N/A	N/A
		p. 6	TBV-3213	3	Description of Babcock & Wilcox (B&W) Mark B 15 x 15 fuel type	3	X	N/A	N/A
		p. 15	N/A	3	Evidence that Controlled Design Assumption (CDA) Key 009 was used in criticality calculations	N/A	N/A	N/A	N/A
		pp. 11-13	TBV-3214	3	Results of a short-term corrosion test in a harsh environment that showed that borated 304 stainless steel has a corrosion rate up to 4 times that of unborated 304 stainless steel and indications that boride particles would corrode quickly	3	X	N/A	N/A
		p. 48	TBV-3215	3	Evidence that adsorption on Fe_2O_3 may provide up to a 1.4% reduction in k_{eff}	3	X	N/A	N/A
		p. 48	TBV-3211	3	Expectation that peak post-closure k_{eff} will occur between 10,000 and 30,000 yr after closure	3	X	N/A	N/A
8	CRWMS M&O 1999. *Simulating the Effect on Criticality of Simultaneous Matrix Degradation and Assembly Collapse for the 21 PWR Waste Package.* CAL-EBS-NU-000002 REV 00A. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990928.0234.	Section 6.	TBV-3216	2, 5, 6	Criticality calculations and supplemental regressions that introduce more variables	3	X	N/A	N/A
9	DOE 1998. *Viability Assessment of a Repository at Yucca Mountain: Preliminary Design Concept for the Repository and Waste Package.* Vol. 2. DOE/RW-0508. Las Vegas, Nevada: DOE. ACC: MOL.19981007.0029.	p. 4-23	TBV-3217	3	Support for the assumption that the waste package is rendered inert with helium before sealing	3	X	N/A	N/A

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10	B&W Fuel Company 1991. *Final Design Package - Babcock & Wilcox BR-100 - 100 Ton Rail/Barge Spent Fuel Shipping Cask.* 51-1203400-01. Lynchburg, Virginia: B&W Fuel Company. ACC: MOV.19960802.0083.	pp. II.6-6 and II-6.7	TBV-3218	3	Evidence supporting the claim that the B&W Mark B assembly is one of the most reactive PWR fuel designs in the 30 GWd/MTU burnup range under intact fuel assembly and fixed basket geometry conditions	3	X	N/A	N/A
11	CRWMS M&O 1997. *Determination of Waste Package Design Configurations.* BBAA00000-01717-0200-00017 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19970805.0310.	pp. 21, 29, 30	TBV-3219	3	Description of the 21 PWR WP design with 7-mm thick borated stainless steel absorber plates	3	X	N/A	N/A
12	CRWMS M&O 1998. *Controlled Design Assumptions Document.* B00000000-01717-4600-00032 REV 05. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980604.0481.	p. 3-22 p. 10-19	TBV-3220 TBV-3273	3 6	Controlled Design Assumption (CDA) Key 009 (burnup credit). CDA TDSS 026 (uniform distribution of drip rates)	3 3	X X	N/A N/A	N/A N/A
13	CRWMS M&O 1997. *Waste Package Materials Selection Analysis.* BBA000000-01717-0200-00020 REV 01. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980324.0242.	p. 96	TBV-3221	3	Neutronit A978 is similar in composition to 316 stainless steel	3	X	N/A	N/A
14	CRWMS M&O 1996. *Second Waste Package Probabilistic Criticality Analysis: Generation and Evaluation of Internal Criticality Configurations.* BBA000000-01717-2200-00005 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19960924.0193.	pp. 38-41 Assump. 4.3.4	TBV-3222 N/A	3 3	Estimates of WP filling and draining times Evidence of consistency with previous assumptions about transfer efficiency	3 N/A	X N/A	N/A N/A	N/A N/A
15	CRWMS M&O 1998. *Calculation of Upper Subcritical Limits for Nuclear Criticality in a Repository.* B00000000-01717-0210-00027 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19980729.0420.	pp. 22, 23	TBV-3223	3	Estimates of bias in MCNP calculations of k_{eff} for benchmark cases	3	X	N/A	N/A
16	CRWMS M&O 1997. *Input Files and Models Used in the Waste Quantity, Mix and Throughput Study.* VA.SAI.MF.03/97.007. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19970811.1264.	File: C1_WSM.ZIP	TBV-3431	3, 5	Enrichment and burnup for PWR SNF.	3	X	N/A	N/A

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17	CRWMS M&O 1999. *Transmittal of Site Recommendation Waste Streams.* WP-SEV-9923.Ta. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990824.0138.	Entire	N/A	3	Not an input. Identification of data that was not used.	N/A	N/A	N/A	N/A
18	CRWMS M&O 1998. *Software Routine Report for WAPDEG (Version 3.09).* 30048-2999 REV 02. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981012.0224.	pp. 5 thru 9, 24	N/A	5	Description of WAPDEG computer program	N/A	N/A	N/A	N/A
19	Modarres, M. 1993. *What Every Engineer Should Know About Reliability and Risk Analysis.* New York, New York: Marcel Dekker, Inc. TIC: 238168.	p. 77	N/A	5	Definition of the Weibull distribution (CDF and pdf)	N/A	N/A	N/A	N/A

