MOL.19980806.0607

MOL.19980806.0607

CRWMS/M&O

Calculation Cover Sheet

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1. QA: L

2. Calculation Title Probability of a PWR Uncanistered Fuel Waste Package Postclosure Criticality			
3. Document Identifier (including Revision Number) BBA000000-01717-0210-00010 REV00			4. Total Pages 42
5. Total Attachments 4	6. Attachment Numbers - Number of pages in each I-18, II-2, III-1,IV-3		
	Print Name	Signature	Date
7. Originator	John R. Massari		7/28/98
8. Checker	Alex Deng		7/30/98
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10. Remarks

PCG compliance review by WE Dullin 8/19/98

Revision History

11. Revision No.	12. Date Approved	13. Description of Revision
00	07/28/98	Initial Issue

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Table of Contents

1. Purpose

The purpose of this calculation is to estimate the probability of criticality in a pressurized water reactor (PWR) uncanistered fuel waste package during the postclosure phase of the repository as a function of various waste package material, loading, and environmental parameters. Parameterization on the upper subcritical limit that is used to define the threshold for criticality will also be performed. The possibility of waste package misload due to human or equipment error during preclosure is also considered in estimating the postclosure criticality probability.

2. Method

The internal degradation scenarios for the 21 PWR absorber plate waste package have been previously developed for the purpose of performing criticality evaluations of the possible degraded configurations (Ref. 7.4, Section 7.1). Figure 2-1 shows a schematic view of the expected sequence of degradation following breach of the package. Since the waste package (WP) interior was inerted with He prior to breach, the initial configuration will be the as-built basket (Fig. 2-1A). Within a few hundred years following breach, the carbon steel and aluminum components will degrade to insoluble corrosion products as shown in Figure 2-1B (Ref. 7.4, Section 7.1, and Ref. 7.18). While structural calculations show that the absorber plates can support the load of the assemblies, localized corrosion in the crevice regions at the corners of each cell will likely cause collapse shortly after failure of the structural components. However, the majority of the borated stainless steel (B-SS) absorber plates will remain largely undegraded and remain between the assemblies, along with corrosion products from the degraded carbon steel tubes (Fig. 2-1C). Eventually, after thousands of years, general corrosion will also fully degrade the absorber plates, allowing the soluble boron neutron absorber to be flushed out of the package (Fig. 2-1D). The zircaloy cladding and spacers represent the most corrosion resistant material in the WP, and thus will be the last to degrade. Rod consolidation will likely occur prior to complete cladding degradation (Fig. 2-1E), as the spacer grids are typically fabricated from strips of zircaloy that are thinner than the cladding. The final internal configuration (Fig 2-1F) is complete degradation of the entire WP contents, with only the insoluble materials remaining. Based on the criticality calculations performed in Reference 7.4 to evaluate the above degraded configurations, only Configurations C and D show potential for criticality if the waste package is flooded and contains sufficiently reactive fuel.

For this calculation, a simple Monte Carlo model is utilized to generate the probability that an absorber plate waste package loaded with a specified range of the PWR waste stream will exceed the specified subcritical limit. Data on the distribution of assembly burnup and enrichment are obtained from the 1995 Energy Information Administration (EIA) database of historical and projected PWR assembly discharges (Ref. 7.9). Probability distributions relating to WP environmental conditions and the time of occurrence of various penetrations in the WP barriers

are abstracted from preliminary Total System Performance Assessment - Viability Assessment (TSPA-VA) modeling results. For each model realization, these distributions are sampled to determine: 1) if the waste package is under a dripping fracture, 2) is breached in such a manner that it will accumulate water, and 3) contains fuel which might be capable of exceeding the subcritical limit. For realizations where all of these criteria are met, a mass balance method is used to track the WP degradation through Configurations C and D, and determine the state of degradation of the waste package at a given time based on information sampled from the above mentioned distributions. The degraded waste package k_{eff} regressions developed in Reference 7.4 (Section 7.6) are utilized in combination with the assembly burnup/enrichment data to determine if the package exceeds the subcritical limit prior to breaching on the bottom and draining. If the limit is exceeded, the time is recorded before starting the next realization. The total number of waste packages that exceed the limit at a given time, divided by the total number of realizations represents the cumulative probability that an absorber plate waste package will exceed the subcritical limit at that time.

The probability that a PWR waste package of any type (no-absorber, absorber plate, or absorber rod) exceeds the subcritical limit during postclosure as a result of human error during loading is conservatively determined by combining the probability of misload per package from Reference 7.16 (Section 6) with the fraction of packages that are breached and flooded as a function of time (e.g., a misloaded package is assumed to exceed the subcritical limit if flooded; see Assumption 3.12).

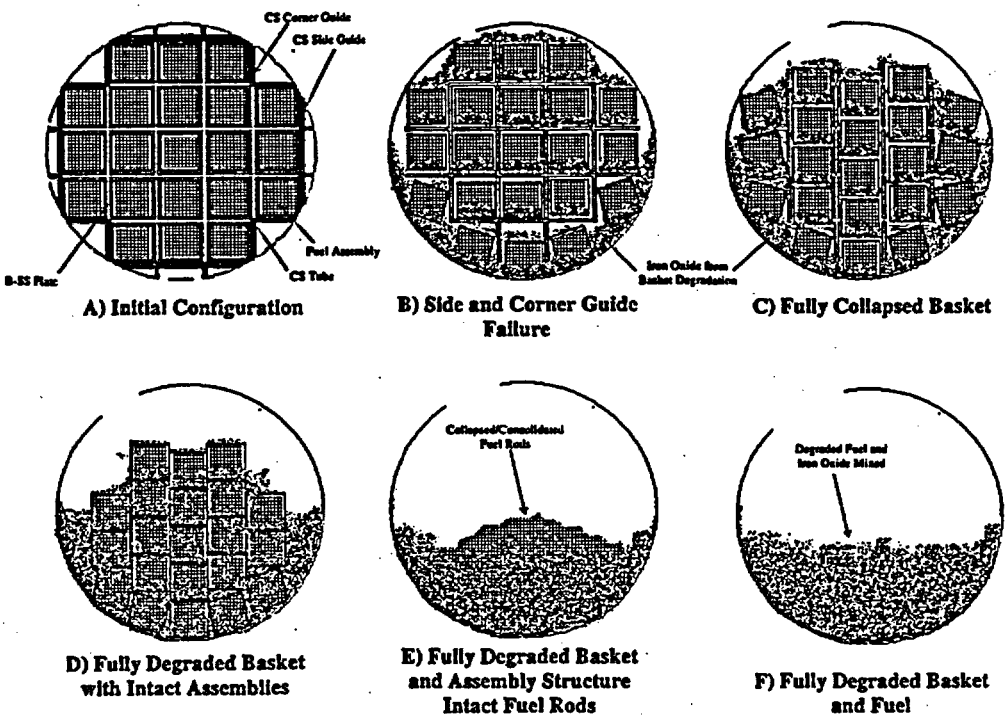


Figure 2-1. Degradation Sequence for the 21 PWR Absorber Plate Waste Package

3. Assumptions

3.1 It is assumed that B&W Mark B 15 x 15 fuel type, which was assumed in the criticality calculations (Ref. 7.4) used to develop the k_{eff} regressions discussed in Section 5.1.7, is bounding for all PWR assembly designs. The basis for this assumption is a previous evaluation performed for the BR-100 transportation cask, which 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. 7.10, p. II.6-6). This assumption is used throughout the calculation.

3.2 The following equation obtained from Reference 7.2, page 7, is assumed to provide representative, but slightly conservative values for PWR spent nuclear fuel (SNF) assembly k_∞ values:

$$k_\infty = 1.06 - 0.01 \cdot b - 0.002 \cdot c + 0.114 \cdot a + 0.00007081 \cdot b^2 + 0.00007565 \cdot c^2 - 0.007 \cdot a^2 - 0.0002671 \cdot b \cdot a - 0.0001145 \cdot b \cdot c + 0.0002318 \cdot c \cdot a + 0.000009366 \cdot b \cdot c \cdot a$$

where: a = initial ^{235}U enrichment in weight percent,
b = assembly burnup in GWd/MTU, and
c = assembly cooling time (i.e., age) in years (< 20 years).

The usage and development of this equation is presented in detail in Reference 7.2. The basis for using this equation is that it was used in defining the WP design configurations, and identifying the conceptual loading strategy for the absorber plate WP design, in Reference 7.5. A constant value of c=10 years was used for consistency with Reference 7.5. This assumption is used in Section 5.3.

3.3 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 (CDA) Key 009 (Ref. 7.15). In addition, this assumption was used in the criticality calculations (Ref. 7.4) used to develop the k_{eff} regressions discussed in Section 5.1.7. This assumption is used throughout this calculation.

3.4 It is assumed that the 304/316 stainless steel general corrosion data can be used to represent the bulk corrosion of Neutronit A978 borated stainless steel in repository environments, when increased by a "boron" factor ranging from 1 to 4. The basis for this assumption is that Neutronit A978 is similar in composition to 316 stainless steel (Ref. 7.14, p. 96), and corrosion data in repository relevant environments is only available for 304/316 stainless steels. The basis for the upper bound of the boron factor 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. 7.4, Section 4.1.4). This assumption is used in Section 5.1.6.

3.5 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. This assumption is conservative based on the discussion of borated stainless steel corrosion in Reference 7.4 (Section 4.1.4), which indicates that the boride particles would corrode relatively quickly because they have a large surface-to-volume ratio and preliminary corrosion testing indicates they have a corrosion rate similar to that of the stainless steel matrix. Neglecting the effects of boron adsorption on iron oxides is also conservative as Reference 7.4 (Section 7.4) indicates 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 in Section 5.3

3.6 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 Reference 7.19 (Section 7.3.2) which indicated that the filling and draining times are relatively short (few tens to hundreds of years) in comparison to the potential duration of flooding discussed in Section 5.1.5 of this calculation and the 1000 year timestep used in the mass-balance calculations (see input files in Section 8). In addition, Reference 7.20 indicates that corrosion product plugging of pits would not significantly extend the time required for draining, as corrosion products were only found to completely plug small aperature cracks if they were compacted by high water pressure. This assumption is used in Section 5.3.

3.7 It is assumed that the carbon steel basket components degrade instantaneously upon breach of the waste package. The basis for this assumption is that Reference 7.4 (Section 7.1) indicates that these components degrade relatively quickly compared to the borated stainless steel components.

3.8 It is assumed that the duration of waste package flooding is independent of waste package breach time. The TSPA results discussed in Section 5.1.5 show that there is a positive correlation of flooding duration and waste package breach time. The assumption of independence is conservative because it allows a greater probability of long flooding durations at early breach times than would normally be the case. This in turn results in a greater probabilty that a waste package which breaches before the 15,000 to 35,000 year time of peak post-closure k_{eff} (Reference 7.4, Section 7.3 to 7.4) will remain flooded long enough for sufficient borated stainless steel degradation to occur and cause the subcritical limit to be exceeded. This assumption in used throughout this calculation.

3.9 It is assumed that the probability that a waste package will be uniformly loaded (all fuel assemblies in package have same enrichment and burnup) with fuel that exceeds the subcritical limit at a given point in its degradation is equal to the probability of selecting such a fuel assembly from the entire PWR waste stream. The basis for this assumption is

that it is conservative because at least 85% of the assemblies in the PWR population will be incapable of exceeding the subcritical limits of 0.93 or greater under any conditions (Ref. 7.1, p. 58). Thus, the small fraction of assemblies which may be capable of exceeding the limit if they were to fill an entire package, are more likely to be mixed in a package with other fuel which is not capable of exceeding the limit. This assumption is used throughout this 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 the calculation performed in Reference 7.24, which performed a statisitical estimate of bias for benchmark calculations using the same code systems used to develop the k_{eff} regressions discussed in Section 5.1.3 (MCNP and SAS2H). This calculation identified a subcritical limit of ≈0.98 (Ref. 7.24, Section 6) if no trending parameters are utilized, and no administrative bias is applied. This assumption is used in Sections 5.2 and 5.3.

3.11 It is assumed for the purposes of estimating the amount of boron removal that 100% of the water flowing onto the WP enters the interior, and that boron saturated internal water is exchanged with unsaturated water from the outside with a 10% efficiency. The basis for the former assumption is that it is very conservative because some fraction of water dripping onto the WP is likely to run off rather than enter, especially when the WP is only initially breached by small pits. The latter assumption is based on the high range of the exchange efficiency used in Reference 7.19 assumption 4.3.4, and the fact that water that is both entering and leaving the WP at the top is not likely to significantly mix with the water in the lower portion of the WP, which is where most of the boron will be. This assumption is used in Section 5.3.

3.12 It is assumed that a misloaded package will exceed the subcritical limit (regardless of its value) if it floods for any length of time once breached. The basis for this assumption is that it is conservative, because the dominant misload sequence is misload of a single assembly. This assumption is used in Section 5.3.

3.13 It is assumed that the degraded WP k_{eff} regressions presented in Section 5.1.7 may be used to estimate probabilities of exceeding various k_{eff} values for times beyond 250,000 years, which is the limit of the data used in their development (Ref. 7.4, Section 7.6). The basis for this assumption is that the k_{eff} regressions appear to produce very conservative k_{eff} values for times greater 250,000 years. Calculations of k_{eff} for times out to 1,000,000 years indicate that k_{eff} values do not significantly change between 250,000 and 1,000,000 years, given that all other configuration parameters remain constant (Ref. 7.6, p. 6.3-142). However, a plot of k_{eff} versus time using the fully degraded basket k_{eff} regression indicates that it produces k_{eff} values at 1,000,000 years that may be as much as 8% greater than those at 250,000 years (Attachment IV, p. 1). This conservatism in predicted k_{eff} will translate to conservative probability estimates for times greater than 250,000 years.

4. Use of Computer Software

4.1 Software Approved for QA Work

No software of this type was used for this calculation.

4.2 Software Routines

Microsoft Excel 97, loaded on a Pentium II PC. Least squares fits to various input data to probability distributions, and graphing of calculation results were performed electronically in this spreadsheet software package. The location of the electronic copy of the PWRprob.xls spreadsheet containing all inputs and outputs is given in Section 8, and Attachment I provides a hard copy. All calculations/data manipulations performed in PWRprob.xlw are described in Section 5 and may also be examined electronically (see Section 8 for location of the file).

MS-DOS Qbasic version 1.1 BASIC interpreter, loaded on a Pentium II PC. The Monte-Carlo mass balance calculation was performed using a BASIC software routine entitled PWRPROB.BAS. The function of the PWRPROB code is to randomly sample the distributions for the waste package repository environment and waste package degradation parameters (described in Section 5.1) and perform the deterministic mass balance as needed to determine if a waste package exceeds the subcritical limit for a given set of parameters. This is repeated until the indicated number of realizations is reached. Further discussion on the operation of the PWRPROB code is provided in Section 5.3, including format for the input and output files. The implementation of the Monte-Carlo process is independently verified as part of the technical check of this calculation and by independent calculation method in Section 5.2. The source code for PWRPROB is provided in Attachment I, and is also available in electronic form (ASCII file) as indicated in Section 8. All ASCII input and output files for the PWRPROB cases run for this calcuation are also included in electronic form as indicated in Section 8.

Mathcad 7 Professional, loaded on a Pentium II PC. An independent calculation is performed in the Mathcad worksheet PWRprob.mcd to provide a check of the PWRPROB code. This calculation is included as Attachment IV, and an electronic copy of the PWRprob.mcd worksheet is included as discussed in Section 8.

5. Calculation

5.1 Calculation Inputs

5.1.1 Climate Changes and Associated Percolation Rates

The draft TSPA-VA climate model was obtained from Reference 7.7. As Reference 7.7 is a draft TSPA-VA chapter, and may change prior to final issuance of the TSPA, this input should be considered unqualified data. In this model, future climate is modeled as a sequence of discrete steady states. Only three discrete climate states were considered for TSPA-VA: present, long-term average, and super pluvial. The present climate represents relatively dry, interglacial conditions. The long-term average represents the typical conditions at Yucca Mountain, between the wet and dry extremes. Because glacial climates dominated globally over the last million years, the long-term average represented an average pluvial period at Yucca Mountain. The super pluvial represents periods of extreme wetness. A detailed summary of the duration, frequency, and percolation rate probability distributions for each climate state is provided below.

Present Day (PD)

Duration: Uniformly distributed from 0 to 20k years, except for the current cycle which has already lasted for 10k years and has a remaining duration that is uniformly distributed from 0 to 10k years. (Ref. 7.7, p. 2.3-14).

Frequency: Three out of every four 100k year cycles (Ref. 7.7, p. 2.3-14).

Percolation Rate:	Minimum:	≈0.50 mm/yr (Ref. 7.7, Table 2.3-101)
	Mean:	7.01 mm/yr (Ref. 7.7, Table 2.3-38)
	95%:	14.6 mm/yr (Ref. 7.7, Table 2.3-38)
	Maximum:	19.5 mm/yr (Ref. 7.7, Table 2.3-38)

Long-Term Average Pluvial (LTA)

Duration: 80 to 100k years (100k years – duration of PD or SP) (Ref. 7.7, p. 2.3-14).

Frequency: Occurs every 100k cycle between two PD climates or between a PD and an super pluvial climate (Ref. 7.7, p. 2.3-14).

Percolation Rate:	Minimum:	≈7.5 mm/yr (Ref. 7.7, Table 2.3-102)
	Mean:	38.8 mm/yr (Ref. 7.7, Table 2.3-38)
	95%:	67.9 mm/yr (Ref. 7.7, Table 2.3-38)
	Maximum:	83.8 mm/yr (Ref. 7.7, Table 2.3-38)

Super-Pluvial (SP)

Duration: Uniformly distributed from 0 to 20k years (Ref. 7.7, p. 2.3-14).

Frequency: 1 out of every 4 100k year cycles (Ref. 7.7, p. 2.3-14). Note that Reference 7.7 also discussed a frequency of every other 100k year cycle for the super pluvial. However, that frequency has not been evaluated in this calculation.

Percolation Rate:	Minimum:	≈10 mm/yr (Ref. 7.7, Table 2.3-103)
	Mean:	105.8 mm/yr (Ref. 7.7, Table 2.3-38)
	95%:	213.4 mm/yr (Ref. 7.7, Table 2.3-38)
	Maximum:	287.9 mm/yr (Ref. 7.7, Table 2.3-38)

To facilitate the use of the percolation rate uncertainty data in the Monte Carlo model used for this calculation, a least-squares fit of the above data to a three-parameter Weibull distribution was performed in the Excel workbook "PWRprob.xlw." The probability density function (pdf) of the Weibull distribution is given by:

$$f(t)=\frac{\beta}{\alpha}\left(\frac{t-\theta}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{t-\theta}{\alpha}\right)^{\beta}\right]$$

where α, β, and θ represent the scale, shape, and location parameters respectively (all > 0) and $t \geq \theta$ (Ref. 7.8, p. 77). The associated Weibull cumulative distribution function (CDF) is given by:

$$F(t)=1-\exp\left[-\left(\frac{t-\theta}{\alpha}\right)^{\beta}\right]$$

for $t \geq \theta$. For values of $t < \theta$, both $f(t)$ and $F(t)$ equal zero. The Weibull distribution was chosen for this application because of its ability to fit a wide variety of distribution shapes, and the ability to set a minimum value for the distribution (θ). The method for performing the least-squares fit is detailed in Reference 7.11, pages I-22 and I-23. The resulting Weibull parameters for each climate percolation rate distribution are given in Table 5.1.1-1. In all cases, a chi-squared test indicated a good fit to the data points. Figure 5.1.1-1 shows the Weibull CDF for the Present Day climate percolation rate, and the data points used in the fit. Figures 5.1.1-2 and 5.1.1-3 provide the same information for the Long-Term Average and Super Pluvial climates, respectively.