Attachment II. Source code for "montecarlo.c"

```
/* montecarlo.c  Program to Monte Carlo simulate the degradation of the waste
   package contents, particularly the oxidation of steel and removal of boron.
   There is also an adjustment for the collapse of the assemblies and the
   simultaneous removal of fission products.  The program operates on the
   range of criticality characteristics for commercial SNF.  The result is
   expressed in terms of the fraction of packages that would go critical
   before a certain time, and the results are expressed as a function of
   time.  Although the program is written to process the input stream of
   commercial SNF, which has a range of criticality affecting characteristics,
   it can also be used for fuels that have only one set of such
   characteristics.

   The program is based on a BASIC program written by John Massari but the
   application of the Monte Carlo technique is somewhat different.  Both
   programs assume that the characteristics of any given assembly are
   available for filling the waste package.  In actual practice each package
   will most likely contain a range of burnup and initial enrichment, and
   the actual criticality would be less than what would be predicted for
   a homogeneously loaded package having the same average burnup and enrichment.
   Therefore the assumption of homogeneous loading is conservative.

   The program has two input files. "data.in" contains the characteristics of
   the commercial SNF waste stream expected to be received at the repository.
   "params.in" contains any overrides on parameters that are nominally
   hard coded.  These overrides are accomplished in a manner similar to the
   FORTRAN namelist.  In the file "params.in" the variable name is preceded
   by a '$' character and then a code line for reading that variable is
   inserted at an appropriate place in the program.  The file "params.in"
   is read in to the array lines[100] (which could be allocated dynamically,
   but will never contain more than 100 lines so why bother).  The lines[]
   array is searched for a match starting in the position 1 of each element
   [line].  At position 0 of each line[] is the '$' character.  This
   capability is extended to arrays of float, with the differences: (1) The
   array name is followed by []; (2) The values on the right side of the '='
   are in a comma separated list; (3) The last element of the list must be
   followed by a comma, after which there can be comments.

   There are two different forms for comments in the file "params.in":
   (1) Anything after the obligatory fields in a keyword statement;
   (2) Any line that begins with an '*'.  Comments of type 1 are copied into
   the input array of lines, but not included in the read of the line of
   lines[] since each keyword keys a read of only a limited number of fields
   in the array lines[].  Comments of type 2 are simply diverted into the
   debugging file, "junk.out", so there is a record that they have been read
   but not used.

   The program presently reads all PWR assembly batches and calculates a
   preliminary keff, with the condition of basket degraded and all
   the boron removed from the waste package.  This preliminary keff is tested
   against a threshold criticality limit, testcl, so that only those batches
   with a reasonable chance of criticality will be subjected to the
   number of Monte Carlo realizations (rlztns).  The number of assemblies
   being subject to the Monte Carlo realizations is counted by the parameter
   nassyin.  The actual criticalities are counted when keff exceeds cl.
   These criticalities are binned according to the time at which they
   occurred (numcrits[]) and tallied in the parameter ntotalcrit.  Since
   these counts are expanded by the number of Monte Carlo realizations (rlztns)
   they are converted to probabilities by dividing by the total number of
   assemblies read (ntotassy) and dividing by the number of realizations
   (rlztns), so that the sample space is expanded to that which it would
```

```
   have been if all the assemblies had been subjected to the number of
   realizations.  The pdf and CDF calculated in this manner are thus on a
   per assembly basis.  To convert to a per package basis, we divide by the
   number of assembilies in a waste package, 21.  The expected number of
   criticalities for all the commercial PWR packages is found by multiplying
   the CDF by ntotassy (which has been expanded by multiplication by
   rlztns) and dividing by the number of assembilies in a waste package and
   by the number of realizations.

   At the present time the drip rate is only used to calculate the rate of
   boron removal, which determines the boron in solution.  This is of little
   importance because all the boron is removed from solution by the next
   increment following complete corrosion of borated stainless steel.  The
   program has the capability to use regressions that come from either the
   uniform or the settled distribution of the iron oxide.  However, the
   recent addition of aluminum thermal shunts to the PWR waste package
   limits the space available for oxide settling, so the nominal model
   of waste package degradation assumes a uniform distribution of the iron
   oxide.
*/

#include <string.h>
#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <malloc.h>
#include <string.h>
#include <ctype.h>
#include <time.h>
#define NUMBINS  250

float getfloat(),InvNorm(float,float),InvUni(float,float),
   InvLWeib(float,float,float),
   kcalc(int,float,float,float,float,float),
   findfloat(char*,int,int); //used to find and read float override
int findint(char*,int,int);  //used to find and read int override
long int ntotassy=0;   //counter for total assemblies read
int getint(),inc=1000; //integration timestep
int rlztns=100,      //number of Monte Carlo realizations
    dripflag=0;      //0 if one rate (or no drip) for each rlztn,
                     //1 if new rate each timestep
char lines[100][100];//for storage of override input file as an array
FILE *ferr,*fout,*fin,*fparams;
float prbt=0.4775, //probability of bathtub
    prdrip=0.26,       //probability of drip on any given bathtub
    ex=.1;        //exchange flushing efficiency
    voidsp0=3.733,             //initial voidspace in CSNF pkg, m^3.
    mbwp=30110*.199,  //initial boron in BSS in gm
    bssthick0=7;               //BSS initial thickness
int get2(char*,char*,char);
void etrim(char*),ftrim(char*);
void getfarray(char*,float*,int,int);

void main()
{int i,it,k=0,numrisk=0,na,ndyr,nocrit,bssgone,nmlns,randflag=0,npyr,
    numpkgs=0,             //number of waste packages used
    usflag=1,              //nominal oxide distribution is uniform
    fueldegflag=1;         //nominal fuel degradation and FP loss
float x,b,a,keff,pkeff,t,stime,etime,ptime,kav=0,ox,flow,mav,
    cl=(float)0.98,testcl=(float)0.93,mbsol,
    clpsts,clpstf,voidsp,bsscr,bssthick,bssdelta,mclps,mfpl,
    ufox=33,          //fully degraded uniform oxide vol %
    sfox=3.5,         //fully degraded settled oxide assy layers covered
    upoxcs=30,        //uniform oxide, part deg, from carbon steel percent
```

```
    upoxss=10,       //unifrm ox, part deg, from stainless  steel percent
    spoxcs=8,          //settled oxide, carbon steel (rows of rods/cell)
    spoxss=2,         //settled oxide from stainless steel (rows of rods/cell)
    btimedist[]={12.099,16.425,0}, //VA breach time alph, beta, theta
    bdurdist[]={10.849,8.228,0},  //VA duration of bathtub alph, beta theta
    fpltsdist[]={10000,20000},//start of fission product loss
    fpltfdist[]={40000,50000},//all fission products lost
    clpstsdist[]={10000,20000},//start of collapse of assemblies
    clpstfdist[]={60000,90000},//all assemblies collapsed
    flowdist[]={.05,.5},         //Flow min max m^3/yr for uniform distribution
    exdist[]={.05,.15},         //Exchg effic min max
    bsscrdist[]={.0001,.0004},//BSS crsn rate (mm/yr) min max, avoids use of bfac
    fplcv=.3,               //CV for fission product (neutron absorber) loss
    clpscv=.3,                  //coefficient of variation for assy collapse
    fplts,fpltf;//start and finish times of fission product loss process
long int numcrits[NUMBINS]={0},
    numccrits[NUMBINS]={0},  //to accumulate criticalities in 1000 yr bins
    ntotalcrit=0,nrecsin=0,nassyin=0,reccount=0;
float pdfcrits[NUMBINS]={0},cdfcrits[NUMBINS]={0};
char buffer[300],type,title[100];
time_t ltime;                          //variable for date & time
time( &ltime );              //fill ltime structure with current time
if ((fin=fopen("data.in","r"))==NULL)       //waste stream
  {printf("Can't open data.in\n");exit(0);}
if ((fparams=fopen("params.in","r"))==NULL) //overrides for this case
  {printf("Can't open params.in\n");exit(0);}
fout=fopen("montecarlo.out","w"); //probability and expected criticalities
fprintf(fout, "The time is %s", ctime( &ltime ) );
ferr=fopen("junk.out","w");       //characteristics of each criticality
fgets(title,90,fparams); //first line of parameter file must be title
i=0;      //read parameter overrides for this case into input array lines[]
while((fgets(buffer,90,fparams)!=NULL)&&(i<100))//read overrides
  {if(buffer[0]=='*') fprintf(ferr,"%s",buffer);//divert comment to "junk.out"
  else strcpy(lines[i++],buffer);}
nmlns=i;                   //number of override parameter lines
printf("%d parameters read\n",nmlns);
if((x=findfloat("$ufox",0,nmlns))>-1) ufox=x;//search for any overrides
if((x=findfloat("$upoxcs",0,nmlns))>-1) upoxcs=x;
if((x=findfloat("$upoxss",0,nmlns))>-1) upoxss=x;
if((x=findfloat("$sfox",0,nmlns))>-1) sfox=x;
if((x=findfloat("$spoxcs",0,nmlns))>-1) spoxcs=x;
if((x=findfloat("$spoxss",0,nmlns))>-1) spoxss=x;
if((x=findfloat("$prbt",0,nmlns))>-1) prbt=x;
if((x=findfloat("$ex",0,nmlns))>-1) ex=x;
getfarray("$btimedist[]",btimedist,3,nmlns);
getfarray("$bdurdist[]",bdurdist,3,nmlns);
getfarray("$clpstsdist[]",clpstsdist,2,nmlns);
getfarray("$clpstfdist[]",clpstfdist,2,nmlns);
getfarray("$fpltsdist[]",fpltsdist,2,nmlns);
getfarray("$fpltfdist[]",fpltfdist,2,nmlns);
getfarray("$flowdist[]",flowdist,2,nmlns);
if((i=findint("$usflag",0,nmlns))>-1) usflag=i;
if((i=findint("$rlztns",0,nmlns))>-1) rlztns=i;
if((i=findint("$randflag",0,nmlns))>-1) randflag=i;
if((i=findint("$fueldegflag",0,nmlns))>-1) fueldegflag=i;
if(randflag==1)
  srand( (unsigned)time( NULL ) ); //random seed for random number generator
while(fgets(buffer,300,fin)!=NULL)
  {if((type=buffer[123])!='P')continue;                //PWR batches only
  stime=20000;            //time value for batch threshold screening only
  t=stime;
  reccount++;
  npyr=getint(buffer,287,4);
  if(reccount%1000==0)printf("recsread= %ld\n",reccount);//Count PWR batches
```

```
ndyr=getint(buffer,71,8);   //discharge year, not used in this calculation
b=getfloat(buffer,51,10)/1000; //burnup converted to GWd/MTU
a=getfloat(buffer,41,10);      //initial enrichment
na=getint(buffer,31,10);       //number of assemblies
if(!((npyr>0)&&(na>0)))continue; //this batch not picked up
keff=kcalc(usflag,a,b,t,sfox*(1-usflag)+usflag*ufox,0);
kav+=na*keff;          //average keff for all assemblies
ntotassy+=na;          //total assemblies
if(keff<testcl)continue;//Criticality possible for this batch?
nassyin+=na;          //number of assemblies passing preliminary screening
nrecsin++;            //number of batch records passing prelim screening
mbsol=0;
for(i=0;i<rlztns;i++)//following lines do bathtub time range from WAPDEG
  {if((dripflag==0)&&(prdrip<(float)rand()/RAND_MAX))continue;
                //this realization of pkg is not dripped on at any time
  stime=InvLWeib(btimedist[0],btimedist[1],btimedist[2]);//breach time
  if(prbt<(float)rand()/RAND_MAX) continue;//breach but no bathtub
  else etime=stime+InvLWeib(bdurdist[0],bdurdist[1],bdurdist[2]);
  t=stime;            //time to start degradation of package components
  nocrit=1;           //no criticality yet
  clpsts=t+InvUni(clpstsdist[0],clpstsdist[1]);//start of assy collapse
  clpstf=t+InvUni(clpstfdist[0],clpstfdist[1]);//finish, from breach time
  fplts=t+InvUni(fpltsdist[0],fpltsdist[1]);//start of fission product loss
  fpltf=t+InvUni(fpltfdist[0],fpltfdist[1]);//finish, from breach time
  voidsp=voidsp0;    //set voidspace to initial value
  bssthick=bssthick0; //set BSS thickness to initial value
  bssgone=0;          //start with BSS present
  pkeff=0;            //reset peak keff
  while((t<etime)&&(nocrit==1)&&(t<NUMBINS*inc))//loop until bathtub
     //duration is exceeded, or criticality occurs, or time limit exceeded
    {if((dripflag==0)||(prdrip>(float)rand()/RAND_MAX))
        flow=InvUni(flowdist[0],flowdist[1]);//flow in m^3/yr
     else flow=0;  //pkg not dripped on during this timestep
    ex=InvUni(exdist[0],exdist[1]);//exchg efficiency of circulatory flow
    bsscr=InvUni(bsscrdist[0],bsscrdist[1]);//generate BSS corosion rate
     if(bssgone==0) //compute thickness of BSS remaining, if any
       {bssdelta=2*bsscr*inc;//BSS thickness reduction this timestep
       if(bssthick>bssdelta)bssthick-=bssdelta;//decrement BSS thickness
       else
          {bssdelta=bssthick;//all remaining BSS is lost in this timestep
          bssthick=0;
          bssgone=1;}   //the next statement updates the boron in solution
      mbsol+=bssdelta*mbwp/bssthick0-ex*flow*inc*mbsol/voidsp;
       if (mbsol<0)mbsol=0;} //truncate negative values to zero
    if(usflag==0)  //for settled oxide
      {if(bssthick>0) ox=spoxcs+spoxss*(bssthick0-bssthick)/bssthick0;
       else ox=sfox;}//constant oxide amount after BSS is gone
     else           //for uniform oxide
      {if(bssthick>0) ox=upoxcs+upoxss*(bssthick0-bssthick)/bssthick0;
       else ox=ufox;}
     keff=kcalc(usflag,a,b,t,ox,bssthick);//primary keff calculation
    x=mbsol;
     if(x>30)       //adjust keff for boron in solution
        keff+=keff*(.0232558-.0356383*log(x)+.0142821*pow(log(x),2)
              -1.91685E-03*pow(log(x),3));
     if((t>clpsts)&&(t<clpstf)) //calculate percent collapsed
    {mclps = 100*(t - clpsts)/(clpstf - clpsts);//mean value
       mclps=InvNorm(mclps,clpscv*mclps);}//generate actual from normal dist.
    else if (t<clpsts) mclps=0;   //no collapse yet
     else mclps=100;              //completely collapsed
     if((t>fplts)&&(t<fpltf))//calculate percent fission product loss
    {mfpl = 100*(t - fplts)/(fpltf - fplts);//mean value
       mfpl=InvNorm(mfpl,fplcv*mfpl);}//generate actual from normal dist.
    else if (t<fplts) mfpl=0;   //no FPL yet
```

```
      else mfpl=100;                //complete loss of fission products
     if(fueldegflag==1)  //adjust keff for collapse and FPL
         keff+= 0.001114*mfpl-0.001333*mclps;
     if(keff>pkeff)   //keep track of the peak keff for this realization