Table 5.1.1-1. Weibull Parameters for Climate Percolation Rate Distributions

Climate Type	α	β	θ	PWRprob.xlw sheet For Fit Calculation
PD	7.900	1.898	0.500	PDperc
LTA	36.881	2.270	7.500	LTAperc
SP	115.505	2.119	10	SPperc

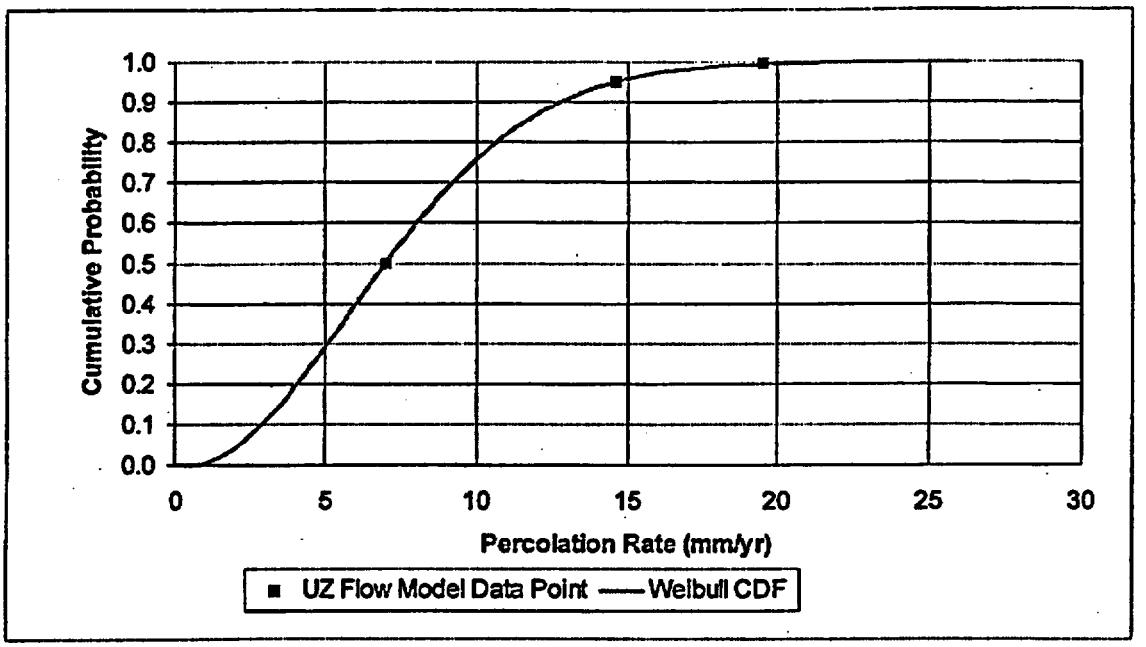


Figure 5.1.1-1. Present Day Climate Percolation Rate Weibull CDF

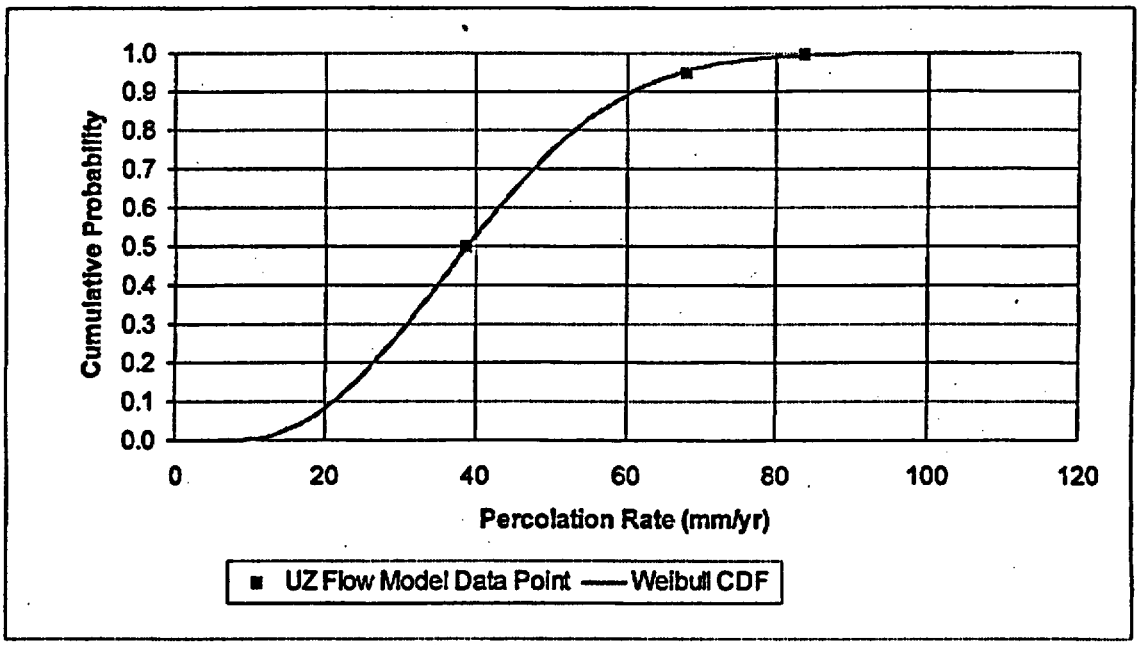


Figure 5.1.1-2. Long-Term Average Climate Percolation Rate Weibull CDF

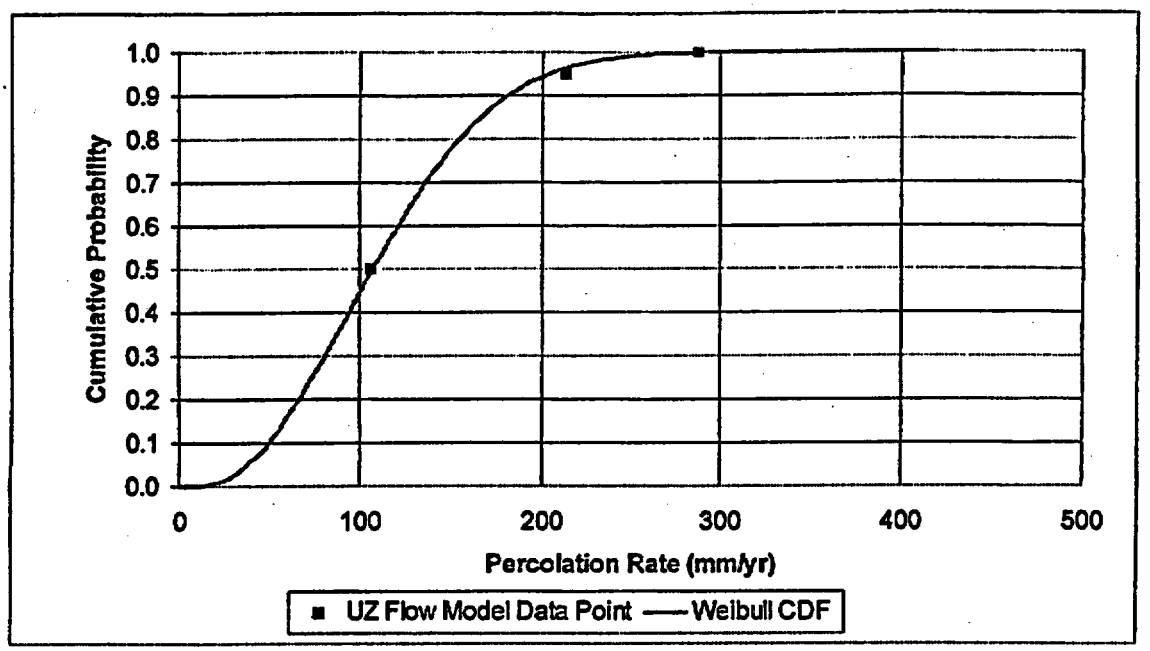


Figure 5.1.1-3. Super Pluvial Climate Percolation Rate Weibull CDF

5.1.2 Seepage Fraction

The preliminary TSPA-VA base case seepage model is based on abstraction of the results of a large number of unsaturated zone flow process-model calculations. The process-model results were abstracted in Reference 7.7 by fitting the calculated seepage fraction (Fseep; the fraction of WPs under dripping fractures) with beta probability distributions for which the mean and standard deviation are functions of the percolation rate in the fractures. The initial abstraction was reported in Tables 2.3-49 and 2.3-50 of Reference 7.7. The final abstracted models were sent via e-mail by the author of Reference 7.7, and are summarized in Table 5.1.2-1. A copy of this e-mail message is included as Attachment II to this calculation. Both the information in Reference 7.7 and the information in Attachment II should be considered unqualified data due to their perliminary nature.

Table 5.1.2-1. Fraction of WPs Under Drips as a Function of Percolation Rate

Percolation Rate (mm/yr)	Mean Fseep	Fseep Standard Deviation
0	0	0
2.2	0	0
3.9	0.00844	0.0144
9.2	0.0462	0.0785
14.6	0.167	0.283
73.2	0.403	0.427
213	0.590	0.398

Percolation Rate (mm/yr)	Mean Fseep	Fseep Standard Deviation
500	0.743	0.386
980	1	0
>980	1	0

5.1.3 Seepage Flow Rate

As with the seepage fraction, the seepage flow rate abstraction was developed in Reference 7.7 by fitting the seepage flow rate (Qseep) results from the UZ flow process model with beta probability distributions for which the mean, standard deviation, and maximum are functions of the percolation rate in the fractures. The initial abstraction was reported in Tables 2.3-49 and 2.3-50 of Reference 7.7. The final abstracted models were sent via e-mail by the author of Reference 7.7, and are summarized in Table 5.1.3-1. A copy of this e-mail message is included as Attachment II to this calculation. Both the information in Reference 7.7 and the information in Attachment II should be considered unqualified data.

Table 5.1.3-1. Drip Flow Rate as a Function of Percolation Rate

Percolation Rate (mm/yr)	Mean Drip Flow Rate (m^3/yr)	Standard Deviation (m^3/yr)	Maximum Drip Flow Rate (m^3/yr)
0.0	0	0	0.
2.2	0	0	0.
3.9	0.0123	0.0111	0.123
9.2	0.0124	0.0112	0.124
14.6	0.0402	0.0364	0.404
73.2	0.361	0.352	3.88
213.0	1.54	1.38	15.3
500.0	4.50	3.77	42.2
>500.0	Extrapolate linearly		

5.1.4 Time of Waste Package Breach

Information on the distribution of waste package breach times for packages under dripping fractures was obtained from draft TSPA-VA results transmited via e-mail by the author of the section on waste package degradation (see Attachment III for a copy of the e-mail and Section 8 for copies of the electronic files which were attached to the e-mail message in the compressed file "outs306.zip"). This information was developed using the WAPDEG v3.06 code (Ref. 7.12). This information should be considered unqualified data, as it represents preliminary results for VA. The specific WAPDEG output files utilized in this calculation were those for the Northeast (NE) and Southcentral (SC) parts of the repository for waste packages always under dripping fractures (files "nesfad100mh.out" and "scsfad100mh.out").

The WAPDEG output for each case lists the times that first penetrations occur on the top and

bottom of the package both for parts of the package under the drip and parts not under the drip. Each output contains this information for a sample of 400 packages. Since breaches on the top of the package are required to allow dripping water to enter, the earliest time of any top penetration was used as the waste package breach time. This is conservative as only top breaches under a drip would be expected to allow significant amounts of water to enter the waste package. This was determined in the "306 NE&SC A drip" sheet of the Excel workbook "PWRprob.xlw" using the Excel MIN function to select the earliest of the top penetration times reported for each of the 800 packages modeled. The natural logs of the 800 breach times were then arranged in ascending order using the Excel sort command, and each assigned a cumulative probability according to the estimator (i - 0.375) / (n + 0.25), where n is the sample size and i is the sample index (Ref. 7.8, p. 91). A least-squares fit to a three-parameter Weibull distribution was then performed in the "WPbreach" sheet in the same manner discussed in Section 5.1.1. The Weibull CDF was found to provide a good fit to the data for a θ corresponding to ln(1) using a chi squared test. The resulting Weibull parameters are: $\alpha = 12.099$, $\beta = 16.425$, and $\theta = 0$. Figure 5.1.4-1 shows the Weibull CDF for the waste package breach time, and the data points used in the fit.

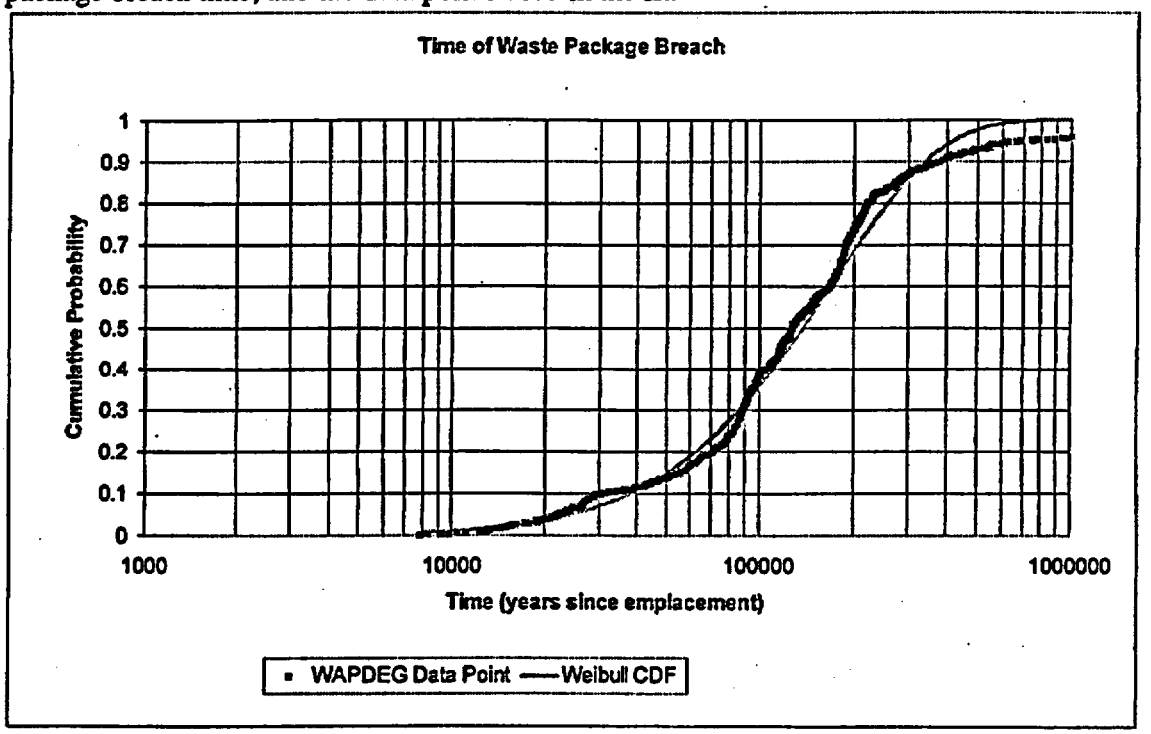


Figure 5.1.4-1. Time of Waste Package Breach

5.1.5 Probability and Duration of Waste Package Flooding

As indicated in Section 5.1.4 above, the WAPDEG output contains information on the time of penetration of both the top and bottom surfaces of the waste package. In order for the waste package to be capable of accumulating 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 Δt between the earliest top penetration, and the earliest bottom penetration, was calculated for each of the 800 waste packages modeled in the WAPDEG output files "nesfad100mh.out" and "scsfad100mh.out". This calculation was performed in the "306 NE&SC A drip" sheet of the Excel workbook "PWRprob.xlw". Out of 800 packages, 418 (52.25%) were found to have a $-\Delta t$, indicating that penetration occured on the bottom of the package first. Thus, at the time of top breach, these packages would be incapable of accumulating water. For the remaining 382 packages the natural logs of the Δt's were arranged in ascending order using the Excel sort command, and each assigned a cumulative probability according to the estimator $(i - 0.375) / (n + 0.25)$, where n is the sample size and i is the sample index (Ref. 7.8, p. 91). A least-squares fit to a three-parameter Weibull distribution was then performed in the "Duration" sheet of "PWRprob.xlw", in the same manner discussed in Section 5.1.1. The Weibull CDF was found to provide a good fit to the data for a θ corresponding to ln(1) using a chi squared test. The resulting Weibull parameters are: $\alpha = 10.849$, $\beta = 8.228$, and $\theta = 0$. Figure 5.1.5-1 shows the Weibull CDF for the duration of flooding for the 47.75% of waste packages which are capable of accumulating water, and the data points used in the fit.

The correlation between flooding duration and waste package breach time was also examined. As can be seen from Figure 5.1.5-2, there is a positive correlation between flooding duration and waste package breach time. This is likely the result of the corrosion resistant material corrosion rate decreasing with decreasing WP surface temperature. This effect will be conservatively ignored for this calculation based on the discussion in assumption 3.8.

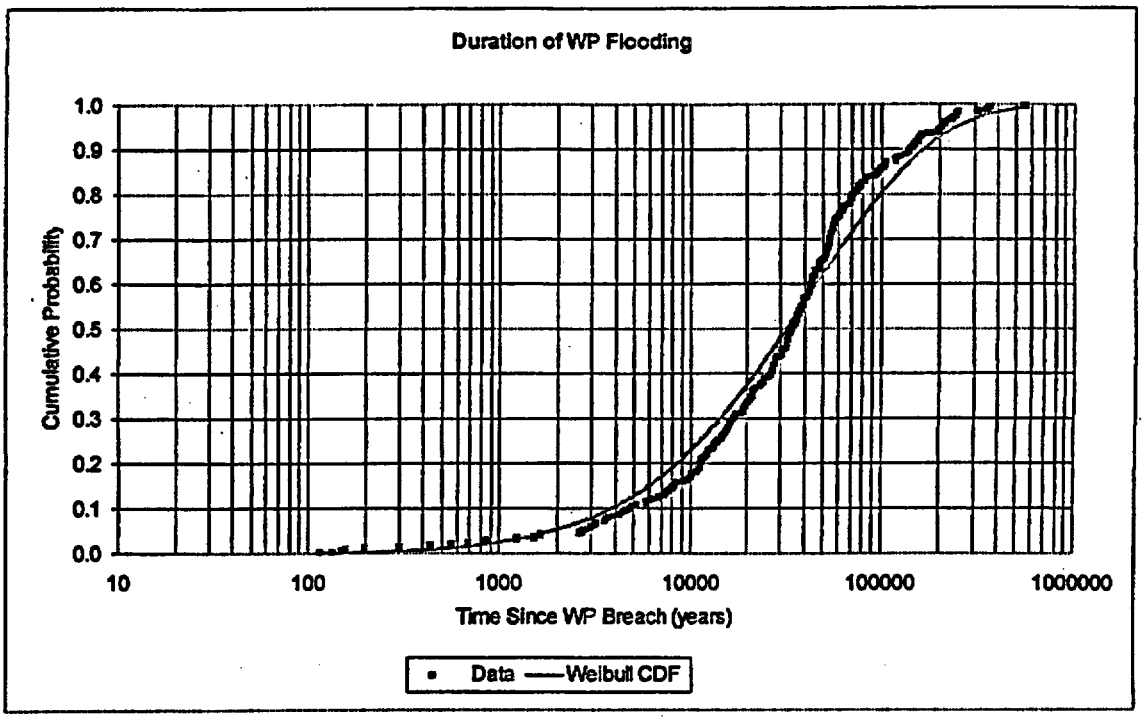


Figure 5.1.5-1. Duration of WP Flooding

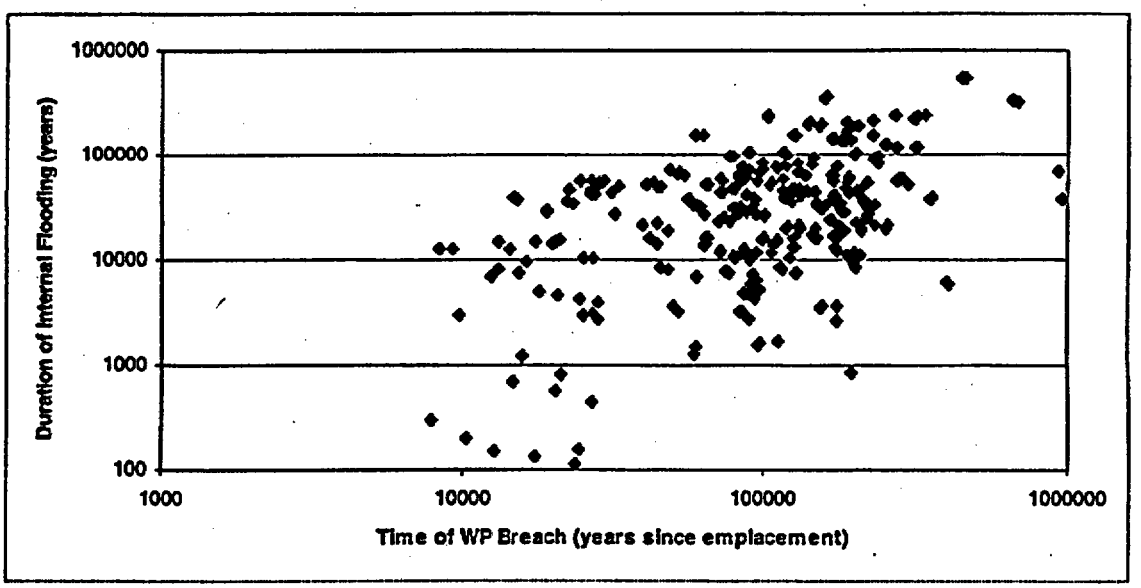


Figure 5.1.5-2. Duration of Flooding as a Function of WP Breach Time

5.1.6 Borated Stainless Steel Corrosion Rate

While the specified criticality control material is Neutronit A978 (Ref. 7.14, with a composition similar to the conceptual borated 316 stainless steel, SS316B6A, in Ref. 7.13), much of the stainless steel corrosion data collected in repository relevant environments is for 304 stainless steels. While this information should be considered unqualified, it is still relevant because 304 stainless steels have performed similarly to 316 stainless steel in repository relevant tests which included both materials. In addition 304 stainless steels are generally recognized as being less corrosion resistant than 316 stainless steels in harsher environments. Reference 7.4 summarizes the results of tests which measured the general corrosion rate of 304 and 316 series stainless steels in J-13 well water environments that roughly bound the range of conditions indicated in CDA assumption TDSS-025 (Ref. 7.15). A summary of this corrosion data for temperatures in the 28 - 100°C range is given in Table 4.1-5 of Reference 7.4. These temperatures cover the range expected for the waste package internal components for times later than 2,000 years after emplacement (Ref. 7.21, p. 5-17).