        {pkeff=keff;
        ptime=t;}
       if(keff>cl) //criticality reached for this realization
         {numcrits[(t/inc>NUMBINS-1)?NUMBINS-1:(int)t/inc]+=na;//increment
             //appropriate timestep bin, or max timestep bin
          ntotalcrit+=na;//increment total criticalities
          fprintf(ferr,"it=%d brnp %.0f enrch %.2f mbsol %.3f bsthck %f nassy %d\n",
           i,b,a,mbsol,bssthick,na);//log characteristics of this criticality
           nocrit=0;}    //criticality found, end this realization
        t+=inc;}                    //end this timestep
}}              //end this potential criticality and MC realization
kav/=ntotassy;
numpkgs=ntotassy/21;
ntotassy*=rlztns;   //escalate for number of realizations
fprintf(ferr,"\n\n\n");             //header for log file
fprintf(ferr,"%12s%12s%12s%12s%12s\n","Kyear","pdf","CDF","Crit pkgs","numcr");
for(it=1;it<NUMBINS;it++)
  {pdfcrits[it]=(float)numcrits[it]/ntotassy;//convert bins to pdf (or ff)
  numccrits[it]=numccrits[it-1]+numcrits[it];//accumulate number of crits
  cdfcrits[it]=(float)numccrits[it]/ntotassy;    //calculate CDF for this bin
  fprintf(fout,"%12d%12.7f\n",it,cdfcrits[it]*numpkgs);
  fprintf(ferr,"%12d%12.7f%12.7f%12.4f%12ld\n",//statistics for this timestep
       it,pdfcrits[it],cdfcrits[it],cdfcrits[it]*numpkgs,numcrits[it]);}
fprintf(ferr,"\n\n");
fprintf(ferr,"10 timestep moving average, to demonstrate smoothing\n");
fprintf(ferr,"%12s%12s\n","Kyear","pdf");
mav=0;                          //reset moving average pdf to zero
for(it=1;it<11;it++)mav+=pdfcrits[it];//initial moving average pdf
mav/=10;
for(it=5;it<NUMBINS-6;it++)
  {fprintf(ferr,"%12d%12.7f\n",it,mav);//print moving average pdf
  mav+=(pdfcrits[it+6]-pdfcrits[it-4])/10;}//moving avg for next timestep
printf("assy read= %ld nrecsin= %ld critpkg= %f\n",ntotassy,
  nrecsin,cdfcrits[NUMBINS-1]*numpkgs);
printf("%s",title);
printf("numcrits@10kyrs=%ld exp100=%f exp249=%f\n",numccrits[10],
     cdfcrits[100]*numpkgs,cdfcrits[249]*numpkgs);//statistics for this run
fprintf(fout,"%s",title); //output file summary
fprintf(fout,"Number of batch records screened in=%ld numberpkgs=%d\n",
           nrecsin,numpkgs);
fprintf(fout,"numcrits@10kyr=%ld exp10=%f exp100=%f exp249=%f\n",numccrits[10],
  cdfcrits[10]*numpkgs,cdfcrits[100]*numpkgs,cdfcrits[249]*numpkgs);}

//function to get a float from a specified character substring
float getfloat(char *string, int start, int length)
{char temp[30];
strncpy(temp,string+start,length);
temp[length]='\0';
return((float)atof(temp));}

//function to get an int from a specified character substring
int getint(char *string, int start, int length)
{char temp[30];
strncpy(temp,string+start,length);
temp[length]='\0';
return(atoi(temp));}

float InvNorm (float mean, float stdev)
{float norm=0;
int i;   //construct normal distribution from the central limit theorem
```

```
for(i=0;i<12;i++) norm = norm + (float)rand()/RAND_MAX;
norm = norm - 6;
return stdev * norm + mean;}

float InvUni (float min, float max)
{return min + (max - min)*(float)rand()/RAND_MAX;}//uniform distribution

float InvLWeib (float alpha, float beta, float theta)//Weib for log(t)
{float x,y;
x=(float)rand()/(RAND_MAX+1);
y=-log(1-x);
return exp(theta + alpha*pow(y,1/beta));}

float kcalc(int D, float a, float b, float t, float O,float th)
{float keff;
if(t>250000)t=250000; //assume constant time dependence beyond range of data
  if(th>0)    //partial degradation
   {if(D==1)   // use regression for uniform oxide distribution
      {keff=2.35498-.0066737*b-1.8096E-05*b*b+.1418*a-.0071354*a*a-.5193*log(t)
        +.059471*pow(log(t),2)-.0022406*pow(log(t),3)-.0050889*O-.074906*th
        +.010646*th*th-5.2334E-04*pow(th,3);
      keff=InvNorm(keff,.00831);}  //account for regression uncertainty
   else            //use regression for settled oxide distribution
      {keff=1.72095-.0067237*b-1.6667E-05*b*b+.13348*a-.0060497*a*a-.31232*log(t)
        +.037442*pow(log(t),2)-.0014715*pow(log(t),3)-.016797*O-.066316*th
        +.0094036*th*th-4.6905E-04*pow(th,3);
      keff=InvNorm(keff, .00846);}}  //account for regression uncertainty
  else
   {if(D==1)    // use regression for uniform oxide distribution
      {keff=-5.12955+1.65615*log(t)-8.52852E-03*b+.29266*a-.153971*pow(log(t),2)
        +.0046707*pow(log(t),3)+6.8964E-05*b*b-1.63227E-07*pow(b,3)
        -.0671372*a*a+5.36083E-03*pow(a,3)-4.08151E-04*log(t)*b
        +7.23708E-03*log(t)*a-5.25978E-03*O;
      keff = InvNorm(keff, .00463);}    //account for regression uncertainty
   else            // use regression for settled oxide distribution
      {keff=-1.25161+.683154*log(t)-6.65133E-03*b+.266145*a-.0640282*pow(log(t),2)
        +1.92631E-03*pow(log(t),3)-2.67041E-05*b*b+6.12197E-07*pow(b,3)
        -.0618276*a*a+5.20352E-03*pow(a,3)-1.36497E-04*log(t)*b
        +.0050849*log(t)*a-.140918*O;
      keff= InvNorm(keff, .00906);}}    //account for regression uncertainty
return keff;}

//Find the float numerical value in a statement that begins with the specified
//keyword (keystr). Presently designed to read from the array lines
float findfloat(char* keystr,int startrow,int numrows)
{int i=0;
char stag[20],tempstr[100];
while ((strncmp(keystr,lines[startrow+i],strlen(keystr))!=0)&&(i<=numrows))
    i++;
if (i==numrows+1) return -1;
strcpy(tempstr,lines[startrow+i]);
get2(stag,tempstr,'=');
return (float)atof(tempstr);}

//Find the int numerical value in a statement that begins with the specified
//keyword (keystr).
int findint(char* keystr,int startrow,int numrows)
{int i=0;
char stag[20],tempstr[100];
while ((strncmp(keystr,lines[startrow+i],strlen(keystr))!=0)&&(i<=numrows))i++;
if (i>=numrows) return -1;
strcpy(tempstr,lines[startrow+i]);
get2(stag,tempstr,'=');
return atoi(tempstr);}
```

```
//copies the strings occurring before and after the separator c (e.g. '=')
int get2(char *stag,char *sdummy,char c)
{int i,index,len;
char *p;
len=strlen(sdummy);
p=strchr(sdummy,c);
i=(int)(p-sdummy);
index=i;
strncpy(stag,sdummy,i);     //copy string before separator
stag[i]='\0';
etrim(stag);
strcpy(sdummy,p+1);        //copy string following separator
i=0;
while((sdummy[i]==' ')&&(i<len))i++;//read through leading blanks
if((i==len)||(sdummy[i]=='\n')) return -1;//can't find a second word on rt side
strcpy(sdummy,sdummy+i); //copy front trimmed string
return index;}

void etrim(char *dummy)//trims trailing blanks
{int i;
i=strlen(dummy)-1;
while(dummy[i]<=32)i--;
dummy[i+1]='\0';}

//trims leading blanks; used in get2 so that fdummy starts with a non-blank
void ftrim(char *dummy)
{int i=0;
while(dummy[i]<=32)i++;
strcpy(dummy,dummy+i);}


//Searches the override array lines[] for a line beginning with the string
//passed in keystr.  If the searchstring (keystr) is not found, it simply
//returns.  Othewise it takes num values in the comma separated list on the
//right side of the '=' and enters them in the float array farray, overriding
//the values that were hard coded.
void getfarray(char *keystr,float *farray,int num,int numrows)
{int i=0;
char stag[20],tempstr[100];
while ((strncmp(keystr,lines[i],strlen(keystr))!=0)&&(i<numrows))
    i++;
if (i==numrows) return;//searchstring not found, so return
strcpy(tempstr,lines[i]);
get2(stag,tempstr,'=');
for(i=0;i<num;i++) //get all the elements from the comma separated list
  {farray[i]=atof(tempstr);
  strcpy(tempstr,strchr(tempstr,',')+1);}}
```