Based on the short term (relative to the time frames being considered) corrosion data in Reference 7.4, Table 4.1-5, the corrosion rate for 304/316 stainless steels in the typical J-13 well water environment ranges between 0.02 - 0.57 μm/yr in tests lasting from less than 100 hours to tests lasting more than 11,000 hours. The middle of this range on a log scale is 0.1 μm/yr, and many of the longer corrosion test show corrosion rates that are comparable or less than this by the end of the test, so this value will be used as the mean corrosion rate for 304/316 stainless steel for this calculation. At a pH slightly below that of the bottom range given in CDA assumption TDSS-025 (pH=4.5), or Cl^- concentrations of 2,500x that of J-13, the corrosion rates of 304/316 stainless steels were 1 to 2 orders of magnitude higher than in the J-13 environment. At a pH near the top of the range in CDA assumption TDSS-025 (pH=10.5), and Cl^- concentrations of 150x J-13, the corrosion rates were at most one order of magnitude higher than the J-13 rates. Therefore, a rate of 1 μm/yr (one order of magnitude higher than the mean) will be used as the corrosion rate at the 5% confidence level for the 304/316 stainless steel corrosion rate. A rate of 10 μm/yr, which was the 304L corrosion rate in the acidic (pH=3.8) high Cl^- environment, will be used as a maximum corrosion rate. The 95% confidence level stainless steel corrosion rate will be taken to be that of the lower range of the J-13 tests, 0.02 μm/yr, to account for the possibility of further passivation of the stainless steel than that which occured during the relatively short duration tests shown in Reference 7.4, Table 4.1-5.

To facilitate the use of the borated stainless steel corrosion rate uncertainty data in the Monte Carlo model used for this calculation, a least-squares fit of the data to a three-parameter Weibull distribution was performed in the "BSScr" sheet of the Excel workbook "PWRprob.xlw." To provide a better fit to the range of corrosion rates (which covers over two orders of magnitude), and allow a maximum corrosion rate to be specified, the fit was performed to the negative natural log of the indicated corrosion rates. The resulting Weibull

parameters are: $\alpha = 4.852$, $\beta = 4.041$, and $\theta = 4.605$. A chi-squared test showed a good fit to the data. Figure 5.1.6-1 shows the Weibull CDF for the stainless steel corrosion rate.

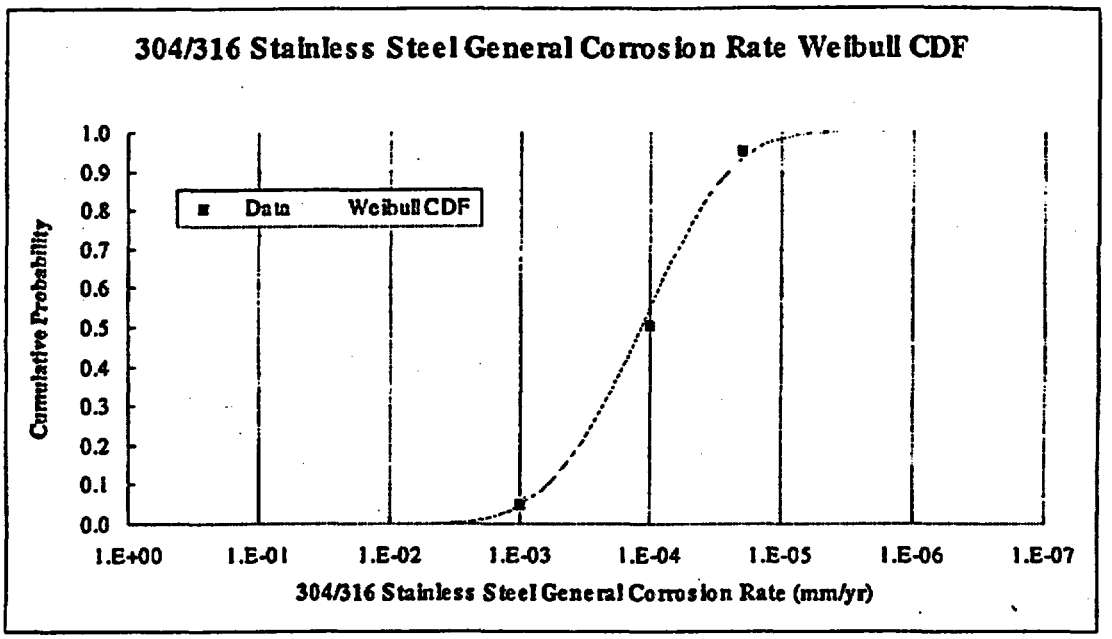


Figure 5.1.6-1. 304/316 Stainless Steel General Corrosion Rate Weibull CDF

Most of the tests in Table 4.1-5 of Reference 7.4 were performed for unborated stainless steel. The one comparison of borated versus unborated 304L stainless steel in a low pH environment found that the borated material (with 1.23 wt% B) had a corrosion rate that was 4x that of the unborated material. However, a six month test in more benign spent fuel pool conditions of 68°C and pH of 5.3 (2,000 ppm boric acid) showed no difference in corrosion resistance for stainless steel with boron concentrations of 1% to 1.75% (Ref. 7.23, p. 3-22). Therefore, to more conservatively model the corrosion of Neutronit A978 with the available data, the corrosion rates sampled from the 304/316 stainless steel distribution will be multiplied by a "boron factor". This boron factor will be sampled from a uniform distribution ranging from 1 to 4.

5.1.7 Degraded Waste Package k_{eff} Regressions

Reference 7.4 (Sect. 7.6) provided regressions which relate the k_{eff} for a particular class of degraded WP configurations (e.g., intact fuel with fully degraded basket and oxide settled to bottom of WP) to various parameters for that class (e.g., time, burnup, enrichment, assemblies covered by oxide, etc.). The k_{eff} values for the various degraded configurations used to develop the regressions were calculated using the neutronics code MCNP4A, with the SAS2H sequence of SCALE 4.3 used to determine assembly isotopics for various enrichment/burnup combinations. Since MCNP is a Monte Carlo code, each result is

reported as a mean and a standard deviation (σ). For conservatism, the regressions were fit to $k_{eff}+2\sigma$ (upper bound at 95% confidence). The coefficients for the partially degraded basket regressions for both a uniform and settled distribution of oxide corrosion products are provided in Table 5.1.7-1, and the form of the regression in both cases is as follows:

$$k_{eff}+2\sigma = C_0+C_1b+C_2b^2+C_3a+C_4a^2+C_5\ln(t)+C_6\ln(t)^2+C_7\ln(t)^3+C_8O+C_9T+C_{10}T^2+C_{11}T^3$$

where b is burnup in GWd/MTU, a is initial enrichment in wt%, t is decay time in years, T is thickness of borated stainless steel remaining in mm, and O is either vol% oxide for the uniform oxide configuration, or fuel rod rows covered for the settled cases.

Table 5.1.7-1. Regression Coefficients for Partially Degraded Basket WP $k_{eff}+2\sigma$

Regression Coefficients	Uniform Oxide	Settled Oxide
C_0	2.35498	1.72095
C_1	-6.6737e-03	-6.7237e-03
C_2	-1.8096e-05	-1.6667e-05
C_3	1.4180e-01	1.3348e-01
C_4	-7.1354e-03	-6.0497e-03
C_5	-5.1930e-01	-3.1232e-01
C_6	5.9471e-02	3.7442e-02
C_7	-2.2406e-03	-1.4715e-03
C_8	-5.0889e-03	-1.6797e-02
C_9	-7.4906e-02	-6.6316e-02
C_{10}	1.0646e-02	9.4036e-03
C_{11}	-5.2334e-04	-4.6905e-04

The coefficients for the fully degraded basket regressions for both a uniform and settled distribution of oxide corrosion products are provided in Table 5.1.7-2 (Ref. 7.4, Section 7.6), and the form of the regression in both cases is as follows:

$$k_{eff}+2\sigma=C_0+ C_1\ln(t)+ C_2b+C_3a+C_4\ln(t)^2+C_5\ln(t)^3+C_6b^2+C_7b^3+C_8a^2+C_9a^3+C_{10}\ln(t)b+C_{11}\ln(t)a+C_{12}O$$

where b is burnup in GWd/MTU, a is initial enrichment in wt%, t is decay time, and O is vol% oxide for the uniform oxide configuration and assembly rows covered for the settled cases.

Table 5.1.7-2. Regression Coefficients for Fully Degraded Basket WP $k_{eff}+2\sigma$

Regression Coefficients	Uniform Oxide	58% Settled Oxide
C_0	-5.12955	-1.25161
C_1	1.65615	6.83155e-01
C_2	-8.52852e-03	-6.65133e-03
C_3	2.92660e-01	2.66145e-01
C_4	-1.53971e-01	-6.40282e-02
C_5	4.67070e-03	1.92631e-03
C_6	6.89640e-05	-2.67041e-05
C_7	-1.63227e-07	6.12197e-07
C_8	-6.71372e-02	-6.18276e-02
C_9	5.36083e-03	5.20352e-03
C_{10}	-4.08151e-04	-1.36497e-04
C_{11}	7.23708e-03	5.08490e-03
C_{12}	-5.25978e-03	-1.40918e-01

Reference 7.4 also provided a multivariate regression for predicting the $\Delta k_{eff}/k_{eff}$ resulting from various amounts of boron remaining in solution for the partially degraded basket with various amounts of iron oxide settled to the bottom of each assembly, and various borated stainless steel plate thickness remaining. While the amount of boron in solution is generally much smaller than in the basket, this correction is justified because it is still an effective neutron absorber until it is removed from the WP. The corrected k_{eff} is obtained using:

$$\text{Corrected } k_{eff} = k_{eff} + \Delta k_{eff} = k_{eff}(1+\Delta k_{eff}/k_{eff})$$

The coefficients of the regression are provided in Table 5.1.7-3, and the form of the regression is as follows:

$$\Delta k_{eff}/k_{eff} = C_0+C_1\ln(B)+C_2\ln(B)^2+C_3\ln(B)^3+C_4T+C_5O$$

where B is the total grams of ^{10}B in solution in the fully flooded WP, T is thickness of borated stainless steel remaining in mm, and O is fuel rod rows covered.

Table 5.1.7-3. Regression Coefficients for $\Delta k/k_{eff}$ as a Function of Dissolved ^{10}B for the Settled Oxide Partially Degraded Basket

C_0	6.37971e-03
C_1	-6.07375e-02
C_2	2.08433e-02
C_3	-2.21564e-03
C_4	3.59713e-04
C_5	4.23685e-03

Reference 7.4 (Section 7.6) also provided a multivariate regression for predicting the $\Delta k/k_{eff}$ resulting from various amounts of boron remaining in solution for the fully degraded basket with 58 vol% iron oxide settled to the bottom. The coefficients for this regression are provided in Table 5.1.7-4, and the form of the regression is as follows:

$$\Delta k_{eff}/k_{eff} = C_0+C_1\ln(B)+C_2\ln(B)^2+C_3\ln(B)^3$$

where B is the total grams of ^{10}B in solution in the fully flooded WP.

Table 5.1.7-4. Regression Coefficients for $\Delta k/k_{eff}$ as a Function of Dissolved ^{10}B for the Settled Oxide Fully Degraded Configuration

C_0	2.32558e-02
C_1	-3.56383e-02
C_2	1.42821e-02
C_3	-1.91685e-03

Finally, Reference 7.4 (Section 7.7.2) provided a regression which predicts the peak k_{eff} for the fully degraded basket with settled oxide configuration as a function of fuel assembly burnup and initial enrichment. The regression coefficients are provided in Table 5.1.7-5, and the form of the regression equation is as follows:

$$\text{Peak } k_{eff}+2\sigma = C_0+C_1B+C_2E+C_3B^2+C_4E^2+C_5B^3+C_6E^3$$

where B is burnup in GWd/MTU, and E is initial enrichment in wt%.

Table 5.1.7-5. Regression Coefficients for Settled Peak k_{eff} as a Function of Burnup and Enrichment

C_0	6.40653e-01
C_1	-1.02912e-02
C_2	3.00169e-01
C_3	-2.54581e-05
C_4	-4.90929e-02
C_5	9.92035e-07
C_6	3.64521e-03

5.1.8 21 PWR Intact Waste Package Loading Curves

Two loading curves will be considered in this calculation. The first is the k_∞-based loading curves utilized in the development of the conceptual PWR waste package designs (Ref. 7.5, Assumptions 4.3.4 and 4.3.5). The 21 PWR absorber plate waste package was conceputally intended for PWR fuel with k_∞ between 1.00 and 1.13, as calculated using the non-linear regression developed by Oak Ridge National Laboratory for a fuel age of 10 years (see Assumption 3.2). The second is a k_{eff}-based intact 21 PWR waste package loading curve developed more recently in Reference 7.17. To utilize this loading curve in this calculation, a multivariate regression of the same form utilized for the fully degraded settled oxide configuration at the end of Section 5.1.7 was performed for the calculated $k_{eff} + 2\sigma$ data from Reference 7.17 (Section 6). This calculation was performed in the "Intact LC" sheet of the Excel 97 spreadsheet "PWRprob.xlw". The results of the fit are shown below in Table 5.1.8-1. The adjusted R^2 for was 0.9973, which indicates a good fit to the data.

Table 5.1.8-1. Intact Waste Package k_{eff} Curve Regression Parameters

C_0	0.562224
C_1	-9.624E-03
C_2	0.245162
C_3	7.535E-05
C_4	-0.035960
C_5	-2.431E-07
C_6	2.272E-03

5.1.9 Frequency of PWR Waste Package Misload

Reference 7.16 examined the probability that any PWR waste package (no-absorber, absorber plate, or absorber rod) would be loaded with fuel that exceeds the loading curve for that package as a result of human or equipment error. The probability ranged from 5.8×10^{-5} per package to 6×10^{-6} per package (Ref. 7.16, Section 6), depending on the assumed loading procedures, for the conceptual k_∞-based loading curves from Reference 7.5. The upper bound of this range does not significantly change for the loading curves considered in this evaluation.

5.1.10 PWR Waste Stream Data

The specific commercial SNF assembly population data (burnup and enrichment) to consider for this calculation were identified in Reference 7.9 and have been developed based upon the best information available. However, it has not yet been qualified. The specific electronic data file used from Reference 7.9 is the uncompressed C1_WSM.ZIP, with only the information on the historic and projected PWR population used for this analysis. However, since the assembly receipt time information in the data file is not being used, any of the files for scenarios C1 through C8 from Reference 7.9 could be used because the burnup and enrichment information does not change. Figure 5.1.10-1 graphically shows the burnup/enrichment distribution of the historical and projected PWR waste stream, and indicates the general coverage of the intact and degraded loading curves (burnup/enrichment pairs below any given load curve would be considered unacceptable for placement in an absorber plate WP, and would be placed in a control rod WP).

5.1.11 Waste Package Data

Intact and degraded waste package data used in this calculation are summarized in Table 5.1.11-1. All of the data was obtained from Reference 7.4 to maintain consistency with the input used to develop the k_{eff} regressions presented in Section 5.1.7. However, it may slightly differ from more recent information on the current 21 PWR absorber plate waste package drawings, and thus should be considered unqualified data.

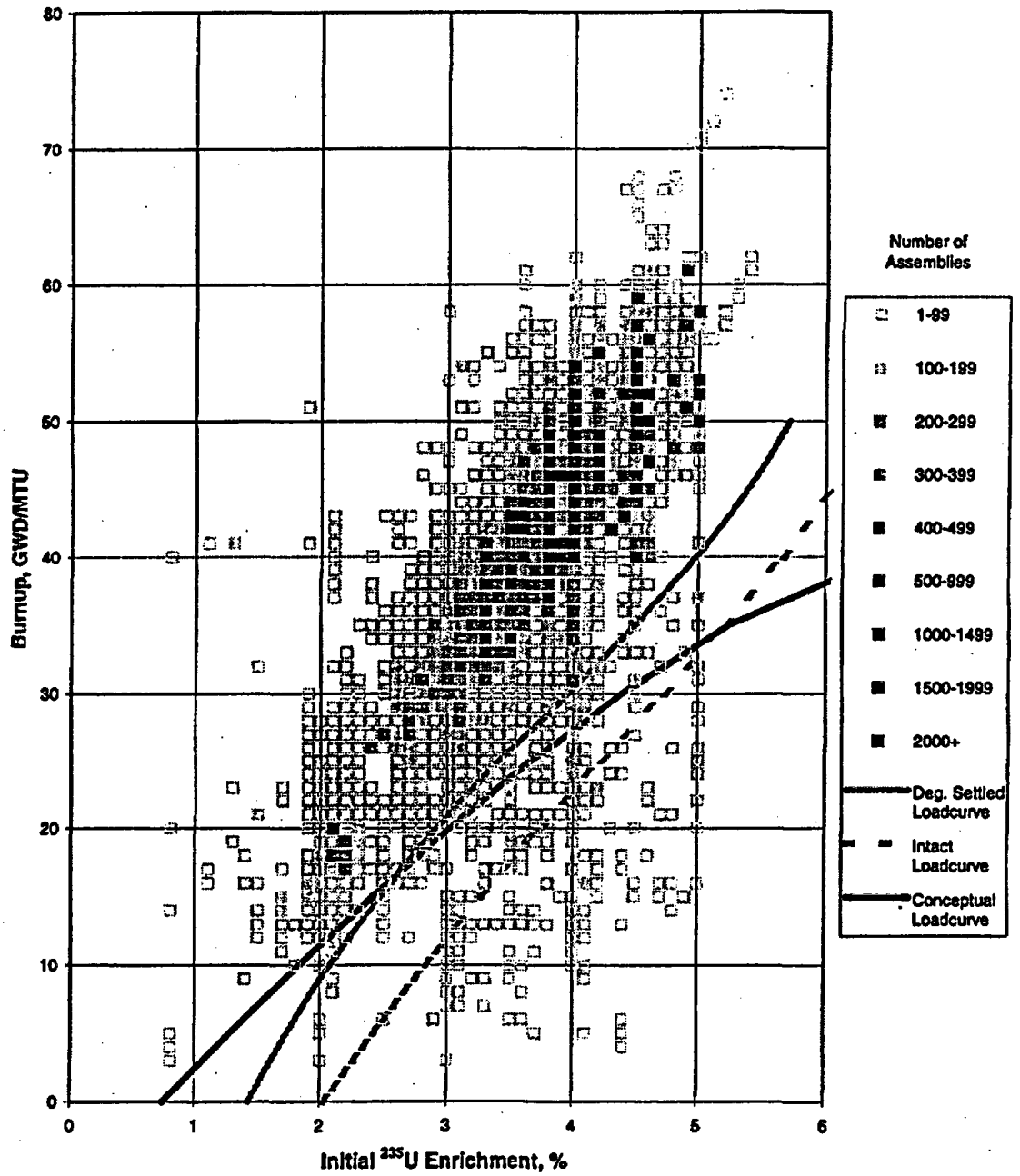


Figure 5.1.10-1. Possible Absorber Plate WP Loading Curves Plotted Against the Burnup/Enrichment Distribution of the Historical and Projected PWR Waste Stream

Table 5.1.11-1. Intact and Degraded Waste Package Data

Parameter	Value	Reference
Intial absorber plate thickness	7 mm	Ref. 7.4, p. 7
Volume inside inner barrier minus volume of 21 PWR fuel assemblies (A)	5.457 m^3	Ref. 7.4, p. III-1
Total intact volume of carbon steel components	0.704 m^3	Ref. 7.4, p. III-1
Total volume of carbon steel degradation products (B)	1.481 m^3	Ref. 7.4, p. III-1
Total intact volume of B-SS components (C)	0.243 m^3	Ref. 7.4, p. III-1
Total volume of B-SS degradation products (D)	0.310 m^3	Ref. 7.4, p. III-1
Void in loaded WP with intact B-SS and degraded carbon steel	3.733 m^3	A - B - C
Volume change from intact to degraded B-SS	0.067 m^3	D - C
Fuel cell space occupied by carbon steel corrosion products for partially degraded basket (uniformly distributed volume % / settled fuel rod rows covered)	30% / 8	Ref. 7.4, p. 30
Fuel cell space occupied by B-SS corrosion products for partially degraded basket (uniformly distributed volume % / settled fuel rod rows covered)	10% / 2	Ref. 7.4, p. 30
Space occupied by corrosion products with fully degraded basket (uniformly distriubted volume% / settled assembly layers covered)	33% / 3.5	Ref. 7.4, p. 30

5.2 Description of Items Evaluated

The effects of the following parameters on the waste package criticality probability will be evaluated:

Subcritical Limit: The probability of exceeding a subcritical limit of 0.98 will be evaluated for each case. This takes into account the bias and uncertainty in the method of calculation used to develop the k_{eff} regressions as discussed in assumption 3.10 (the uncertainty in the regressions themselves are factored into the Monte Carlo calculation discussed in Section 5.3). In addition, a subcritical limit of 0.93 will also be evaluated for one case to allow consideration of the 5% administrative limit of 10CFR60.131(h).