Attachment III, Input Files

"params.in"

Nominal VA Case with randomization to generate standard deviation

```
*VA uniform with fuel degradation, with randomization
$randflag=1  //randomize using the clock
$fueldegflag=1  //=1 for fuel degradation

$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
$rlztns=500    //extra iterations
```

Comparison cases for Table 6-1.

```
*VA uniform with fuel degradation, no randomization
$randflag=1  //randomize using the clock
$fueldegflag=1  //=1 for fuel degradation
$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
$rlztns=500    //extra iterations

*VA uniform with fuel degradation, delayed assy collapse no randomization
$fueldegflag=1  //=1 for fuel degradation
$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
$rlztns=500    //extra iterations
$clpstsdist[]=60000,70000, //delayed collapse start
$clpstfdist[]=80000,90000, //delayed collapse finish

*VA uniform with fuel degradation, drastic iron loss no randomization
$fueldegflag=1  //=1 for fuel degradation
$ufox=13         //drastic loss of iron oxide, uniform ox
$upoxcs=13       //drastic loss of iron oxide, uniform ox
$upoxss=5      //drastic loss of iron oxide, uniform ox
$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
$rlztns=500    //extra iterations
*$flowdist[]=.05,.05, //current drip rate

*EDA2 uniform with fuel degradation, no randomization
*$randflag=1  //randomize using the clock
$fueldegflag=1  //=1 for fuel degradation
$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
```

```
$rlztns=500    //extra iterations

*EDA2 uniform with fuel degradation, delayed assy collapse no randomization
*$randflag=1  //randomize using the clock
$fueldegflag=1  //=1 for fuel degradation
$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
$rlztns=500    //extra iterations
$btimedist[]=2.347,4.810,10.820,   //EDA breach time alph, beta, theta
$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
$clpstsdist[]=60000,70000, //delayed collapse start
$clpstfdist[]=80000,90000, //delayed collapse finish

*EDA2 uniform with fuel degradation, drastic iron loss no randomization
$fueldegflag=1  //=1 for fuel degradation
$ufox=13         //drastic loss of iron oxide, uniform ox
$upoxcs=13       //drastic loss of iron oxide, uniform ox
$upoxss=5      //drastic loss of iron oxide, uniform ox
$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
$rlztns=500    //extra iterations
$btimedist[]=2.347,4.810,10.820,   //EDA breach time alph, beta, theta
$bdurdist[]=11.881,10.218,0,    //EDA duration of bathtub alph, beta theta
```

Comparison case: drip rate at current best estimate

```
*VA uniform with fuel degradation, drip rate reduced to current value
$fueldegflag=1  //=1 for fuel degradation
$pnobt=0.5225   //probability of no bathtub
$ex=.1        //exchange flushing efficiency
$cl=0.98      //criticality threshold
$testcl=0.93
$rlztns=500    //extra iterations
$flowdist[]=.05,.05, //current drip rate
```

Attachment IV, Output Files

Nominal VA Case, without randomization, for Table 6-1 basic comparison

```
The time is Mon Aug 16 23:36:55 1999
          1   0.0000000
          2   0.0000000
          3   0.0000000
          4   0.0000000
          5   0.0000000
          6   0.0000000
          7   0.0000000
          8   0.0000000
          9   0.0000000
         10   0.0000000
         11   0.0000000
         12   0.0002857
         13   0.0026664
         14   0.0036186
         15   0.0094275
         16   0.0103797
         17   0.0179979
         18   0.0282824
         19   0.0349483
         20   0.0496133
         21   0.0646592
         22   0.0746580
         23   0.0898943
         24   0.1027500
         25   0.1136059
         26   0.1258902
         27   0.1397933
         28   0.1531251
         29   0.1759796
         30   0.1912159
         31   0.2057857
         32   0.2270213
         33   0.2443526
         34   0.2668262
         35   0.2853002
         36   0.3129161
         37   0.3400558
         38   0.3628151
         39   0.3845268
         40   0.4118570
         41   0.4419487
         42   0.4677553
         43   0.4852770
         44   0.5204158
         45   0.5466985
         46   0.5671723
         47   0.6012636
         48   0.6270701
         49   0.6553526
         50   0.6918245
         51   0.7287726
```

52	0.7574360
53	0.7870515
54	0.8188574
55	0.8518060
56	0.8868495
57	0.9121799
58	0.9442714
59	0.9875045
60	1.0224529
61	1.0592105
62	1.0857788
63	1.1159659
64	1.1511999
65	1.1868148
66	1.2139545
67	1.2414751
68	1.2691861
69	1.3082292
70	1.3452725
71	1.3882199
72	1.4211686
73	1.4546884
74	1.4838279
75	1.5124913
76	1.5535341
77	1.5897203
78	1.6189551
79	1.6497134
80	1.6816145
81	1.7199910
82	1.7464641
83	1.7784603
84	1.8229315
85	1.8547373
86	1.9040648
87	1.9412986
88	1.9746281
89	2.0094813
90	2.0454771
91	2.0866152
92	2.1293721
93	2.1562261
94	2.1869844
95	2.2279319
96	2.2571668
97	2.2955434
98	2.3213497
99	2.3577267
100	2.3941033
101	2.4282898
102	2.4628572
103	2.5038049
104	2.5421814
105	2.5732254
106	2.6047456
107	2.6427410
108	2.6790225