WP Loading Curve: Four waste package loading strategies will be considered for this evaluation: 1) using the absorber plate waste package for the entire PWR waste stream (no loading curve case), 2) using the k_∞-based loading curves from Reference 7.5, 3) using the intact k_{eff}-based loading curve discussed in Section 5.1.8, and 4) using the degraded loading curve discussed at the end of Section 5.1.7.

Oxide Distribution: Both uniform and settled oxide distributions will be evaluated for the above loading curves.

5.3 Procedure

As discussed in Section 2, there are two scenarios which must be considered in calculating the probability that a PWR waste package will exceed a given subcritical limit at some time during the postclosure period: 1) breach, flooding, and internal degradation of a correctly loaded absorber plate waste package, and 2) breach and flooding of any type of waste package which was misloaded with fuel which exceeds the criticality design basis. To estimate probabilies for the above two scenarios, a simple deterministic mass-balance model has been developed (similar to that discussed in Reference 7.1) with a Monte Carlo front end to repeatedly sample the distributions presented in Section 5.1 to provide the input parameters. The commented BASIC source code for the Monte Carlo mass-balance model, PWRPROB, is provided in Attachment I and the environment in which it was run is discussed in Section 4.2. The functioning of the PWRPROB code is basically divided into three parts: 1) loading the problem input file and waste stream data, 2) sampling the environment and waste package degradation distributions for each Monte Carlo realization, and 3) performing the mass-balance to track internal degradation of the waste package for a given realization if the sampled parameters indicate the waste package may be capable of exceeding the subcritical limit. Figure 5.3-1 shows the overall flow of the program, including points at which information is output to one of the three output files created.

When the program is executed, the first operation performed is to load the user-specified input file. This input file conains all of the information on the probability distributions for repository environmental conditions and waste package degradation parameters. It also contains other information necessary for the problem such as the loading curves to be evaluated (if any), waste package physical parameters (voidspace, B-SS thickness, amounts of oxide formed from degradation of various components), oxide distribution to use (uniform or settled), number of realizations to perform, and time step size (in years) to use for the mass-balance. The format for this input file is provided in Table 5.3-1 in the form of a commented sample input. Input information is entered on lines beginning with "$#" (with the # specific to the type of information being entered as indicated on the sample input), comments are entered on lines beginning with "C", and tabular input data is entered on lines beginning with "T" (note that comments should not be placed between rows of tabular data). The input information must also be entered in certain positions on each line, as is indicated by brackets (e.g., [9-16]) in the comments of the sample input. As each line of the input file is read, the program assigns the information to the appropriate variables (see Attachment I for more detail). Once the input file has been read, the program opens the waste stream data file "Case1.wsm" (see Section 5.1.10) and stores the burnup, enrichment, and number of assemblies data for PWR assembly batches which fall within the specified loading curves for the absorber plate waste package and could have a k_{eff} > the subcritical limit - 0.02 if the

worst degraded configuration occurs at the time of the postclosure peak. The program then uses this information to calculate the fraction of the PWR waste stream meeting the loading criteria for the absorber plate waste package, and the fraction of PWR assemblies meeting the absorber plate loading criteria which could exceed the subcritical limit - 0.02.

Once the input file and waste stream data have been loaded and processed, the program performs the requested number of Monte Carlo realizations. For each realization, the distributions given in Section 5.1 are sampled to determine if the waste package is subject to conditions which may allow it to exceed the subcritical limit. These conditions are: 1) the WP is under a drip, 2) water accumulates in the WP (bathtub), and 3) the WP contains fuel which could exceed the subcritical limit - 0.02. The methods for sampling the probability distributions were obtained from Reference 7.11(p. I-32) for the Weibull, and Reference 7.3 (Chapter 5) for the Normal, Uniform, and Beta. In a given realization, if all of the above three conditions are met, additional probability distributions are sampled to determine parameters used in the mass balance (e.g., the time of breach, the duration of flooding, the corrosion rate of the borated stainless steel) and the mass-balance is run for that realization. If one of the three conditions is not met, the package is considered not to have exceeded the subcritical limit, and the next realization is begun.

Figure 5.3-2 shows the flow of the mass-balance portion of the calculation. The starting time for internal degradation is taken to be the time of waste package breach, and the waste package is assumed to be instantaneously flooded with all of the carbon steel components degraded (see assumption 3.6). For each timestep, the parameters tracked are the thickness of borated stainless steel remaining between the assemblies, the amount and physical distribution of the corrosion products remaining in the package, and the amount of boron in solution (used for the settled case only). The k_{eff} regressions provided in Section 5.1.7 are used at each timestep to calculate k_{eff} for each batch of assemblies for which burnup and enrichment were stored, and the fraction of the total stored assemblies which would exceed the subcritical limit at the given timestep and degree of degradation is determined. If the fraction reaches a value that is randomly sampled from a uniform distribution between 0 and 1 for that realization, the waste package will be considered to have exceeded the subcritical limit, the time that this occurs will be recorded in an output file, and the next realization will begin. If the fraction does not exceed the limit before the waste package drains, then the waste package will be considered to not have exceeded the subcritical limit, and the next realization will begin. Once the user specified number of realizations has been completed, program execution will terminate.

Three types of output files are produced by the PWRPROB code. All output files will have the same filename as the input file, but have different extensions. Each output file has the input file echoed at the beginning of the file. Files with a "sum" extension contain a summary of the pertinent information for each realization. This includes whether each of the three conditions discussed above is met, as well as the time of waste package breach, the duration of flooding (if any), and the time that the subcritical limt is exceeded (if this occurs).

If one of the conditions is not met, times for subsequent conditions will be reported as "-1" because they will not be sampled. Files with a "crt" extension contain the same information as the "sum" files, but only for those realizations in which the subcritical limit was exceeded. This is the primary output file used to obtain results for this calculation. Files with an "out" extension record the state of basket degradation at each time step and the fraction exceeding the subcritical limit for all realizations where the mass balance was performed.

For a given case, the cumulative probability of exceeding the subcritical limit for the absorber plate waste package as a function of time, P_{ap}, is calculated from the results reported in the "crt" file. The times that the subcritical limit was exceeded are simply arranged in ascending order and assigned a cumulative probability according to their order in the list divided by the total number of realiztions performed. Similarly, the cumulative probability that any waste package exceeds the subcritical limit as a result of misload, P_m, is conservatively determined using the information in the "sum" file. In this case, the breach times of all cases where flooding of any duration occured are arranged in ascending order and assigned a cumulative probability (P_f) according to their order in the list divided by the total number of realizations performed and multiplied by the probability of misload. The cumulative probability that a waste package exceeds the subcritical limit at time t is then computed by multiplying $P_{ap}(t)$ by the fraction of the PWR waste stream in the absorber plate waste package, and adding $P_m(t)$. This logic is graphically illustrated in Figure 5.3-3.

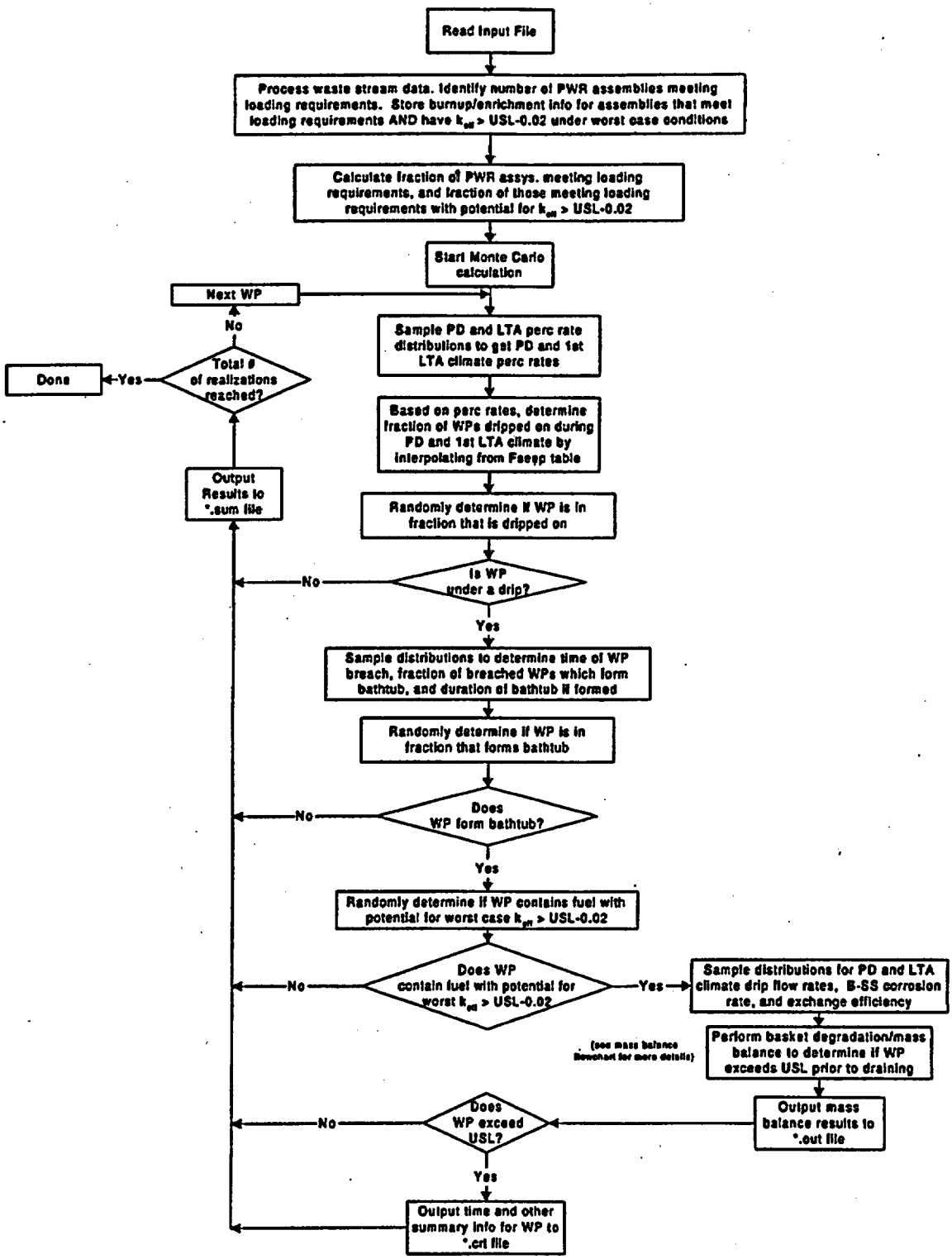


Figure 5.3-1. Flow Chart of Main Monte Carlo Module of PWRPROB Code

Table 5.3-1. Sample input file format for PWRPROB

```
C       TSPA-VA Rev 0 WAPDEG v3.06, Uniform Oxide, USL=0.93
C       Intact keff 0.93 upper load curve, kinf 1.00 lower load curve
C       BSS=7mm, No Additional CS
C
C       Parameters not defined by probability distributions [9-24 unless noted]
$5      7                 'BSS thickness in mm
$6      3.733             'void space in m^3 in loaded 21 PWR w/ intact BSS and degraded CS
$7      0.067             'delta between intact and degraded BSS volume in m^3
C       Oxide amounts (part basket CS [9-19], part basket SS [20-29], fully deg. [30-39])
$8      30        10        33        'uniform oxide
$9      8         2         3.5       'settled oxide
C
$10     0                 'Oxide Distribution (1=settled,0=uniform)
$11     0.93              'Subcritical limit keff value
$12     100000            'number of realizations
$13     Y                 'use upper loading curve [9-9]
$14     0.93              'limiting value for upper loading if upper load curve used
$15     Y                 'use lower loading curve [9-9]
$16     1.00              'limiting value for lower loading if lower load curve used
$17     -1                'random number generator seed (-1 = seed from clock)
$18     AP                'WP type to evaluate (NA,AP,CR,ALL)
$19     1000               'time increment in years to use in degradation steps
C
C       Upper loading curve parameters  [9-24 unless noted]
C
$20     0.562224          ' loading curve parameter 1 (constant)
$21     -9.624E-03        ' loading curve parameter 2 (b)
$22     0                 ' loading curve parameter 3 (t)
$23     0.245162          ' loading curve parameter 4 (e)
$24     7.535E-05         ' loading curve parameter 5 (b^2)
$25     0                 ' loading curve parameter 6 (t^2)
$26     -0.035960         ' loading curve parameter 7 (e^2)
$27     0                 ' loading curve parameter 8 (b*e)
$28     0                 ' loading curve parameter 9 (b*t)
$29     0                 ' loading curve parameter 10 (e*t)
$30     0                 ' loading curve parameter 11 (b*e*t)
$31     -2.431E-07        ' loading curve parameter 12 (b^3)
$32     2.272E-03         ' loading curve parameter 13 (e^3)
C
C       Lower loading curve parameters  [9-24 unless noted]
C
$34     1.06              ' loading curve parameter 1 (constant)
$35     -.01              ' loading curve parameter 2 (b)
$36     -.002             ' loading curve parameter 3 (t)
$37     .114              ' loading curve parameter 4 (e)
$38     7.081E-05         ' loading curve parameter 5 (b^2)
$39     7.565E-05         ' loading curve parameter 6 (t^2)
$40     -.007             ' loading curve parameter 7 (e^2)
$41     -.0002671         ' loading curve parameter 8 (b*e)
$42     -.0001145         ' loading curve parameter 9 (b*t)
$43     .0002318          ' loading curve parameter 10 (e*t)
$44     9.366E-06         ' loading curve parameter 11 (b*e*t)
$45     0                 ' loading curve parameter 12 (b^3)
$46     0                 ' loading curve parameter 13 (e^3)
C
C       Parameters defined by probability distributions
C
C       Water flow (requires Qseep table, Fseep table, & climate params.)
C
C       Qseep Table
C       (drip rate of water onto WP under drip in m^3/yr as a function of
C       perc rate in mm/yr)
C       Table order: perc. rate [9-16], mean qseep [17-24], std. dev. qseep [25-32],
C       max qseep [33-40]
$50     8                 ' number of parameters in Qseep table [9-10]
T       0       0       0       0
T       2.2     0       0       0
T       3.9     0.0123  0.0111  0.123
T       9.2     0.0124  0.0112  0.124
T       14.6    0.0402  0.0364  0.404
T       73.2    0.361   0.352   3.88
T       213     1.54    1.38    15.3
T       500     4.5     3.77    42.2
```

```
C
C       Fseep Table
C       (fraction of WPs getting dripped on as a function of perc rate in mm/yr)
C       Table order: perc. rate [9-16], mean fseep [18-24], std. dev. fseep [25-32]
C
$51     9                 ' number of parameters in Fseep table [9-10]
T       0       0         0
T       2.2     0         0
T       3.9     0.00844   0.0144
T       9.2     0.0462    0.0785
T       14.6    0.167     0.283
T       73.2    0.403     0.427
T       213     0.59      0.398
T       500     0.743     0.386
T       980     1         0
C
C       Format for remainder unless otherwise noted:
C       Distribution [9-10], parameter 1 [15-24], parameter 2 [25-34], parameter 3 [35-44]
C       The following cumulative distributions may be used for sampling:
C       F=Fixed at parameter 1 value, U = uniform between parameters 1 & 2, LU=log uniform,
C       W=Weibul with parameters 1,2,&3 as α,β,&θ, LW=log Weibul, NW=reversed Weibul with θ as
C       maximum, N-Normal with parameters 1 & 2 as μ & σ
C
C       Climate Model
C
$52     U       0         10000       'Duration of current PD climate
$53     F       100000     'Climate cycle duration (PD&LTA or SP&LTA)
C
C       Prob. that non-LTA climate is PD [9-24]
$54     0.75
C
C       Present Day (PD) Percolation Rate (mm/yr)
$55     U       0         20000       ' Subsequent cycle duration (years)
$56     W       7.900     1.898     0.5         'Distribution
C
C       Long Term Average (LTA) Perc Rate (mm/yr)
$57     W       36.881    2.270     7.5         'Distribution
C
C       Super Pluvial (SP) Perc Rate (mm/yr)
$58     W       115.505   2.119     10          'Distribution
C
C       Use Late Drip Distributions (Y/N)? [9-10]
$59     N
C
C       Early Drip WP breach time (years since emplacement)
$60     LW      12.099    16.425    0           'Distribution
C
C       Probability of no bathtub for early drip
$61     F       0.5225
C
C       Early Drip duration of WP flooding (years since breach)
$62     LW      10.849    8.228     0           'Distribution
C
C       Late Drip WP breach time (years since emplacement)
$64     LW      12.099    16.425    0           'Distribution
C
C       Probability of no bathtub for late drip
$65     F       0.5225
C
C       Late Drip duration of WP flooding (years since breach)
$66     LW      10.849    8.228     0           'Distribution
C
C       Exchange efficiency
$70     F       0.1                             'Distribution
C
C       SS corrosion rate in mm/yr
$72     NW      4.852     4.041     4.605       'Distribution
C
C       Boron factor
$74     U       1         4                     'Distribution
```

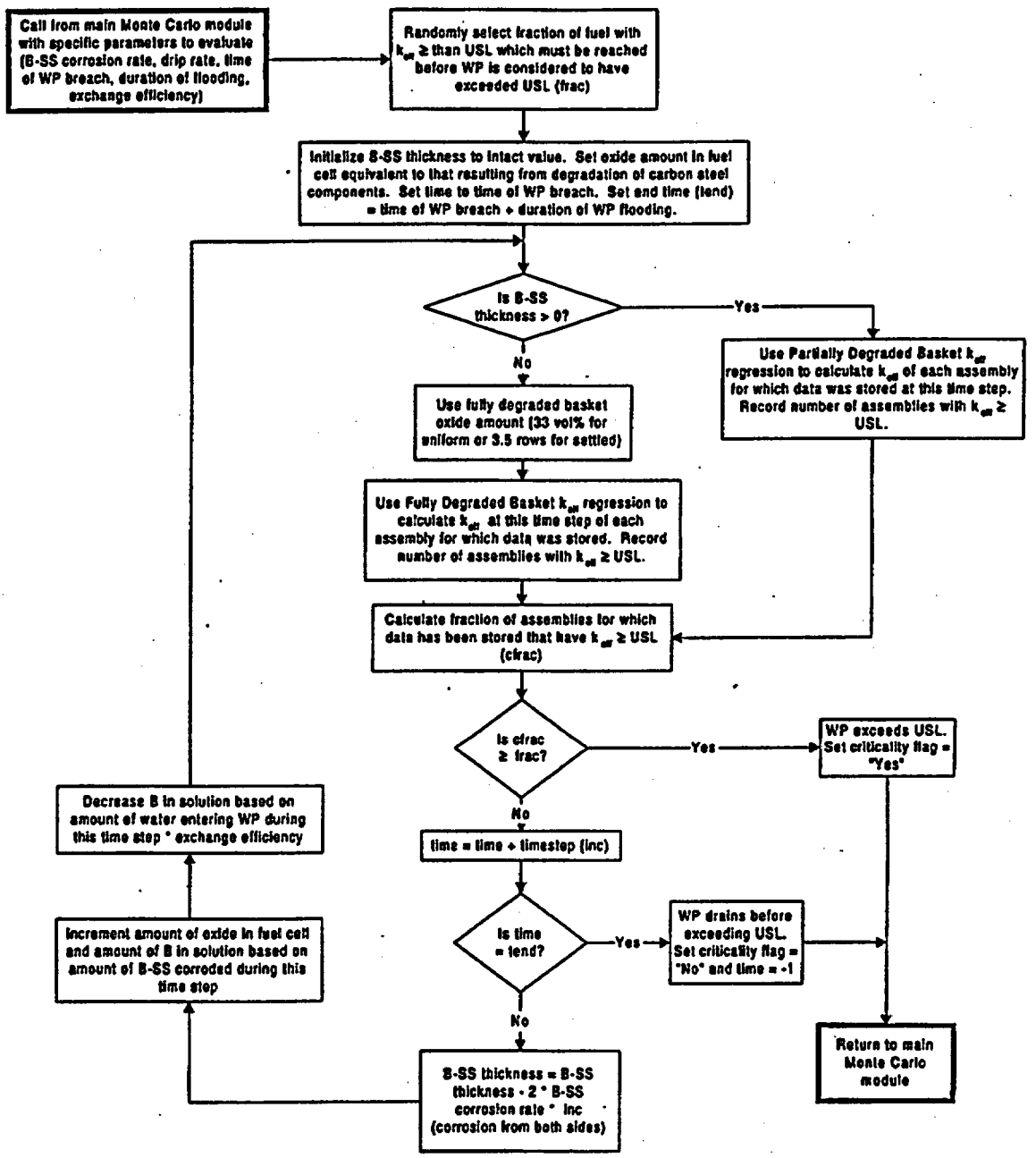


Figure 5.3-2. Flow Chart of Mass-Balance Module of PWRPROB Code

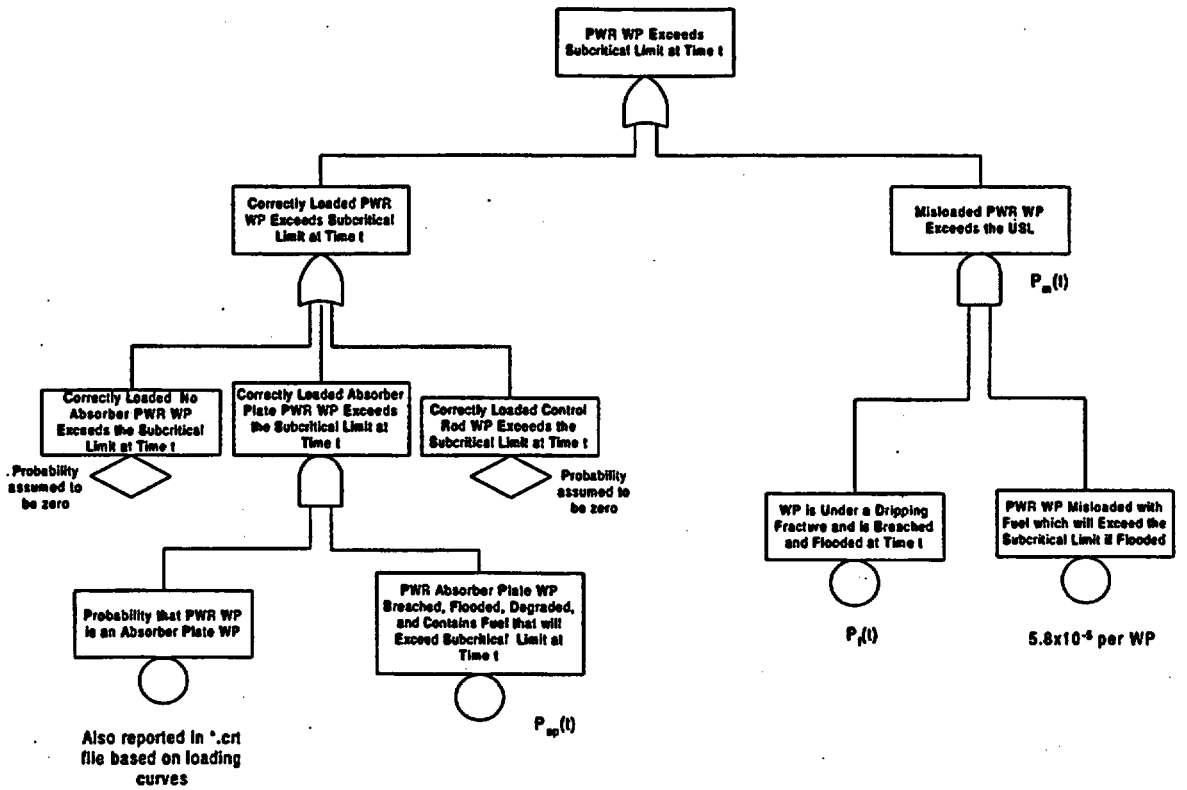


Figure 5.3-3. Logic for Estimating Cumulative Probability of Exceeding the Subcrital Limit Using Monte Carlo Simulation Output and WP Misload Probability

6. Results

For each of the cases discussed in Section 5.2, 1,000,000 realizations were performed, and the results processed as discussed in Section 5.3. Figure 6-1 shows the results for the uniform oxide distribution with a subcritical limit of 0.98 for each of the four loading strategies discussed. The PWRPROB input and output files for these cases (see Section 8 for the location of these files) are labeled as follows: caseC1.* = no loadcurve case; caseC2.* = conceptual loadcurve case; caseC3.* = intact loadcurve case. The degraded loadcurve case includes only the contribution from misload, as discussed in Section 5.3. A specific case for the degraded loadcurve was not run because it would not have resulted in any packages exceeding the limit due to degradation of the absorber plates. To provide some perspective on the cumulative probabilities indicated, the point at which the per waste package probability reaches a value where one package would be expected to have exceeded the subcritical limit has been indicated. This point is based on CDA Key Assumption 003 (Ref. 7.15) which indicates that a total of 4,792 PWR waste packages would be emplaced (from Ref. 7.5, Table 3-9; 155 + 1,454 + 2,653 + 132 + 398 = 4,792). Figure 6-2 shows the results for the settled oxide distribution at a subcritical limit of 0.98. The PWRPROB input and output files for these cases (see Section 8 for the location of these files) are labeled as follows: caseA1.* = no loadcurve case; caseA2.* = conceptual loadcurve case; caseA3.* = intact loadcurve case. Figure 6-3 shows the results for the uniform oxide distribution at a subcritical limit of 0.93. The PWRPROB input and output files for these cases (see Section 8 for the location of these files) are labeled as follows: caseD1.* = no loadcurve case; caseD2.* = conceptual loadcurve case; caseD3.* = intact loadcurve case. Table 6-1 presents the average frequency (probability per package-year) of exceeding the subcritical limit for various loading strategies, subcritical limit values, and oxide distributions. Since this frequency is time dependent, it has been calculated (in the Results sheet of the Excel 97 spreadsheet PWRPROB.xlw) for various time periods by taking the slope of the cumulative probability distribution for those times.

Two calculations were also performed using Mathcad 7 to check that the PWRPROB Monte Carlo code was providing correct output. These calculations are reported in Attachment IV. First, the fully degraded basket k_{eff} regressionwas utilized, along with the waste stream data, to calculate the fraction of the waste stream which would exceed a k_{eff} of 0.98 in a fully degraded basket with oxide uniformly distributed at 33 vol%. The results are shown in the Figure on page 2 of Attachment IV. A similar case was run for one realization using the PWRPROB code and fixed value inputs, and the results are provided Figure 6-4 (plotted from the Ufrac.out file). Figure 6-4 provides nearly identical results to those in Attachment IV following full degradation of the basket, which occured by approximately 20,000 years in this case. This indicates that the PWRPROB code is correctly utilizing the waste stream data and k_{eff} regressions. An additional check of the cumulative probability of exceeding 0.98 k_{eff} for a uniform oxide distribution at 100,000 years for a no loading curve case was also performed in Attachment IV, based on mean values from the probability distributions in Section 5.1. The cumulative probability was estimated to be approximately 8×10^{-4} per PWR WP, which agrees very closely with the Monte Carlo result presented in Figure 6-1.

Table 6-1. Average Frequency (per package-year) of Exceeding Subcritical Limit for Various Subcritical Limits, Loading Strategies, Oxide Distributions, and Time Since Emplacement

Case	Time (years since emplacement)	Loading Strategy			
		No Loadcurve	Conceptual Loadcurve	Intact Loadcurve	Degraded Loadcurve
Uniform Oxide USL= 0.98	0 to 5,000	< 2.0E-12	1.6E-12	1.6E-12	1.6E-12
	5,000 to 10,000	1.4E-10	7.3E-12	7.3E-12	7.3E-12
	10,000 to 50,000	3.8E-09	4.7E-11	9.7E-10	2.5E-11
	50,000 to 100,000	6.7E-09	4.5E-11	6.2E-10	3.2E-11
	100,000 to 500,000	2.8E-09	5.3E-11	2.6E-10	1.3E-11
	500,000 to 1,000,000	1.6E-10	2.1E-11	7.8E-11	3.1E-13
Uniform Oxide USL=0.93	0 to 5,000	< 2.0E-12	1.6E-12	1.6E-12	1.6E-12
	5,000 to 10,000	1.4E-10	6.6E-11	2.2E-10	7.3E-12
	10,000 to 50,000	8.0E-09	1.8E-09	3.5E-09	2.5E-11
	50,000 to 100,000	1.2E-08	2.1E-09	5.4E-09	3.2E-11
	100,000 to 500,000	4.6E-09	8.2E-10	2.1E-09	1.3E-11
	500,000 to 1,000,000	2.5E-10	9.6E-11	1.7E-10	3.1E-13
Settled Oxide USL=0.98	0 to 5,000	< 2.0E-12	1.6E-12	1.6E-12	1.6E-12
	5,000 to 10,000	3.3E-10	1.1E-10	8.3E-11	7.3E-12
	10,000 to 50,000	5.8E-09	9.8E-10	2.4E-09	2.5E-11
	50,000 to 100,000	1.1E-08	1.3E-09	3.9E-09	3.2E-11
	100,000 to 500,000	4.0E-09	5.6E-10	1.6E-09	1.3E-11
	500,000 to 1,000,000	2.0E-10	2.4E-11	7.4E-11	3.1E-13

Since unqualified inputs were used in the development of the results presented in this section, they should be considered TBV (to be verified). This document will not directly support any construction, fabrication or procurement activity, and therefore, the inputs and results are not required to be procedurally controlled as TBV. However, use of any data from this analysis for input into documents supporting procurement, fabrication, or construction is required to be controlled as TBV in accordance with appropriate procedures.

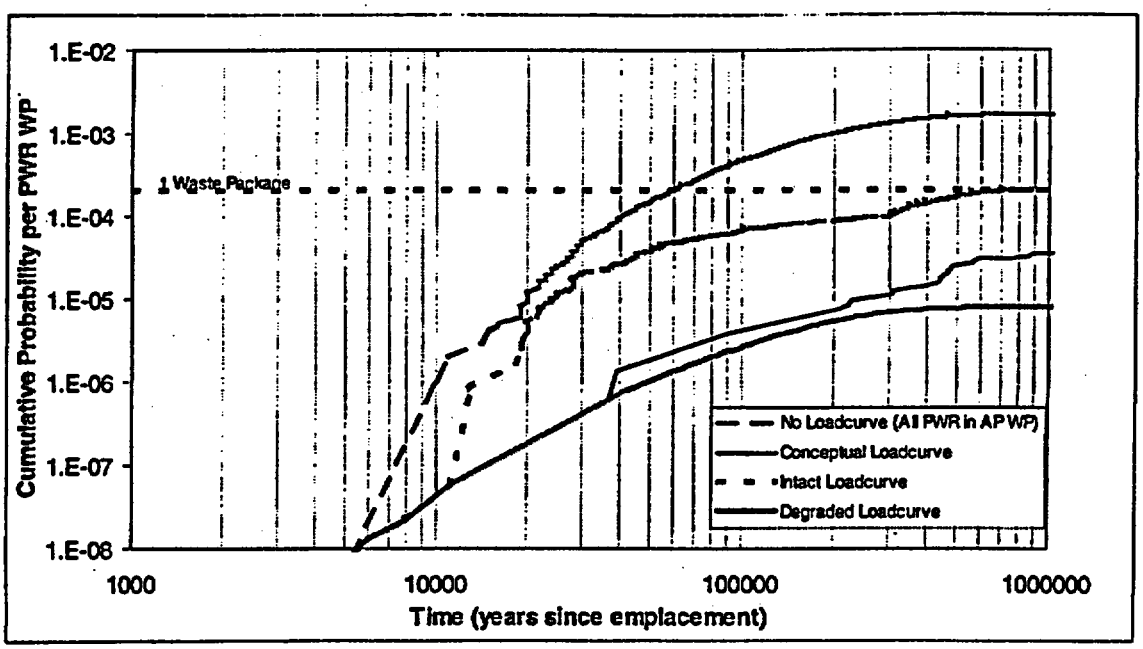


Figure 6-1. Probability of a PWR WP Exceeding a Subcritical Limit of 0.98 with a Uniform Oxide Distribution

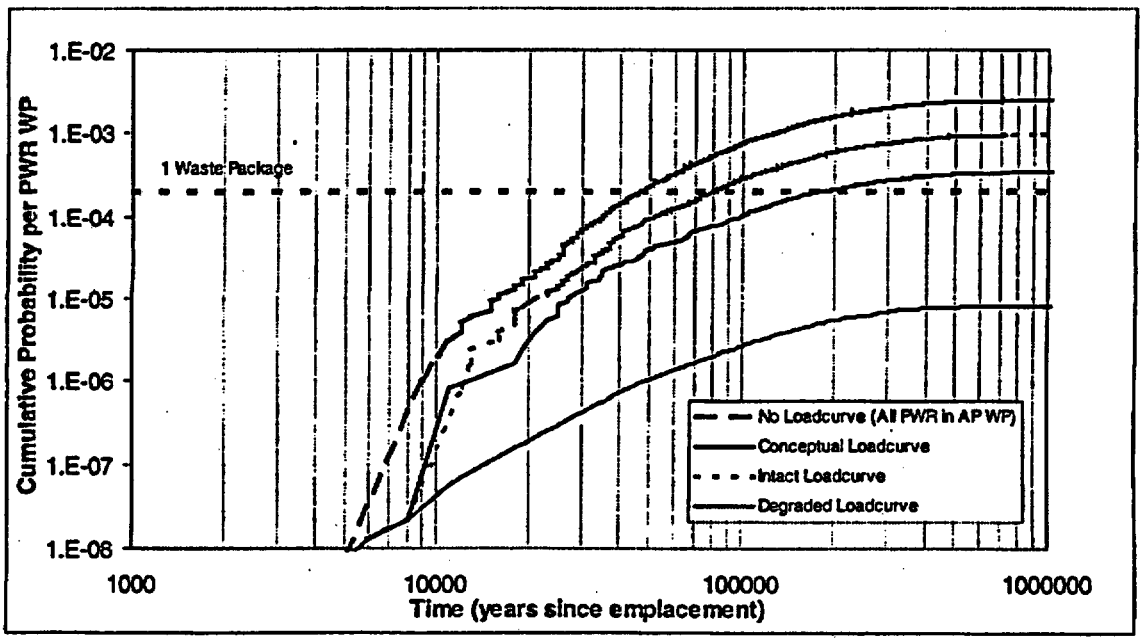


Figure 6-2. Probability of a PWR WP Exceeding a Subcritical Limit of 0.98 with a Settled Oxide Distribution

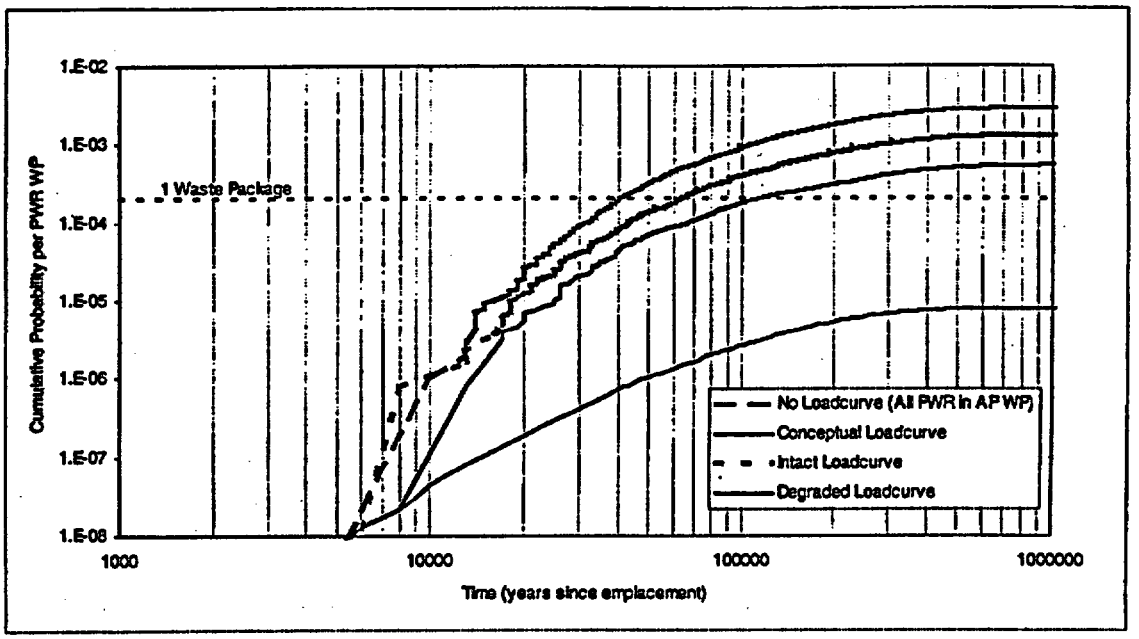


Figure 6-3. Probability of a PWR WP Exceeding a Subcritical Limit of 0.93 with a Uniform Oxide Distribution

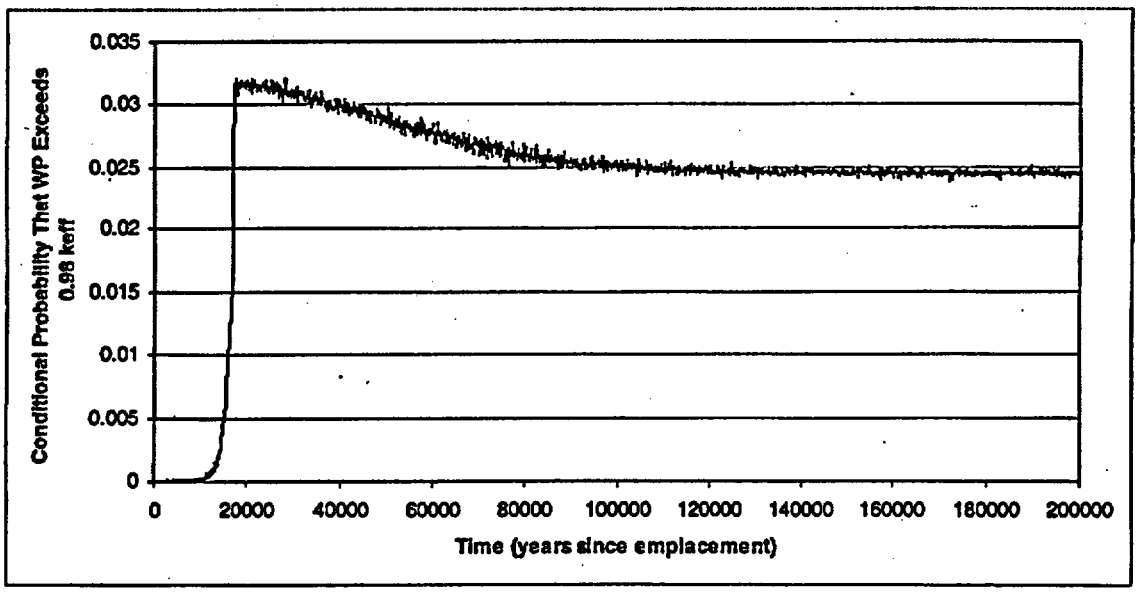


Figure 6-4. Fraction of PWR Waste Stream Which Would Exceed k_{eff} of 0.98 in an Absorber Plate Waste Package

7. References

7.1 *3rd Waste Package Probabilistic Criticality Analysis: Methodology for Basket Degradation with Application to Commercial Spent Nuclear Fuel*, Document Identifier Number (DI#): BBA000000-01717-0200-00049 REV 00, Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O). MOL.19980116.0070.

7.2 *Reactivity and Isotopic Composition of Spent PWR Fuel as a Function of Initial Enrichment, Burnup, and Cooling Time*, ORNL/CSD/TM-244, Oak Ridge National Laboratory, October 1987. TIC 224481.

7.3 Morgan, M.G., Henrion, M., Small, M., *Uncertainty – A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*, International Standard Book Number (ISBN) 0-521-36542-2, Cambridge University Press, 1990. TIC 238185

7.4 *Criticality Evaluation of Degraded Internal Configurations for the PWR AUCF Waste Package Designs*, DI#: BBA000000-01717-0200-00056 REV 00, CRWMS M&O. MOL.19971231.0251.

7.5 *Determination of WP Design Configurations*, DI#: BBAA00000-01717-0200-00017 REV 00, CRWMS M&O. MOL.19970805.0310.

7.6 *Mined Geologic Disposal System Advanced Conceptual Design Report, Volume III of IV, Engineered Barrier Segment/Waste Package*, DI#: B00000000-01717-5705-00027 REV 00, CRWMS M&O. MOL.19960826.0096.