109	2.7244460
110	2.7607275
111	2.7933902
112	2.8260531
113	2.8647154
114	2.8914741
115	2.9163283
116	2.9655607
117	3.0041278
118	3.0427899
119	3.0679298
120	3.0957361
121	3.1315415
122	3.1604907
123	3.2065805
124	3.2403861
125	3.2820955
126	3.3187580
127	3.3535157
128	3.3860834
129	3.4034147
130	3.4277929
131	3.4573132
132	3.4902619
133	3.5387325
134	3.5742522
135	3.6088196
136	3.6501481
137	3.6828108
138	3.7168070
139	3.7471845
140	3.7748956
141	3.8036541
142	3.8305080
143	3.8650756
144	3.8871682
145	3.9272586
146	3.9556363
147	3.9941080
148	4.0192480
149	4.0645761
150	4.0902875
151	4.1104756
152	4.1398056
153	4.1627554
154	4.1897998
155	4.2217961
156	4.2443650
157	4.2670290
158	4.2981681
159	4.3244507
160	4.3436867
161	4.3769208
162	4.4052985
163	4.4337716
164	4.4769094
165	4.5106199

166	4.5431874
167	4.5768978
168	4.6108937
169	4.6366051
170	4.6649826
171	4.6935508
172	4.7190719
173	4.7439259
174	4.7675423
175	4.8000146
176	4.8252497
177	4.8578178
178	4.8821002
179	4.9091449
180	4.9316184
181	4.9673287
182	4.9980871
183	5.0217987
184	5.0575085
185	5.0804582
186	5.1065503
187	5.1337853
188	5.1582586
189	5.1792090
190	5.2042533
191	5.2312028
192	5.2589136
193	5.2860535
194	5.3050035
195	5.3319530
196	5.3553791
197	5.3803282
198	5.3955644
199	5.4278464
200	5.4533676
201	5.4895537
202	5.5062183
203	5.5353580
204	5.5536414
205	5.5742106
206	5.6058260
207	5.6319181
208	5.6502020
209	5.6638195
210	5.6926732
211	5.7099093
212	5.7310495
213	5.7437149
214	5.7609510
215	5.7861861
216	5.8124685
217	5.8319900
218	5.8571299
219	5.8788421
220	5.8956019
221	5.9229321
222	5.9456915

```
223   5.9657845
224   5.9917814
225   6.0087315
226   6.0258724
227   6.0500603
228   6.0708199
229   6.0915789
230   6.1151953
231   6.1312890
232   6.1536673
233   6.1718555
234   6.1945198
235   6.2098512
236   6.2307059
237   6.2501322
238   6.2642260
239   6.2934604
240   6.3219335
241   6.3547869
242   6.3753557
243   6.3974485
244   6.4214455
245   6.4374440
246   6.4577273
247   6.4782960
248   6.4885809
249   6.5061976
*EDA2 uniform with fuel degradation, no randomization
Number of batch records screened in=599 numberpkgs=4516
numcrits@10kyr=0 exp10=0.000000 exp100=2.394103 exp249=6.506198
```

Nominal VA Case with randomization to generate standard deviation

```
The time is Mon Aug 09 22:51:38 1999
*VA uniform with fuel degradation, with randomization
Number of batch records screened in=597 numberpkgs=4516
numcrits@10kyr=34 exp10=0.003238 exp100=2.455525 exp249=6.548669

The time is Mon Aug 09 22:52:32 1999
*VA uniform with fuel degradation, with randomization
Number of batch records screened in=602 numberpkgs=4516
numcrits@10kyr=6 exp10=0.000571 exp100=2.383628 exp249=6.222231

The time is Mon Aug 09 23:03:35 1999
*VA uniform with fuel degradation, with randomization
Number of batch records screened in=591 numberpkgs=4516
numcrits@10kyr=18 exp10=0.001714 exp100=2.424766 exp249=6.370975

The time is Mon Aug 09 23:05:40 1999
*VA uniform with fuel degradation, with randomization
Number of batch records screened in=586 numberpkgs=4516
numcrits@10kyr=16 exp10=0.001524 exp100=2.319540 exp249=6.262226
```

Comparison cases for Table 6-1.

```
The time is Mon Aug 16 23:52:01 1999
     1   0.0000000
     2   0.0000000
     3   0.0000000
     4   0.0000000
     5   0.0000000
     6   0.0000000
     7   0.0007618
     8   0.0015236
     9   0.0015236
    10   0.0022854
    11   0.0023807
    12   0.0037139
    13   0.0038091
    14   0.0070468
    15   0.0147602
    16   0.0178075
    17   0.0240924
    18   0.0318058
    19   0.0429474
    20   0.0472326
    21   0.0600883
    22   0.0764673
    23   0.0880850
    24   0.0951318
    25   0.1076066
    26   0.1185577
    27   0.1354129
    28   0.1524585
    29   0.1683614
    30   0.1867402
    31   0.2231170
    32   0.2493996
    33   0.2793962
    34   0.2951086
    35   0.3194868
    36   0.3515783
    37   0.3742423
    38   0.3973825
    39   0.4291883
    40   0.4639462
    41   0.5015609
    42   0.5305099
    43   0.5551737
    44   0.5892650
    45   0.6217374
    46   0.6703032
    47   0.7037279
    48   0.7311533
    49   0.7607689
    50   0.7898131
    51   0.8198097
    52   0.8599003
    53   0.8885636
    54   0.9238928
    55   0.9603648
```

56	0.9914088
57	1.0327374
58	1.0687332
59	1.1037768
60	1.1376775
61	1.1843388
62	1.2273814
63	1.2722334
64	1.2997540
65	1.3381306
66	1.3868868
67	1.4237396
68	1.4625923
69	1.5047779
70	1.5494393
71	1.6036236
72	1.6491421
73	1.6922799
74	1.7295137
75	1.7667474
76	1.8059809
77	1.8626411
78	1.9068264
79	1.9485360
80	2.0017679
81	2.0382398
82	2.0791874
83	2.1146118
84	2.1564165
85	2.1983164
86	2.2460253
87	2.2861157
88	2.3279206
89	2.3633449
90	2.4067685
91	2.4378124
92	2.4915206
93	2.5347536
94	2.5674165
95	2.6135064
96	2.6493119
97	2.6924497
98	2.7380632
99	2.7804393
100	2.8312907
101	2.8645248
102	2.9060439
103	2.9572760
104	2.9908912
105	3.0228875
106	3.0705961
107	3.1025926
108	3.1499203
109	3.1812500
110	3.2181981
111	3.2658118
112	3.2973318