7.7 *Preliminary Draft Chapter of the Unsaturated Zone Flow Abstraction for TSPA-VA*, Interoffice Correspondence (IOC) #: LV.PA.RWA.02/98-041, CRWMS M&O, February 20, 1998. MOL.19980428.0202

7.8 Modarres, M., *What Every Engineer Should Know About Reliability and Risk Analysis*, ISBN 0-8247-8958-X, Marcel Dekker, Inc., 1993. TIC 238168.

7.9 *Input Files and Models Used in the Waste Quantity, Mix and Throughput Study*, IOC#: VA.SAI.MF.03/97.007, CRWMS M&O, March 21, 1997. MOL.19970811.1264.

7.10 *Final Design Package - Babcock & Wilcox BR-100 - 100 Ton Rail/Barge Spent Fuel Shipping Cask*, Document No. 51-1203400-01, B&W Fuel Company, November 1991. MOV.19960802.0081.

7.11 *Initial Waste Package Probabilistic Criticality Analysis: Uncanistered Fuel*, DI#: B00000000-01717-2200-00079 REV 01, CRWMS M&O. MOL.19960422.0336.

7.12 *Software Routine Report for WAPDEG (Version 3.06)*, DI#: 30048-2999 REV 00, CRWMS M&O. MOL.19980609.0061.

7.13 *Material Compositions and Number Densities for Neutronics Calculations*, DI#: BBA000000-01717-0200-00002 REV 00, CRWMS M&O. MOL.19960624.0023.

7.14 *Waste Package Materials Selection Analysis*, DI#: BBA000000-01717-0200-00020 REV 01, CRWMS M&O. MOL.19980324.0242.

7.15 *Controlled Design Assumptions Document*, DI#: B00000000-01717-4600-00032 REV 05, CRWMS M&O. MOL.19980804.0481.

7.16 *Frequency of SNF Misload for Uncanistered Fuel Waste Packages*, DI#: BBA000000-01717-0210-00011 REV 00, CRWMS M&O. MOL.19980806.0604

7.17 *Principle Isotope Burnup Credit Loading Curves for the 21 PWR Waste Package*, DI#: BBA000000-01717-0210-00008 REV 00, CRWMS M&O. MOL.19980825.0003.

7.18 *EQ6 Calculations for Chemical Degradation of PWR Spent Fuel Waste Packages*, DI#: BBA000000-01717-0210-00009 REV 00, CRWMS M&O. MOL.19980701.0483

7.19 *Second Waste Package Probabilistic Criticality Analysis: Generation and Evaluation of Internal Criticality Configurations*, DI#: BBA000000-01717-2200-00005 REV 00, CRWMS M&O. MOL.19960924.0193.

7.20 *Information on Plugging of Pits by Corrosion Products*, IOC#: LV.WP.JRM.2/96.048, CRWMS M&O, February 29, 1996. MOL.19960813.0012.

7.21 *Year-end Status Report on Design Basis Models*, DI#: B00000000-01717-5703-00006 REV 00, CRWMS M&O. MOL.19980127.0257

7.22 *Electronic Files for BBA000000-01717-0210-00010 REV 00*, Colorado Trakker tape,CRWMS M&O. MOL.19980803.0617.

7.23 *Borated Stainless Steel Application in Spent-fuel Storage Racks*, EPRI TR-100784, Electric Power Research Institute (EPRI), June 1992. TIC 225730.

7.24 *Calculation of Subcritical Limits for Nuclear Criticality in a Repository*, DI#: B00000000-01717-0210-00027 REV 00, CRWMS M&O. MOL.19980729.0420.

8. Attachments

Attachments are listed in Table 8-1 below.

Table 8-1. List of Attachments

Attachment Number	Description	Size
I	Source code for PWRPROB.BAS	18 pp.
II	E-mail update of seepage fraction and drip rate models for TSPA-VA	2 pp.
III	E-mail transmitting WAPDEG v3.06 output files	1 p.
IV	Independent Mathcad 7 check of PWRPROB.BAS (PWRprob.mcd)	3 pp.

The following supporting documents are in electronic form on a Colorado Trakker® tape (Ref. 7.25). Each file is identified by it's name, size (in bytes), and the date and time of last access.

DOS Filename		Byte Size	Date	Time	WIN95 Filename
case1	wsm	8,742,952	02-12-97	6:58p	case1.wsm
CASEA1	CRT	246,182	07-25-98	1:44p	CASEA1.CRT
casea1	inp	5,732	06-19-98	3:42p	casea1.inp
CASEA1	OUT	19,525,217	07-25-98	1:44p	CASEA1.OUT
CASEA1	SUM	18,945,451	07-25-98	1:44p	CASEA1.SUM
CASEA2	CRT	50,381	07-26-98	2:25a	CASEA2.CRT
casea2	inp	5,736	06-19-98	3:42p	casea2.inp
CASEA2	OUT	19,741,980	07-26-98	2:25a	CASEA2.OUT
CASEA2	SUM	18,929,610	07-26-98	2:25a	CASEA2.SUM
CASEA3	CRT	126,591	07-26-98	8:35p	CASEA3.CRT
casea3	inp	5,779	06-19-98	3:43p	casea3.inp
CASEA3	OUT	21,868,374	07-26-98	8:35p	CASEA3.OUT
CASEA3	SUM	18,869,117	07-26-98	8:35p	CASEA3.SUM
CASEC1	CRT	168,956	06-20-98	7:58a	CASEC1.CRT
caseC1	inp	5,732	06-19-98	3:00p	caseC1.inp
CASEC1	OUT	6,728,377	06-20-98	7:58a	CASEC1.OUT
CASEC1	SUM	19,789,711	06-20-98	7:58a	CASEC1.SUM
CASEC2	CRT	9,603	06-20-98	1:57a	CASEC2.CRT
caseC2	inp	5,736	06-19-98	3:01p	caseC2.inp
CASEC2	OUT	4,079,724	06-20-98	1:57a	CASEC2.OUT
CASEC2	SUM	19,947,710	06-20-98	1:57a	CASEC2.SUM
CASEC3	CRT	31,980	06-20-98	2:31a	CASEC3.CRT
caseC3	inp	5,779	06-19-98	3:02p	caseC3.inp
CASEC3	OUT	6,486,542	06-20-98	2:31a	CASEC3.OUT
CASEC3	SUM	19,859,265	06-20-98	2:31a	CASEC3.SUM
CASED1	CRT	285,708	07-22-98	7:12a	CASED1.CRT
caseD1	inp	5,731	06-19-98	12:03p	caseD1.inp
CASED1	OUT	17,256,919	07-22-98	7:12a	CASED1.OUT
CASED1	SUM	18,944,059	07-22-98	7:12a	CASED1.SUM
CASED2	CRT	77,213	07-23-98	1:51a	CASED2.CRT

```
caseD2    inp          5,735  06-19-98 12:04p caseD2.inp
CASED2    OUT     16,005,730  07-23-98  1:51a CASED2.OUT
CASED2    SUM     18,881,435  07-23-98  1:51a CASED2.SUM
CASED3    CRT        175,234  07-24-98  6:04a CASED3.CRT
caseD3    inp          5,778  06-19-98 12:05p caseD3.inp
CASED3    OUT     19,071,747  07-24-98  6:04a CASED3.OUT
CASED3    SUM     18,869,382  07-24-98  6:04a CASED3.SUM
NESFAD~1  OUT        105,830  02-28-98  3:11p nesfad100mh.out
outs306   zip        282,128  03-18-98  1:29p outs306.zip
pwr       prn      1,428,632  12-06-97  8:52p pwr.prn
PWRprob   bas         55,202  07-21-98  3:13p PWRprob.bas
PWRprob   mcd         18,456  07-16-98 10:16a PWRprob.mcd
PWRprob   xlw      2,669,568  07-27-98  6:23p PWRprob.xlw
SCSFAD~1  OUT        105,440  02-28-98  3:13p scsfad100mh.out
UFRAC     CRT          5,755  07-17-98  5:33p UFRAC.CRT
Ufrac     inp          5,701  07-15-98 11:26a Ufrac.inp
UFRAC     OUT        108,814  07-17-98  5:33p UFRAC.OUT
UFRAC     SUM          6,371  07-17-98  5:33p UFRAC.SUM
        48 file(s)    318,558,785 bytes
```

```
DECLARE FUNCTION InvNorm! (mean!, stdev!)
DECLARE FUNCTION InvBeta! (min!, mean!, stdev!, max!)
DECLARE FUNCTION Fseep! (perc!)
DECLARE FUNCTION Qseep! (perc!)
DECLARE FUNCTION Sample! (Dist$, param1!, param2!, param3!)
DECLARE SUB SetDeg (time, frac, pfrac, ptime)
DECLARE SUB UniDeg (time, frac, pfrac, ptime)
DECLARE FUNCTION InvUni! (min!, max!)
DECLARE FUNCTION InvWeib! (alpha!, beta!, theta!)
DECLARE FUNCTION Flow! (t!)
DECLARE FUNCTION FullCfrac! (D!, t!, O!, b!, limit!)
DECLARE FUNCTION PartCfrac! (D!, t!, O!, th!, b!, limit!)
DECLARE FUNCTION BPart! (b!, th!, O!)
DECLARE FUNCTION BFull! (b!)
DECLARE FUNCTION kFullDeg! (D!, a!, b!, t!, O!)
DECLARE FUNCTION kPartDeg! (D!, a!, b!, t!, O!, th!)
'
' initialize arrays
'
' $DYNAMIC
DIM numassy(2000)    ' number of assemblies in batch
DIM enrich(2000)     ' batch average enrichment
DIM burnup(2000)     ' batch average burnup in MWd/MTU
CLS
'
' Initialize variables
'
n = 0                  ' counter for number of assembly batch records loaded
count = 0              ' counter for number of records read from waste stream file
totassy = 0            ' number of PWR assemblies in this WP that exceed limit-.02
totpwr = 0             ' total number of PWR assemblies in waste stream
BSSthick = 7           ' initial thickness of BSS plate
BSSvol = .067          ' delta between intact and degraded BSS vol. in m^3
Bwp = 30110 * .199     ' total mass of B-10 per WP in grams
Void = 4.511 - .777    ' void space in m^3 in loaded 21 PWR w/ intact BSS and degraded carbon steel components
UCSox = 30             ' partial basket CS tube uniform oxide vol% (dist. in assy. void only)
UBSSox = 10            ' partial basket BSS plate uniform oxide vol% (dist. in assy. void only)
UFDox = 33             ' fully degraded basket uniform oxide vol% (dist. in WP void)
SCSox = 8              ' partial basket CS tube settled oxide rod rows covered (assy. void only)
SBSSox = 2             ' partial basket BSS plate settled oxide rod rows covered (assy. void only)
SFDox = 3.5            ' fully degraded basket settled oxide assy layers covered
seed = -1              ' seed from timer if not specified in input file
Lnum = 0               ' number of assemblies below lower loading limit
Mnum = 0               ' number of assemblies in this WP
Unum = 0               ' number of assemblies above upper loading limit
Lloadcurv$ = "N"       ' don't use lower loading curve if not specified in input file
Uloadcurv$ = "N"       ' don't use upper loading curve if not specified in input file
Lfrac = 0              ' fraction of PWR waste stream below lower loading limit
Ufrac = 0              ' fraction of PWR waste stream above upper loading limit
CMfrac = 0             ' fraction of fuel in this WP with peak keff exceeding limit - 0.02
WPtype$ = "AP"         ' type of WP to evaluate (NA = no abs., AP = abs. plate, CR = cont. rod, ALL = all)
inc = 100              ' time increment in years for degradation steps
Ldrip$ = "N"           ' use late drip distributions
'
' Read in user defined variables
'
IF COMMAND$ = "" THEN
        INPUT "Enter name of input file (leave off .inp extension)"; file$
```

```
ELSE
        file$ = COMMAND$
END IF
PRINT
PRINT "Loading input file"
PRINT
infile$ = file$ + ".inp"
OPEN infile$ FOR INPUT ACCESS READ AS #1
sumfile$ = file$ + ".sum"        'holds summary information for each realization
outfile$ = file$ + ".out"        'holds detailed output for each realization using mass balance
crtfile$ = file$ + ".crt"        'holds summary information for WPs which exceed limit
OPEN sumfile$ FOR OUTPUT ACCESS WRITE AS #2
OPEN outfile$ FOR OUTPUT ACCESS WRITE AS #3
OPEN crtfile$ FOR OUTPUT ACCESS WRITE AS #4
PRINT #2, "Run started at "; TIME$; " on "; DATE$
PRINT #3, "Run started at "; TIME$; " on "; DATE$
PRINT #4, "Run started at "; TIME$; " on "; DATE$
DO UNTIL EOF(1)
        LINE INPUT #1, Line$
        PRINT #2, Line$          'echo input file to output summary file
        PRINT #3, Line$          'echo input file to output detail file
        PRINT #4, Line$          'echo input file to output crit file
        linetype$ = LEFT$(Line$, 3)
        SELECT CASE linetype$
        '
        ' User defined parameters not defined by probability distributions
        '
        CASE "$5 "       ' BSS thickness in mm
            BSSthick = VAL(MID$(Line$, 9, 16))
        CASE "$6 "       'void space in m^3 in loaded 21 PWR w/ intact BSS & deg. CS
            Void = VAL(MID$(Line$, 9, 16))
        CASE "$7 "       ' sample size
            BSSvol = VAL(MID$(Line$, 9, 16))
        CASE "$8 "       ' uniform oxide vol% parameters
            UCSox = VAL(MID$(Line$, 9, 10))
            UBSSox = VAL(MID$(Line$, 20, 10))
            UFDox = VAL(MID$(Line$, 30, 10))
        CASE "$9 "       ' settled oxide coverage parameters
            SCSox = VAL(MID$(Line$, 9, 10))
            SBSSox = VAL(MID$(Line$, 20, 10))
            SFDox = VAL(MID$(Line$, 30, 10))
        CASE "$10"       ' distribution of oxides (0 for uniform, 1 for settled)
            D = VAL(MID$(Line$, 9, 16))
        CASE "$11"       ' keff threshold
            limit = VAL(MID$(Line$, 9, 16))
        CASE "$12"       ' sample size
            Samplesize = VAL(MID$(Line$, 9, 16))
        CASE "$13"       ' upper loading curve on/off switch
            Uloadcurv$ = MID$(Line$, 9, 1)
        CASE "$14"       ' upper loading curve limit
            Uloadlim = VAL(MID$(Line$, 9, 16))
        CASE "$15"       ' lower loading curve on/off switch
            Lloadcurv$ = MID$(Line$, 9, 1)
        CASE "$16"       ' lower loading curve limit
            Lloadlim = VAL(MID$(Line$, 9, 16))
        CASE "$17"       ' random number generator seed value (-1 = seed from clock)
            seed = VAL(MID$(Line$, 9, 16))
        CASE "$18"       ' random number generator seed value (-1 = seed from clock)
```

```
        WPtype$ = LTRIM$(RTRIM$(MID$(Line$, 9, 16)))
CASE "$19"        ' random number generator seed value (-1 = seed from clock)
        inc = VAL(MID$(Line$, 9, 16))
CASE "$20"        ' upper loading curve parameter 1 (constant)
        L1 = VAL(MID$(Line$, 9, 16))
CASE "$21"        ' upper loading curve parameter 2 (b)
        L2 = VAL(MID$(Line$, 9, 16))
CASE "$22"        ' upper loading curve parameter 3 (t)
        L3 = VAL(MID$(Line$, 9, 16))
CASE "$23"        ' upper loading curve parameter 4 (e)
        L4 = VAL(MID$(Line$, 9, 16))
CASE "$24"        ' upper loading curve parameter 5 (b^2)
        L5 = VAL(MID$(Line$, 9, 16))
CASE "$25"        ' upper loading curve parameter 6 (t^2)
        L6 = VAL(MID$(Line$, 9, 16))
CASE "$26"        ' upper loading curve parameter 7 (e^2)
        L7 = VAL(MID$(Line$, 9, 16))
CASE "$27"        ' upper loading curve parameter 8 (b*e)
        L8 = VAL(MID$(Line$, 9, 16))
CASE "$28"        ' upper loading curve parameter 9 (b*t)
        L9 = VAL(MID$(Line$, 9, 16))
CASE "$29"        ' upper loading curve parameter 10 (e*t)
        L10 = VAL(MID$(Line$, 9, 16))
CASE "$30"        ' upper loading curve parameter 11 (b*e*t)
        L11 = VAL(MID$(Line$, 9, 16))
CASE "$31"        ' upper loading curve parameter 12 (b^3)
        L12 = VAL(MID$(Line$, 9, 16))
CASE "$32"        ' upper loading curve parameter 13 (e^3)
        L13 = VAL(MID$(Line$, 9, 16))
CASE "$34"        ' lower loading curve parameter 1 (constant)
        LL1 = VAL(MID$(Line$, 9, 16))
CASE "$35"        ' lower loading curve parameter 2 (b)
        LL2 = VAL(MID$(Line$, 9, 16))
CASE "$36"        ' lower loading curve parameter 3 (t)
        LL3 = VAL(MID$(Line$, 9, 16))
CASE "$37"        ' lower loading curve parameter 4 (e)
        LL4 = VAL(MID$(Line$, 9, 16))
CASE "$38"        ' lower loading curve parameter 5 (b^2)
        LL5 = VAL(MID$(Line$, 9, 16))
CASE "$39"        ' lower loading curve parameter 6 (t^2)
        LL6 = VAL(MID$(Line$, 9, 16))
CASE "$40"        ' lower loading curve parameter 7 (e^2)
        LL7 = VAL(MID$(Line$, 9, 16))
CASE "$41"        ' lower loading curve parameter 8 (b*e)
        LL8 = VAL(MID$(Line$, 9, 16))
CASE "$42"        ' lower loading curve parameter 9 (b*t)
        LL9 = VAL(MID$(Line$, 9, 16))
CASE "$43"        ' lower loading curve parameter 10 (e*t)
        LL10 = VAL(MID$(Line$, 9, 16))
CASE "$44"        ' lower loading curve parameter 11 (b*e*t)
        LL11 = VAL(MID$(Line$, 9, 16))
CASE "$45"        ' lower loading curve parameter 12 (b^3)
        LL12 = VAL(MID$(Line$, 9, 16))
CASE "$46"        ' lower loading curve parameter 13 (e^3)
        LL13 = VAL(MID$(Line$, 9, 16))
'
' Parameters defined by probability distributions
```

```
'Qseep table for drip rate (m^3/yr) as a function of perc rate (mm/yr)
'
CASE "$50"
        numQ = VAL(MID$(Line$, 9, 2))  'length of Qseep table
        DIM Qperc(numQ), Qmean(numQ), Qsd(numQ), Qmax(numQ)
        FOR i = 1 TO numQ
                'Read in the Qseep table
                LINE INPUT #1, Line$
                PRINT #2, Line$          'echo input file to output summary file
                Qperc(i) = VAL(MID$(Line$, 9, 8))    'get perc rate
                Qmean(i) = VAL(MID$(Line$, 17, 8))   'get mean Qseep
                Qsd(i) = VAL(MID$(Line$, 25, 8))     'get std dev for Qseep
                Qmax(i) = VAL(MID$(Line$, 33, 8))    'get max Qseep
        NEXT i
'
'Fseep table for fraction of WP under drips as a function of perc rate
'
CASE "$51"
        numF = VAL(MID$(Line$, 9, 2))   'length of Fseep table
        DIM Fperc(numF), Fmean(numF), Fsd(numF)
        FOR i = 1 TO numF
                'Read in the Fseep table
                LINE INPUT #1, Line$
                PRINT #2, Line$          'echo input file to output summary file
                Fperc(i) = VAL(MID$(Line$, 9, 8))    'get perc rate
                Fmean(i) = VAL(MID$(Line$, 17, 8))   'get mean Qseep
                Fsd(i) = VAL(MID$(Line$, 25, 8))     'get std dev for Qseep
        NEXT i
CASE "$52"      ' Duration of current Present Day (PD) climate
        CPDdist$ = RTRIM$(MID$(Line$, 9, 2))
        CPDdur1 = VAL(MID$(Line$, 15, 10))
        CPDdur2 = VAL(MID$(Line$, 25, 10))
        CPDdur3 = VAL(MID$(Line$, 35, 10))
CASE "$53"      ' Climate cycle duration (PD&LTA or SP&LTA)
        CCdist$ = RTRIM$(MID$(Line$, 9, 2))
        CCdur1 = VAL(MID$(Line$, 15, 10))
        CCdur2 = VAL(MID$(Line$, 25, 10))
        CCdur3 = VAL(MID$(Line$, 35, 10))
CASE "$54"      ' Probability that non-LTA climate is a PD climate
        PDprob = VAL(MID$(Line$, 9, 16))
CASE "$55"      ' Distribution of Subsequent PD climate duration
        SPDdist$ = RTRIM$(MID$(Line$, 9, 2))
        SPDdur1 = VAL(MID$(Line$, 15, 10))
        SPDdur2 = VAL(MID$(Line$, 25, 10))
        SPDdur3 = VAL(MID$(Line$, 35, 10))
CASE "$56"      ' Distribution of percolation rate (mm/yr) for PD climate
        PDPdist$ = RTRIM$(MID$(Line$, 9, 2))
        PDperc1 = VAL(MID$(Line$, 15, 10))
        PDperc2 = VAL(MID$(Line$, 25, 10))
        PDperc3 = VAL(MID$(Line$, 35, 10))
CASE "$57"      ' Distribution of percolation rate for Long Term Average climate
        LTPdist$ = RTRIM$(MID$(Line$, 9, 2))
        LTperc1 = VAL(MID$(Line$, 15, 10))
        LTperc2 = VAL(MID$(Line$, 25, 10))
        LTperc3 = VAL(MID$(Line$, 35, 10))
CASE "$58"      ' Distribution of percolation rate for SP climate
        SPPdist$ = RTRIM$(MID$(Line$, 9, 2))
        SPperc1 = VAL(MID$(Line$, 15, 10))
```

```
            $Pperc2 = VAL(MID$(Line$, 25, 10))
            $Pperc3 = VAL(MID$(Line$, 35, 10))
        CASE "$59"      'use late drip distributions (Y or N)
            Ldrip$ = RTRIM$(MID$(Line$, 9, 2))
        CASE "$60"      ' distribution to use for Early Drip WP breach time (years since emplacement)
            ESdist$ = RTRIM$(MID$(Line$, 9, 2))
            Estarttime1 = VAL(MID$(Line$, 15, 10))
            Estarttime2 = VAL(MID$(Line$, 25, 10))
            Estarttime3 = VAL(MID$(Line$, 35, 10))
        CASE "$61"      ' probability that WP breaches on bottom before top for early drip (no bathtub)
            EBdist$ = RTRIM$(MID$(Line$, 9, 2))
            Ebath1 = VAL(MID$(Line$, 15, 10))
            Ebath2 = VAL(MID$(Line$, 25, 10))
            Ebath3 = VAL(MID$(Line$, 35, 10))
        CASE "$62"      ' distribution to use for Early Drip duration of WP flooding (years since breach)
            EDdist$ = RTRIM$(MID$(Line$, 9, 2))
            Eduration1 = VAL(MID$(Line$, 15, 10))
            Eduration2 = VAL(MID$(Line$, 25, 10))
            Eduration3 = VAL(MID$(Line$, 35, 10))
        CASE "$64"      ' distribution to use for Late Drip WP breach time (years since emplacement)
            LSdist$ = RTRIM$(MID$(Line$, 9, 2))
            Lstarttime1 = VAL(MID$(Line$, 15, 10))
            Lstarttime2 = VAL(MID$(Line$, 25, 10))
            Lstarttime3 = VAL(MID$(Line$, 35, 10))
        CASE "$65"      ' probability that WP breaches on bottom before top for Late Drip (no bathtub)
            LBdist$ = RTRIM$(MID$(Line$, 9, 2))
            Lbath1 = VAL(MID$(Line$, 15, 10))
            Lbath2 = VAL(MID$(Line$, 25, 10))
            Lbath3 = VAL(MID$(Line$, 35, 10))
        CASE "$66"      ' distribution to use for Late Drip duration of WP flooding (years since breach)
            LDdist$ = RTRIM$(MID$(Line$, 9, 2))
            Lduration1 = VAL(MID$(Line$, 15, 10))
            Lduration2 = VAL(MID$(Line$, 25, 10))
            Lduration3 = VAL(MID$(Line$, 35, 10))
        CASE "$70"      ' distribution to use for duration of WP flooding
            Exdist$ = RTRIM$(MID$(Line$, 9, 2))
            ex1 = VAL(MID$(Line$, 15, 10))
            ex2 = VAL(MID$(Line$, 25, 10))
            ex3 = VAL(MID$(Line$, 35, 10))
        CASE "$72"      ' distribution to use for SS corrosion rate in mm/yr
            SSSdist$ = RTRIM$(MID$(Line$, 9, 2))
            SSScr1 = VAL(MID$(Line$, 15, 10))
            SSScr2 = VAL(MID$(Line$, 25, 10))
            SSScr3 = VAL(MID$(Line$, 35, 10))
        CASE "$74"      ' distribution to use for boron factor
            Bfacdist$ = RTRIM$(MID$(Line$, 9, 2))
            Bfac1 = VAL(MID$(Line$, 15, 10))
            Bfac2 = VAL(MID$(Line$, 25, 10))
            Bfac3 = VAL(MID$(Line$, 35, 10))
        END SELECT
LOOP
CLOSE #1
'
' Load waste stream data
'
PRINT "Loading waste stream data"
PRINT
PRINT "Records Loaded:"
```

```
OPEN "casel.wen" FOR INPUT ACCESS READ AS #1
DO UNTIL EOF(1)
        LOCATE 7, 17
        PRINT n; " of "; count
        count = count + 1
        LINE INPUT #1, Line$
        numassy(n) = VAL(MID$(Line$, 32, 10))
        enrich(n) = VAL(MID$(Line$, 42, 10))
        burnup(n) = VAL(MID$(Line$, 52, 10))
        ' discharge = VAL(MID$(Line$, 72, 8)) discharge year not used in calc
        ' assytype = VAL(MID$(Line$, 88, 3))  assembly model number not used in calc
        ' reactnum = VAL(MID$(Line$, 91, 3))  reactor ID not used in calc
        reactype$ = LTRIM$(RTRIM$(MID$(Line$, 124, 4)))
        b = burnup(n) / 1000
        e = enrich(n)
        t = 10          ' set time at 10 years for kinf based loadcurv
        IF reactype$ = "PWR" THEN
                totpwr = totpwr + numassy(n)
                IF Uloadcurv$ = "Y" AND Lloadcurv$ = "N" THEN
                        ' Include only PWR assemblies that meet upper loading limit
                        k = L1 + L2 * b + L3 * t + L4 * e + L5 * b ^ 2 + L6 * t ^ 2 + L7 * e ^ 2
                        k = k + L8 * b * e + L9 * b * t + L10 * e * t + L11 * b * e * t + L12 * b ^ 3 + L13 * e ^ 3
                        IF k < Uloadlim THEN
                                Nnum = Nnum + numassy(n)
                                pkeff = 0
                                IF D = 0 THEN
                                    O = UFDox
                                ELSE
                                    O = SFDox
                                END IF
                                FOR i = 5000 TO 60000 STEP 100
                                        keff = kFullDeg(D, e, b, i, O)
                                        IF keff > pkeff THEN pkeff = keff
                                NEXT i
                                IF pkeff > (limit - .02) THEN
                                        totassy = totassy + numassy(n)
                                        n = n + 1
                                END IF
                        ELSE
                                Unum = Unum + numassy(n)
                        END IF
                ELSEIF Uloadcurv$ = "N" AND Lloadcurv$ = "Y" THEN
                        ' Include only PWR assemblies that meet lower loading limit
                        Lk = LL1 + LL2 * b + LL3 * t + LL4 * e + LL5 * b ^ 2 + LL6 * t ^ 2 + LL7 * e ^ 2
                        Lk = Lk + LL8 * b * e + LL9 * b * t + LL10 * e * t + LL11 * b * e * t + LL12 * b ^ 3 + LL13 * e ^ 3
                        IF Lk > Lloadlim THEN
                                Nnum = Nnum + numassy(n)
                                pkeff = 0
                                IF D = 0 THEN
                                    O = UFDox
                                ELSE
                                    O = SFDox
                                END IF
                                FOR i = 5000 TO 60000 STEP 100
                                        keff = kFullDeg(D, e, b, i, O)
                                        IF keff > pkeff THEN pkeff = keff
                                NEXT i
                                IF pkeff > (limit - .02) THEN
```

```
                                        totassy = totassy + numassy(n)
                                        n = n + 1
                                END IF
                        ELSE
                                Lnum = Lnum + numassy(n)
                        END IF
                ELSEIF Uloadcurv$ = "Y" AND Lloadcurv$ = "Y" THEN
                        ' Include only PWR assemblies that meet both loading limits
                        k = L1 + L2 * b + L3 * t + L4 * e + L5 * b ^ 2 + L6 * t ^ 2 + L7 * e ^ 2
                        k = k + L8 * b * e + L9 * b * t + L10 * e * t + L11 * b * e * t + L12 * b ^ 3 + L13 * e ^ 3
                        Lk = LL1 + LL2 * b + LL3 * t + LL4 * e + LL5 * b ^ 2 + LL6 * t ^ 2 + LL7 * e ^ 2
                        Lk = Lk + LL8 * b * e + LL9 * b * t + LL10 * e * t + LL11 * b * e * t + LL12 * b ^ 3 + LL13 * e ^ 3
                        IF (k < Uloadlim) AND (Lk > Lloadlim) THEN
                                Mnum = Mnum + numassy(n)
                                pkeff = 0
                                IF D = 0 THEN
                                    O = UFDox
                                ELSE
                                    O = SFDox
                                END IF
                                FOR i = 5000 TO 60000 STEP 100
                                        keff = kFullDeg(D, e, b, i, O)
                                        IF keff > pkeff THEN pkeff = keff
                                NEXT i
                                IF pkeff > (limit - .02) THEN
                                        totassy = totassy + numassy(n)
                                        n = n + 1
                                END IF
                        ELSEIF Lk < Lloadlim THEN
                                Lnum = Lnum + numassy(n)
                        ELSE
                                Unum = Unum + numassy(n)
                        END IF
                ELSE
                        ' Include entire PWR population
                                Mnum = Mnum + numassy(n)
                                pkeff = 0
                                IF D = 0 THEN
                                    O = UFDox
                                ELSE
                                    O = SFDox
                                END IF
                                FOR i = 5000 TO 60000 STEP 100
                                        keff = kFullDeg(D, e, b, i, O)
                                        IF keff > pkeff THEN pkeff = keff
                                NEXT i
                                IF pkeff > (limit - .02) THEN
                                        totassy = totassy + numassy(n)
                                        n = n + 1
                                END IF
                END IF
        END IF
LOOP
CLOSE #1
PRINT
'Calculate fraction of PWR waste stream in above, below, and within the loading range
Lfrac = Lnum / totpwr           'fraction of PWR fuel below loading range
Mfrac = Mnum / totpwr           'fraction of PWR fuel within loading range
```

```
Hfrac = Unum / totpwr            'fraction of PWR fuel above loading range
'Fraction of fuel in loading range with peak keff that exceeds limit - 0.02
CMfrac = totassy / Hnum
'
PRINT "Total PWR assemblies in waste stream = "; totpwr
'
' Start calculation
'
PRINT #2, "Fraction of PWR waste stream below loading range for AP WP = "; Lfrac
PRINT #2, "Fraction of PWR waste stream in AP WP = "; Mfrac
PRINT #2, "Fraction of PWR waste stream above loading range for AP WP = "; Hfrac
PRINT #3, "Fraction of PWR waste stream below loading range for AP WP = "; Lfrac
PRINT #3, "Fraction of PWR waste stream in AP WP = "; Mfrac
PRINT #3, "Fraction of PWR waste stream above loading range for AP WP = "; Hfrac
PRINT #4, "Fraction of PWR waste stream below loading range for AP WP = "; Lfrac
PRINT #4, "Fraction of PWR waste stream in AP WP = "; Mfrac
PRINT #4, "Fraction of PWR waste stream above loading range for AP WP = "; Hfrac
PRINT
PRINT "Fraction of PWR waste stream below loading range for AP WP = "; Lfrac
PRINT "Fraction of PWR waste stream in AP WP = "; Mfrac
PRINT "Fraction of PWR waste stream above loading range for AP WP = "; Hfrac
PRINT
PRINT #2, "Max. fraction of fuel in AP WP capable of exceeding limit = "; CMfrac
PRINT #3, "Max. fraction of fuel in AP WP capable of exceeding limit = "; CMfrac
PRINT #4, "Max. fraction of fuel in AP WP capable of exceeding limit = "; CMfrac
PRINT "Max. fraction of fuel in AP WP capable of exceeding limit = "; CMfrac
PRINT
'
' Seed random number generator
'
IF seed = -1 THEN seed = TIMER
' print output column headers
PRINT #2, "Seed value = "; seed
PRINT #2, "-----------------------------------------------------------------------------"
PRINT #2, "WP#  Drip?  Type   Breach   Bath?  Duration  Crit?  Time   frac   pfrac   ptime"
PRINT #2, "-----------------------------------------------------------------------------"
PRINT #4, "Seed value = "; seed
PRINT #4, "-----------------------------------------------------------------------------"
PRINT #4, "WP#  Drip?  Type   Breach   Bath?  Duration  Crit?  Time   frac   pfrac   ptime"
PRINT #4, "-----------------------------------------------------------------------------"
PRINT "Seed value = "; seed
PRINT "-----------------------------------------------------------------------"
PRINT "WP#  Drip?  Type   Breach   Bath?  Dur  Crit?  Time   frac   pfrac   ptime"
PRINT "-----------------------------------------------------------------------"
FOR i = 1 TO Samplesize
        RANDOMIZE TIMER 'reseed from timer
        '
        'Sample probability distributions for this realization
        '
        'perc rate and duration for first PD climate
        CPDperc = Sample(PDPdist$, PDperc1, PDperc2, PDperc3)
        CPDdur = Sample(CPDdist$, CPDdur1, CPDdur2, CPDdur3)
        'perc rate for first LTA climate
        LTApercA = Sample(LTPdist$, LTperc1, LTperc2, LTperc3)
        ' Get fraction of WPs dripped on during current PD and first LTA climate
        PDfrac = Fseep(CPDperc)
        LTAfrac = Fseep(LTApercA)
        ' See if WP gets dripped on and sample from appropriate
```

```
' WP breach time and bathtub duration if necessary
DRIPfrac = RND
IF DRIPfrac <= PDfrac THEN  'WP dripped on early
        drip$ = "YES"
        starttime = Sample(ESdist$, Estarttime1, Estarttime2, Estarttime3)
        duration = Sample(EDdist$, Eduration1, Eduration2, Eduration3)
        bathfrac = Sample(EBdist$, Ebath1, Ebath2, Ebath3)
ELSEIF DRIPfrac <= LTAfrac THEN ' WP dripped on late
        drip$ = "YES"
        IF Ldrip$ = "Y" THEN ' use late drip distributions
                starttime = Sample(LSdist$, Lstarttime1, Lstarttime2, Lstarttime3)
                duration = Sample(LDdist$, Lduration1, Lduration2, Lduration3)
                bathfrac = Sample(LBdist$, Lbath1, Lbath2, Lbath3)
        ELSE
                starttime = CPDdur + Sample(ESdist$, Estarttime1, Estarttime2, Estarttime3)
                duration = Sample(EDdist$, Eduration1, Eduration2, Eduration3)
                bathfrac = Sample(EBdist$, Ebath1, Ebath2, Ebath3)
        END IF
ELSE drip$ = "NO"   'WP not dripped on
        starttime = -1
        duration = -1
        bathfrac = 0
END IF
'Determine what type of WP this is if not given
IF WPtype$ = "ALL" THEN
        WPfrac = RND
        IF WPfrac <= Lfrac THEN
                WPtype$ = "NA"
        ELSEIF WPfrac <= (Lfrac + Mfrac) AND WPfrac > Lfrac THEN
                WPtype$ = "AP"
        ELSE
                WPtype$ = "CR"
        END IF
END IF
Crit$ = "NO"
frac = 0
pfrac = 0
ptime = 0
'Determine if bathtub is formed for WP under drip
bath$ = "NO"
IF drip$ = "YES" AND RND >= bathfrac THEN bath$ = "YES" ELSE duration = -1
time = -1
'
'See if this WP has a chance of exceeding limit
'
'WP not under drip or not absorber plate WP or not bathtub
IF WPtype$ <> "AP" OR drip$ = "NO" OR bath$ = "NO" THEN 100
'WP is absorber plate under a drip but doesn't contain right fuel
IF RND >= CNfrac AND Samplesize > 2 THEN 100
'
' Sample for duration of climates for this realization
'
CCdur = Sample(CCdist$, CCdur1, CCdur2, CCdur3)
SPDdurA = Sample(SPDdist$, SPDdur1, SPDdur2, SPDdur3)
SPDdurB = Sample(SPDdist$, SPDdur1, SPDdur2, SPDdur3)
SPDdurC = Sample(SPDdist$, SPDdur1, SPDdur2, SPDdur3)
'
' Sample for percolation rates of later climates for this realization
```

```
'
'perc rate for second LTA climate
LTApercB = Sample(LTPdist$, LTperc1, LTperc2, LTperc3)
'perc rate for third LTA climate
LTApercC = Sample(LTPdist$, LTperc1, LTperc2, LTperc3)
'perc rate for fourth LTA climate
LTApercD = Sample(LTPdist$, LTperc1, LTperc2, LTperc3)
'perc rate for second PD or SP climate
IF RND <= PDprob THEN
        SPDpercA = Sample(SPDdist$, PDperc1, PDperc2, PDperc3)
ELSE SPDpercA = Sample(SPPdist$, SPperc1, SPperc2, SPperc3)
END IF
'perc rate for third PD or SP climate
IF RND <= PDprob THEN
        SPDpercB = Sample(SPDdist$, PDperc1, PDperc2, PDperc3)
ELSE SPDpercB = Sample(SPPdist$, SPperc1, SPperc2, SPperc3)
END IF
'perc rate for fourth PD or SP climate
IF RND <= PDprob THEN
        SPDpercC = Sample(SPDdist$, PDperc1, PDperc2, PDperc3)
ELSE SPDpercC = Sample(SPPdist$, SPperc1, SPperc2, SPperc3)
END IF
'Figure out times when climate changes and flow rates
Ftime1 = CPDdur
Ftime2 = CCdur
Ftime3 = CCdur + SPDdurA
Ftime4 = 2 * CCdur
Ftime5 = 2 * CCdur + SPDdurB
Ftime6 = 3 * CCdur
Ftime7 = 3 * CCdur + SPDdurC
Fflow1 = Qseep(CPDperc)
Fflow2 = Qseep(LTApercA)
Fflow3 = Qseep(SPDpercA)
Fflow4 = Qseep(LTApercB)
Fflow5 = Qseep(SPDpercB)
Fflow6 = Qseep(LTApercC)
Fflow7 = Qseep(SPDpercC)
Fflow8 = Qseep(LTApercD)
'
'Sample for other parameters
'
ex = Sample(Exdist$, ex1, ex2, ex3) ' get exchange efficiency
cr = 1000 * Sample(BSSdist$, BSScr1, BSScr2, BSScr3)'get SS corrosion rate
fac = Sample(Bfacdist$, Bfac1, Bfac2, Bfac3)'get boron factor
BSScr = fac * cr
'critical fraction that must be reached before WP is considered
'to have exceeded limit
frac = RND
IF Samplesize < 2 THEN frac = 1  ' shuts off Monte-carlo for single realization cases
'
' Perform mass balance for this WP
'
PRINT #3, "WP#", i
PRINT #3, "-------------------------------------------------------------"
PRINT #3, "Time     cfrac   BSSthick    Oxide    Bsol"
PRINT #3, "-------------------------------------------------------------"
SELECT CASE D
CASE 0
```

```
                        CALL UniDeg(time, frac, pfrac, ptime)
                CASE 1
                        CALL SetDeg(time, frac, pfrac, ptime)
                END SELECT
                '
                'Output results to screen and summary file
                '
100             IF drip$ = "YES" THEN
                        PRINT #2, i; " "; drip$; " "; WPtype$; " "; starttime; " "; bath$; " "; duration; " "; Crit$; " "; time; " "; frac;
" "; pfrac; " "; ptime
                        PRINT i; " "; drip$; " "; WPtype$; " "; starttime; " "; bath$; " "; duration; " "; Crit$; " "; time; " "; frac; "
"; pfrac; " "; ptime
                        IF Crit$ = "YES" THEN
                                PRINT #4, i; " "; drip$; " "; WPtype$; " "; starttime; " "; bath$; " "; duration; " "; Crit$; " "; time; "
"; frac; " "; pfrac; " "; ptime
                        END IF
                END IF
        NEXT i
        PRINT #2, "Run finished at "; TIME$; " on "; DATE$
        PRINT #3, "Run finished at "; TIME$; " on "; DATE$
        PRINT #4, "Run finished at "; TIME$; " on "; DATE$
        CLOSE #2
        CLOSE #3
        CLOSE #4
        END

REM $STATIC
FUNCTION BFull (b)
        '
        ' Function to calculate delta-k/k from boron in solution for fully degraded basket
        '
        BF = .0232558 - .0356383 * LOG(b) + .0142821 * LOG(b) ^ 2 - 1.91685E-03 * LOG(b) ^ 3
        BFull = InvNorm(BF, .01905)  'account for regression uncertainty
END FUNCTION

FUNCTION BPart (b, th, O)
        '
        ' Function to calculate delta-k/k from boron in solution for partially degraded basket
        '
        BP = 6.37971E-03 - .0607375 * LOG(b) + .0208433 * LOG(b) ^ 2 - 2.21564E-03 * LOG(b) ^ 3 + 3.59713E-04 * th + 4.23685E-03 * O
        BPart = InvNorm(BP, .00676)
END FUNCTION

FUNCTION Flow (t)
        '
        ' Flow onto WP to model climate change
        '
        SHARED Ftime1, Ftime2, Ftime3, Ftime4, Ftime5, Ftime6, Ftime7
        SHARED Fflow1, Fflow2, Fflow3, Fflow4, Fflow5, Fflow6, Fflow7, Fflow8
        SELECT CASE t
        CASE IS < Ftime1
                Flow = Fflow1
        CASE IS >= Ftime1
                Flow = Fflow2
        CASE IS >= Ftime2
                Flow = Fflow3
        CASE IS >= Ftime3
                Flow = Fflow4
```

```
        CASE IS >= Ftime4
                Flow = Pflow5
        CASE IS >= Ftime5
                Flow = Pflow6
        CASE IS >= Ftime6
                Flow = Pflow7
        CASE IS >= Ftime7
                Flow = Pflow8
        END SELECT
END FUNCTION

FUNCTION Fseep (perc)
        '
        'Samples for fraction of WPs dripped on at a given percolation rate
        '
        SHARED Fperc(), Fmean(), Fsd(), numF
        i = 0
        DO UNTIL Fperc(i) >= perc OR i > numF
                i = i + 1
        LOOP
        IF i > numF THEN        'if perc is off-scale then Fseep=1
                Fseep = 1
        ELSEIF Fperc(i) = perc THEN        'if perc exactly matches an Fseep table entry
                Fseep = InvBeta(0, Fmean(i), Fsd(i), 1)
        ELSE                    'linearly interpolate from Fseep table
                mean = Fmean(i) - (Fperc(i) - perc) / (Fperc(i) - Fperc(i - 1)) * (Fmean(i) - Fmean(i - 1))
                stdev = Fsd(i) - (Fperc(i) - perc) / (Fperc(i) - Fperc(i - 1)) * (Fsd(i) - Fsd(i - 1))
                Fseep = InvBeta(0, mean, stdev, 1)
        END IF
END FUNCTION

FUNCTION FullCfrac (D, t, O, b, limit)
        '
        ' Function to determine critical fraction for fully degraded basket
        '
        SHARED numassy(), enrich(), burnup(), n, totassy   ' variables shared with main program
        totalcrit = 0   ' total number of assemblies which exceed keff limit
        FOR i = 0 TO n - 1
                k = kFullDeg(D, enrich(i), burnup(i) / 1000, t, O)
                IF D = 1 THEN
                        IF b < 30 THEN
                                BF = 0
                        ELSE
                                BF = BFull(b)
                        END IF
                        k = k * (1 + BF)
                END IF
                IF k >= limit THEN totalcrit = totalcrit + numassy(i)
        NEXT i
        FullCfrac = totalcrit / totassy
END FUNCTION

FUNCTION InvBeta (min, mean, stdev, max)
        '
        ' Function to randomly sample beta CDF
        '
        'make zero lower end of distribution
        '
```

```
        mean = mean - min
        max = max - min
        '
        'normalize distribution
        '
        IF max = 0 THEN
                InvBeta = 0    'result is zero
                GOTO 200
        END IF
        IF mean = 1 AND stdev = 0 THEN
                InvBeta = 1     'result is one
                GOTO 200
        END IF
        mu = mean / max
        sig = stdev / max
        IF mu = 0 AND sig = 0 THEN
                InvBeta = 0     'result is zero
                GOTO 200
        END IF
        '
        'calculate beta distribution parameters
        '
        alpha = (mu ^ 2 - mu ^ 3 - mu * sig ^ 2) / sig ^ 2
        beta = (1 - mu) / mu * alpha
        '
        DO UNTIL test <= 1 AND test > 0
                u1 = RND
                u2 = RND
                test = u1 ^ (1 / alpha) + u2 ^ (1 / beta)
        LOOP
        InvBeta = min + u1 ^ (1 / alpha) / test * max
200     '
END FUNCTION

FUNCTION InvNorm (mean, stdev)
        '
        ' Function to randomly sample normal CDF
        '
        'generate a random value that is normally distributed with
        'a mean of zero and variance of 1
        '
        norm = 0
        FOR i = 1 TO 12
                norm = norm + RND
        NEXT i
        norm = norm - 6
        InvNorm = stdev * norm + mean
END FUNCTION

FUNCTION InvUni (min, max)
        '
        ' Function to randomly sample uniform CDF
        '
        InvUni = min + RND * (max - min)  ' Sample the uniform distribution
END FUNCTION

FUNCTION InvWeib (alpha, beta, theta)
        '
```

```
        ' Function to randomly sample three parameter weibull CDF
        '
        InvWeib = theta + alpha * (-LOG(1 - RND)) ^ (1 / beta)    ' Sample the weibull distribution
END FUNCTION

FUNCTION kFullDeg (D, a, b, t, O)
        '
        ' Function to calculate keff for fully degraded basket configurations
        '
        IF D = 0 THEN  ' use regression for uniform oxide distribution
                k = -5.12955 + 1.65615 * LOG(t) - 8.52852E-03 * b + .29266 * a - .153971 * LOG(t) ^ 2 + .0046707 * LOG(t) ^ 3 + 6.8964E-05 * b ^ 2 -
1.63227E-07 * b ^ 3 - .0671372 * a ^ 2 + 5.36083E-03 * a ^ 3 - 4.08151E-04 * LOG(t) * b +  _
7.23708E-03 * LOG(t) * a - 5.25978E-03 * O
                kFullDeg = InvNorm(k, .00463) 'account for regression uncertainty
        ELSE            ' use regression for settled oxide distribution
                k = -1.25161 + .683154 * LOG(t) - 6.65133E-03 * b + .266145 * a - .0640282 * LOG(t) ^ 2 + 1.92631E-03 * LOG(t) ^ 3 - 2.67041E-05 * b
^ 2 + 6.12197E-07 * b ^ 3 - .0618276 * a ^ 2 + 5.20352E-03 * a ^ 3 - 1.36497E-04 * LOG(t) * b +  _
.0050849 * LOG(t) * a - .140918 * O
                kFullDeg = InvNorm(k, .00906) 'account for regression uncertainty
        END IF
END FUNCTION

FUNCTION kPartDeg (D, a, b, t, O, th)
        '
        ' Function to calculate keff for partially degraded basket configurations
        '
        IF D = 0 THEN  ' use regression for uniform oxide distribution
                k = 2.35498 - .0066737 * b - 1.8096E-05 * b ^ 2 + .1418 * a - .0071354 * a ^ 2 - .5193 * LOG(t) + .059471 * LOG(t) ^ 2 - .0022406 *
LOG(t) ^ 3 - .0050889 * O - .074906 * th + .010646 * th ^ 2 - 5.2334E-04 * th ^ 3
                kPartDeg = InvNorm(k, .00831)  'account for regression uncertainty
        ELSE            ' use regression for settled oxide distribution
                k = 1.72095 - .0067237 * b - 1.6667E-05 * b ^ 2 + .13348 * a - .0060497 * a ^ 2 - .31232 * LOG(t) + .037442 * LOG(t) ^ 2 - .0014715
* LOG(t) ^ 3 - .016797 * O - .066316 * th + .0094036 * th ^ 2 - 4.6905E-04 * th ^ 3
                kPartDeg = InvNorm(k, .00846)  'account for regression uncertainty
        END IF
END FUNCTION

FUNCTION PartCfrac (D, t, O, th, b, limit)
        '
        ' Function to determine critical fraction for partially degraded basket
        '
        SHARED numassy(), enrich(), burnup(), n, totassy
        totalcrit = 0   ' total number of assemblies which exceed keff limit
        FOR i = 0 TO n - 1
                k = kPartDeg(D, enrich(i), burnup(i) / 1000, t, O, th)
                IF D = 1 THEN
                        IF b < 30 THEN
                                BF = 0
                        ELSE
                                BF = BPart(b, th, O)
                        END IF
                        k = k * (1 + BF)
                END IF
                IF k >= limit THEN totalcrit = totalcrit + numassy(i)
        NEXT i
        PartCfrac = totalcrit / totassy
END FUNCTION
```

```
FUNCTION Qseep (perc)
        '
        'Samples for drip flow rate at a given percolation rate
        '
        SHARED Qperc(), Qmean(), Qsd(), Qmax(), numQ
        i = 0
        'Locate perc is on Qseep table
        DO UNTIL Qperc(i) >= perc OR i > numQ
                i = i + 1
        LOOP
        IF i > numQ THEN        'if perc is off-scale then linearly extrapolate
                mean = Qmean(i - 1) + (Qmean(i - 1) - Qmean(i - 2)) / (Qperc(i - 1) - Qperc(i - 2)) * perc
                stdev = Qsd(i - 1) + (Qsd(i - 1) - Qsd(i - 2)) / (Qperc(i - 1) - Qperc(i - 2)) * perc
                max = Qmax(i - 1) + (Qmax(i - 1) - Qmax(i - 2)) / (Qperc(i - 1) - Qperc(i - 2)) * perc
                Qseep = InvBeta(0, mean, stdev, max)
        ELSEIF Qperc(i) = perc THEN       'if perc exactly matches an Qseep table entry
                Qseep = InvBeta(0, Qmean(i), Qsd(i), Qmax(i))
        ELSE                            'linearly interpolate from Qseep table
                mean = Qmean(i) - (Qperc(i) - perc) / (Qperc(i) - Qperc(i - 1)) * (Qmean(i) - Qmean(i - 1))
                stdev = Qsd(i) - (Qperc(i) - perc) / (Qperc(i) - Qperc(i - 1)) * (Qsd(i) - Qsd(i - 1))
                max = Qmax(i) - (Qperc(i) - perc) / (Qperc(i) - Qperc(i - 1)) * (Qmax(i) - Qmax(i - 1))
                Qseep = InvBeta(0, mean, stdev, max)
        END IF
END FUNCTION

FUNCTION Sample (Dist$, param1, param2, param3)
        '
        ' Function to select and sample the desired distribution
        '
        SELECT CASE Dist$
        CASE "F"        'Fixed value
                Sample = param1
        CASE "U"        'Uniform distribution
                Sample = InvUni(param1, param2)
        CASE "LU"       'Log Uniform distribution
                Sample = EXP(InvUni(param1, param2))
        CASE "W"        'Weibull distribution
                Sample = InvWeib(param1, param2, param3)
        CASE "LW"
                Sample = EXP(InvWeib(param1, param2, param3))
        CASE "NW"
                Sample = EXP(-InvWeib(param1, param2, param3))
        CASE "N"
                Sample = InvNorm(param1, param2)
        CASE ELSE
                PRINT "Unknown Distribution Specified in Input"
                END
        END SELECT
END FUNCTION

SUB SetDeg (time, frac, pfrac, ptime)
        '
        ' Subroutine for determining critical fraction as a function
        ' of time and degradation for settled oxide distributions
        '
        SHARED starttime, duration, D, ex, BSScr, limit, inc, Samplesize
        SHARED BSSthick, Bwp, Void, Crit$, BSSvol, SCSox, SBSSox, SFDox
        '
```

```
' Set local variables
'
Oxide = SCSox                'Assume that all of carbon steel corrodes before any other degradation occurs
tstart = CINT(starttime / inc)          'Round start time to the nearest inc years
time = tstart * inc
durat = CINT(duration / inc)                 'Round duration to the nearest inc years
tend = time + durat * inc
Thickness = BSSthick
Voidspace = Void
BorSol = 0
cfrac = 0
pfrac = 0
ptime = 0
'
' Calculate critical fraction at each time between breach of WP and draining of WP
' accounting for the amount of basket degradation which has occured
'
DO UNTIL (time > tend) OR (cfrac >= frac)
        '
        ' Calculate critical fraction at time
        '
        IF Thickness > 0 THEN
                cfrac = PartCfrac(1, time, Oxide, Thickness, BorSol, limit)
        ELSEIF OldThick > 0 THEN
                '
                ' Smooth transition between oxide settled to bottom of cells and
                ' oxide settled to bottom of waste package
                '
                cfracpart = PartCfrac(1, time, (SCSox + SBSSox), 0, BorSol, limit)
                cfracfull = FullCfrac(1, time, SFDox, BorSol, limit)
                cfrac = (cfracpart + cfracfull) / 2
        ELSE
                cfrac = FullCfrac(1, time, Oxide, BorSol, limit)
        END IF
        PRINT #3, time; " "; cfrac; " "; Thickness; " "; Oxide; " "; BorSol
        '
        'Update the peak critical fraction and time counters if
        'this critical fraction is higher than the previous
        '
        IF cfrac > pfrac THEN
                pfrac = cfrac
                ptime = time
        END IF
        '
        time = time + inc          ' increment time by inc years
        '
        ' Degrade basket for next timestep
        '
        OldThick = Thickness                                  ' BSS thickness at time
        Thickness = Thickness - 2 * BSScr / 1000 * inc    ' BSS thickness at time + inc years
        '
        ' Amount of oxide at next timestep
        '
        IF Thickness > 0 THEN
                Oxide = SCSox + (BSSthick - Thickness) / BSSthick * SBSSox
        ELSE
                Oxide = SFDox       ' Oxide amount constant once BSS finisbes degrading
        END IF
```

```
                '
                ' Account for reduction in Voidspace caused by oxidation of BSS
                '
                IF Thickness > 0 THEN
                        Voidspace = Void + (BSSthick - Thickness + BSScr / 1000 * inc) / BSSthick * BSSvol
                ELSE
                        Voidspace = Void + BSSvol
                END IF
                '
                ' Calculate amount of boron in solution lost to exchange flushing in inc years
                '
                BorLost = (ex * Flow(time) * inc) / Voidspace * BorSol
                IF BorLost > BorSol THEN BorLost = BorSol        ' Prevents loss of more boron than in solution
                IF OldThick < 0 THEN
                        BorSol = BorSol - BorLost        ' BSS completely degraded at previous timestep so no more supply term
                ELSEIF Thickness > 0 THEN
                        BorSol = BorSol - BorLost + (OldThick - Thickness) / BSSthick * Bwp      ' Some BSS remaining at next timestep
                ELSE
                        BorSol = BorSol - BorLost + OldThick / BSSthick * Bwp  ' BSS completely degrades between timesteps
                END IF
        LOOP
        IF NOT (cfrac >= frac) THEN time = -1 ELSE Crit$ = "YES"
END SUB

SUB UniDeg (time, frac, pfrac, ptime)
        '
        ' Subroutine for determining critical fraction as a function
        ' of time and degradation for uniform oxide distributions
        '
        SHARED starttime, duration, D, ex, BSScr, limit, inc, Samplesize
        SHARED BSSthick, Bwp, Void, Crit$, BSSvol, UCSox, UBSSox, UPDox
        '
        ' Set local variables
        '
        Oxide = UCSox                'Assume that all of carbon steel corrodes before any other degradation occurs
        tstart = CINT(starttime / inc)              'Round start time to the nearest inc years
        time = tstart * inc
        durat = CINT(duration / inc)                 'Round duration to the nearest inc years
        tend = time + durat * inc
        Thickness = BSSthick
        Voidspace = Void
        BorSol = 0
        cfrac = 0
        pfrac = 0
        ptime = 0
        '
        ' Calculate critical fraction at each time between breach of WP and draining of WP
        ' accounting for the amount of basket degradation which has occured
        ' Do this until basket drains or a criticality occurs
        '
        DO UNTIL (time > tend) OR (cfrac >= frac)
                '
                ' Calculate critical fraction at time
                '
                IF Thickness > 0 THEN
                        cfrac = PartCfrac(0, time, Oxide, Thickness, BorSol, limit)
                ELSEIF OldThick > 0 THEN
                        '
```

```
                ' Smooth transition between oxide distributed uniformly in cells+
                ' and oxide distributed uniformly in waste package
                '
                cfracpart = PartCfrac(0, time, (UCSox + UBSSox), 0, BorSol, limit)
                cfracfull = FullCfrac(0, time, UFDox, BorSol, limit)
                cfrac = (cfracpart + cfracfull) / 2
        ELSE
                cfrac = FullCfrac(0, time, Oxide, BorSol, limit)
        END IF
        PRINT #3, time; " "; cfrac; " "; Thickness; " "; Oxide; " "; BorSol
        '
        'Update the peak critical fraction and time counters if
        'this critical fraction is higher than the previous
        '
        IF cfrac > pfrac THEN
                pfrac = cfrac
                ptime = time
        END IF
        '
        time = time + inc          ' increment time by inc years
        '
        ' Degrade basket for next timestep
        '
        OldThick = Thickness                                  ' BSS thickness at time
        Thickness = Thickness - 2 * BSScr / 1000 * inc    ' BSS thickness at time + inc years
        '
        ' Amount of oxide at time + inc years
        '
        IF Thickness > 0 THEN
                Oxide = UCSox + (BSSthick - Thickness) / BSSthick * UBSSox
        ELSE
                Oxide = UFDox        ' Oxide amount constant once BSS finishes degrading
        END IF
        '
        ' Account for reduction in voidspace caused by oxidation of BSS
        '
        IF Thickness > 0 THEN
                Voidspace = Void + (BSSthick - Thickness + BSScr / 1000 * inc) / BSSthick * BSSvol
        ELSE
                Voidspace = Void + BSSvol
        END IF
        '
        ' Calculate amount of boron in solution lost to exchange flushing in inc years
        '
        BorLost = (ex * Flow(time) * inc) / Voidspace * BorSol
        IF BorLost > BorSol THEN BorLost = BorSol        ' Prevents loss of more boron than in solution
        IF OldThick < 0 THEN
                BorSol = BorSol - BorLost        ' BSS completely degraded during previous timestep so no more supply term
        ELSEIF Thickness > 0 THEN
                BorSol = BorSol - BorLost + (OldThick - Thickness) / BSSthick * Bwp      ' Some BSS remaining at next timestep
        ELSE
                BorSol = BorSol - BorLost + OldThick / BSSthick * Bwp  ' BSS completely degrades between timesteps
        END IF
    LOOP
    IF NOT (cfrac >= frac) THEN time = -1 ELSE Crit$ = "YES"
END SUB
```