113	3.3354226
114	3.3812270
115	3.4136993
116	3.4561705
117	3.4901667
118	3.5424462
119	3.5779660
120	3.6132000
121	3.6491958
122	3.6873818
123	3.7334716
124	3.7677535
125	3.8150812
126	3.8553622
127	3.8915486
128	3.9385908
129	3.9624926
130	4.0096303
131	4.0404836
132	4.0752416
133	4.1145705
134	4.1611364
135	4.1996081
136	4.2420793
137	4.2798844
138	4.3094048
139	4.3573993
140	4.3866340
141	4.4297718
142	4.4660536
143	4.5010968
144	4.5410923
145	4.5807067
146	4.6129888
147	4.6570787
148	4.6968840
149	4.7384026
150	4.7706846
151	4.8071567
152	4.8474377
153	4.8835287
154	4.9204771
155	4.9489496
156	4.9855169
157	5.0236077
158	5.0736022
159	5.1072169
160	5.1554975
161	5.1908267
162	5.2181568
163	5.2563428
164	5.2969093
165	5.3267157
166	5.3598546
167	5.3939457
168	5.4230854
169	5.4587952

170	5.4991719
171	5.5416431
172	5.5705920
173	5.6101113
174	5.6462022
175	5.6711519
176	5.7016243
177	5.7300974
178	5.7646648
179	5.7925664
180	5.8297998
181	5.8533210
182	5.8786513
183	5.9136950
184	5.9355018
185	5.9751167
186	5.9932098
187	6.0282529
188	6.0616779
189	6.0909128
190	6.1179570
191	6.1496675
192	6.1748075
193	6.2009952
194	6.2263255
195	6.2501322
196	6.2787004
197	6.3117442
198	6.3400265
199	6.3628811
200	6.3960201
201	6.4226836
202	6.4556323
203	6.4817243
204	6.5054359
205	6.5406699
206	6.5736185
207	6.6079956
208	6.6297072
209	6.6530376
210	6.6824628
211	6.7139831
212	6.7452178
213	6.7696912
214	6.7911168
215	6.8204469
216	6.8522526
217	6.8819638
218	6.9033900
219	6.9253871
220	6.9626210
221	6.9885227
222	7.0183286
223	7.0413740
224	7.0644189
225	7.0812739
226	7.1018431

```
        227   7.1274589
        228   7.1481233
        229   7.1689780
        230   7.1937368
        231   7.2116395
        232   7.2319233
        233   7.2620146
        234   7.2866788
        235   7.3093426
        236   7.3333401
        237   7.3622890
        238   7.3837152
        239   7.4082837
        240   7.4221866
        241   7.4354235
        242   7.4515167
        243   7.4753234
        244   7.4928450
        245   7.5043674
        246   7.5202708
        247   7.5456011
        248   7.5612185
        249   7.5855961
*EDA2 uniform with fuel degradation, no randomization
Number of batch records screened in=595 numberpkgs=4516
numcrits@10kyr=24 exp10=0.002285 exp100=2.831291 exp249=7.585596


The time is Tue Aug 10 00:05:21 1999
*VA uniform with fuel degradation, drastic iron loss no randomization
Number of batch records screened in=8589 numberpkgs=4516
numcrits@10kyr=249 exp10=0.023712 exp100=28.652296 exp249=78.759530

The time is Mon Aug 16 16:24:31 1999
          1   0.0000000
          2   0.0000000
          3   0.0000000
          4   0.0000000
          5   0.0000000
          6   0.0000000
          7   0.0000000
          8   0.0000000
          9   0.0000000
         10   0.0000000
         11   0.0000000
         12   0.0000000
         13   0.0000000
         14   0.0000000
         15   0.0000000
         16   0.0000000
         17   0.0000000
         18   0.0000000
         19   0.0000000
         20   0.0000000
         21   0.0000000
         22   0.0000000
         23   0.0000000
```

24	0.0000000
25	0.0000000
26	0.0000000
27	0.0000000
28	0.0000000
29	0.0000000
30	0.0000000
31	0.0000000
32	0.0000000
33	0.0000000
34	0.0000000
35	0.0000000
36	0.0000000
37	0.0000000
38	0.0000000
39	0.0000000
40	0.0000000
41	0.0000000
42	0.0000000
43	0.0000000
44	0.0000000
45	0.0000000
46	0.0000000
47	0.0000000
48	0.0000000
49	0.0000000
50	0.0000000
51	0.0000000
52	0.0000000
53	0.0000000
54	0.0000000
55	0.0000000
56	0.0000000
57	0.0000000
58	0.0000000
59	0.0000000
60	0.0000000
61	0.0000000
62	0.0000000
63	0.0000000
64	0.0000000
65	0.0000000
66	0.0000000
67	0.0000000
68	0.0000000
69	0.0000000
70	0.0000000
71	0.0000000
72	0.0000000
73	0.0000000
74	0.0000000
75	0.0000000
76	0.0000000
77	0.0000000
78	0.0000000
79	0.0000000
80	0.0000000

81	0.0000000
82	0.0000000
83	0.0000000
84	0.0000000
85	0.0000952
86	0.0000952
87	0.0000952
88	0.0000952
89	0.0000952
90	0.0003809
91	0.0003809
92	0.0015236
93	0.0016189
94	0.0018093
95	0.0018093
96	0.0018093
97	0.0018093
98	0.0025711
99	0.0025711
100	0.0027616
101	0.0028568
102	0.0029520
103	0.0029520
104	0.0037139
105	0.0054279
106	0.0056184
107	0.0057136
108	0.0084752
109	0.0087609
110	0.0102845
111	0.0114272
112	0.0117129
113	0.0119034
114	0.0128557
115	0.0128557
116	0.0146650
117	0.0147602
118	0.0179027
119	0.0255208
120	0.0297108
121	0.0334247
122	0.0340913
123	0.0362815
124	0.0382813
125	0.0415190
126	0.0459947
127	0.0470422
128	0.0488515
129	0.0529462
130	0.0549460
131	0.0563744
132	0.0591360
133	0.0626594
134	0.0690396
135	0.0703728
136	0.0733248
137	0.0738962

138	0.0778005
139	0.0837046
140	0.0884659
141	0.0915132
142	0.0950366
143	0.0982743
144	0.1076066
145	0.1132250
146	0.1174150
147	0.1222715
148	0.1283661
149	0.1307467
150	0.1361747
151	0.1420788
152	0.1445547
153	0.1466497
154	0.1560771
155	0.1596005
156	0.1686471
157	0.1757891
158	0.1827407
159	0.1895970
160	0.1952155
161	0.2026432
162	0.2101661
163	0.2153084
164	0.2259738
165	0.2313065
166	0.2419719
167	0.2488283
168	0.2569226
169	0.2689212
170	0.2779678
171	0.2849193
172	0.2918709
173	0.2994891
174	0.3132018
175	0.3306283
176	0.3387226
177	0.3558635
178	0.3671003
179	0.3746232
180	0.3830032
181	0.3965254
182	0.4058577
183	0.4157613
184	0.4221415
185	0.4300454
186	0.4455673
187	0.4559471
188	0.4684219
189	0.4798491
190	0.4854675
191	0.4915620
192	0.5040368
193	0.5171781
194	0.5278435

195	0.5354617
196	0.5409849
197	0.5511742
198	0.5637442
199	0.5814564
200	0.5908839
201	0.6014540
202	0.6085009
203	0.6166904
204	0.6330694
205	0.6427826
206	0.6509721
207	0.6561143
208	0.6820162
209	0.6915389
210	0.7050611
211	0.7153456
212	0.7286774
213	0.7439137
214	0.7578169
215	0.7667682
216	0.7750530
217	0.7886704
218	0.8006690
219	0.8158101
220	0.8287610
221	0.8440926
222	0.8622809
223	0.8769459
224	0.8930393
225	0.9156081
226	0.9317967
227	0.9529371
228	0.9695066
229	0.9817909
230	1.0068356
231	1.0197865
232	1.0334992
233	1.0544491
234	1.0747325
235	1.0902545
236	1.1073954
237	1.1252980
238	1.1366301
239	1.1556754
240	1.1679598
241	1.1852911
242	1.2055744
243	1.2200490
244	1.2348092
245	1.2453794
246	1.2612823
247	1.2780422
248	1.2888982
249	1.3195612

*EDA2 uniform with fuel degradation, no randomization
Number of batch records screened in=600 numberpkgs=4516

```
numcrits@10kyr=0 exp10=0.000000 exp100=0.002762 exp249=1.319561

The time is Mon Aug 16 23:54:54 1999
          1   0.0000000
          2   0.0000000
          3   0.0000000
          4   0.0000000
          5   0.0000000
          6   0.0000000
          7   0.0000000
          8   0.0000000
          9   0.0000000
         10   0.0000000
         11   0.0000000
         12   0.0000000
         13   0.0000000
         14   0.0000000
         15   0.0000000
         16   0.0000000
         17   0.0000000
         18   0.0000000
         19   0.0000000
         20   0.0000000
         21   0.0000000
         22   0.0000000
         23   0.0000000
         24   0.0000000
         25   0.0000000
         26   0.0000000
         27   0.0000000
         28   0.0000000
         29   0.0000000
         30   0.0000000
         31   0.0000000
         32   0.0000000
         33   0.0000000
         34   0.0000000
         35   0.0000000
         36   0.0000000
         37   0.0000000
         38   0.0000000
         39   0.0000000
         40   0.0000000
         41   0.0000000
         42   0.0000000
         43   0.0000000
         44   0.0000000
         45   0.0000000
         46   0.0000000
         47   0.0000000
         48   0.0000000
         49   0.0000000
         50   0.0000000
         51   0.0000000
         52   0.0000000
         53   0.0000000
         54   0.0000000
```

55	0.0000000
56	0.0000000
57	0.0000000
58	0.0000000
59	0.0000000
60	0.0000000
61	0.0000000
62	0.0000000
63	0.0000952
64	0.0000952
65	0.0000952
66	0.0000952
67	0.0000952
68	0.0000952
69	0.0000952
70	0.0000952
71	0.0000952
72	0.0000952
73	0.0000952
74	0.0000952
75	0.0000952
76	0.0000952
77	0.0000952
78	0.0000952
79	0.0000952
80	0.0008570
81	0.0008570
82	0.0008570
83	0.0009523
84	0.0014284
85	0.0014284
86	0.0019998
87	0.0028568
88	0.0029520
89	0.0030473
90	0.0030473
91	0.0038091
92	0.0038091
93	0.0040948
94	0.0047614
95	0.0060945
96	0.0061898
97	0.0079991
98	0.0079991
99	0.0085704
100	0.0092370
101	0.0093323
102	0.0098084
103	0.0105702
104	0.0105702
105	0.0110463
106	0.0126652
107	0.0127604
108	0.0141888
109	0.0173313
110	0.0188550
111	0.0193311

112	0.0215213
113	0.0228545
114	0.0261874
115	0.0316154
116	0.0352340
117	0.0354245
118	0.0368529
119	0.0379004
120	0.0399001
121	0.0447567
122	0.0463756
123	0.0505656
124	0.0565649
125	0.0582790
126	0.0628499
127	0.0676112
128	0.0737057
129	0.0738962
130	0.0779910
131	0.0803716
132	0.0836093
133	0.0897991
134	0.0958936
135	0.1004645
136	0.1106538
137	0.1128441
138	0.1187481
139	0.1276042
140	0.1332226
141	0.1421740
142	0.1504587
143	0.1572199
144	0.1646476
145	0.1718848
146	0.1775984
147	0.1796934
148	0.1810266
149	0.1848357
150	0.1880734
151	0.2026432
152	0.2104518
153	0.2166415
154	0.2311160
155	0.2365440
156	0.2586367
157	0.2664453
158	0.2695878
159	0.2764441
160	0.2793962
161	0.2898712
162	0.2997748
163	0.3136779
164	0.3181536
165	0.3284381
166	0.3333899
167	0.3428174
168	0.3504355

169	0.3615771
170	0.3666242
171	0.3800512
172	0.3871932
173	0.3967159
174	0.4070956
175	0.4207131
176	0.4310928
177	0.4428058
178	0.4516619
179	0.4582326
180	0.4700407
181	0.4860389
182	0.5013704
183	0.5119406
184	0.5246058
185	0.5377472
186	0.5489839
187	0.5656487
188	0.5866939
189	0.5953595
190	0.6184045
191	0.6333551
192	0.6431635
193	0.6678273
194	0.6782070
195	0.6870632
196	0.6968716
197	0.7148694
198	0.7304867
199	0.7439137
200	0.7550553
201	0.7723866
202	0.7953363
203	0.8076206
204	0.8200001
205	0.8370458
206	0.8479969
207	0.8638045
208	0.8777077
209	0.9027524
210	0.9178935
211	0.9266544
212	0.9406528
213	0.9505564
214	0.9665546
215	0.9801720
216	0.9973129
217	1.0132158
218	1.0269285
219	1.0439741
220	1.0579725
221	1.0719709
222	1.0867311
223	1.1013961
224	1.1272979
225	1.1392012

```
226   1.1554850
227   1.1747208
228   1.1888145
229   1.2024320
230   1.2182397
231   1.2321428
232   1.2466173
233   1.2672815
234   1.3003253
235   1.3179423
236   1.3371782
237   1.3603184
238   1.3837442
239   1.4097413
240   1.4249776
241   1.4516411
242   1.4701152
243   1.4995404
244   1.5236329
245   1.5390595
246   1.5587716
247   1.5771504
248   1.5982908
249   1.6164792
*EDA2 uniform with fuel degradation, delayed collapse no randomization
Number of batch records screened in=591 numberpkgs=4516
numcrits@10kyr=0 exp10=0.000000 exp100=0.009237 exp249=1.616479


The time is Mon Aug 09 23:50:12 1999
*EDA2 uniform with fuel degradation, drastic iron loss no randomization
Number of batch records screened in=8583 numberpkgs=4516
numcrits@10kyr=0 exp10=0.000000 exp100=0.038377 exp249=15.583335
```

Comparison case: drip rate at current best estimate

```
The time is Tue Aug 10 10:03:19 1999
*VA uniform with fuel degradation, drip rate reduced to current value
Number of batch records screened in=593 numberpkgs=4516
numcrits@10kyr=0 exp10=0.000000 exp100=2.330492 exp249=6.161190
```