To: John Massari@CRWMS
cc:
From: David Sevougian
Office Phone:
Date: 02/23/98 04:42:30 PM
Subject: Final (?) seepage-model update

John,
Here is the "final" seepage model? The reference is YMP Milestone #SLX01MM3, completed 1/27/98, WBS# 1.2.5.4.1, entitled "Complete Draft VA UZ Abstraction/Test Document". As I said on the phone, the information in that document is slightly outdated from the info below. The final document will be the TSPA-VA Technical Bases Document due this summer.

Dave

---------- Forwarded by David Sevougian on 02/23/98 04:41 PM ----------

mlwilso@snark.nwer.sandia.gov on 02/16/98 08:40:52 PM

To: David Sevougian, Vinod Vallikat
cc: Jerry McNeish, Robert Andrews, bsramara@duke-energy.com, cftsang@lbl.gov, ckho@mailguy.nwer.sandia.gov, ctstock@mailguy.nwer.sandia.gov, gsbodvarsson@lbl.gov, guomin@hydra.lbl.gov, hadocke@mailguy.nwer.sandia.gov, jhgauth@mailguy.nwer.sandia.gov, rjmacki@mailguy.nwer.sandia.gov
Subject: Final (?) seepage-model update

To all:

With any luck, this e-mail will be the final update of the TSPA-VA base-case seepage model. The biggest difference from previous versions is at very high percolation fluxes -- several hundred mm/yr. However, there are minor changes in numbers throughout, caused by improved numerical procedures that were introduced to solve problems that became obvious only at very high fluxes. The method for using these numbers is the same as described in previous e-mails.

percolation (mm/yr)	mean fseep	st.dev. fseep
0.	0.	0.
2.2	0.	0.
3.9	0.00844	0.0144
9.2	0.0462	0.0785
14.6	0.167	0.283
73.2	0.403	0.427
213	0.590	0.398
500	0.743	0.386
980	1.	0.
> 980	1.	0.

percolation (mm/yr)	mean Qseep (m^3/yr)	st.dev. Qseep (m^3/yr)	upper bound (mean+10*sigma) (m^3/yr)
0.	0.	0.	0.
2.2	0.	0.	0.

3.9	0.0123	0.0111	0.123
9.2	0.0124	0.0112	0.124
14.6	0.0402	0.0364	0.404
73.2	0.361	0.352	3.88
213	1.54	1.38	15.3
500	4.50	3.77	42.2
>500	extrapolate linearly		

If anyone has comments or suggestions, please let me know.

-- Mike Wilson

To: John Massari @ C R W M S
cc: Joon Lee @ C R W M S
From: Kevin Mon
Office Phone:
Date: 03/18/98 01:32:08 PM
Subject: TSPAVA rev.01

John -

Here is the six regions for TSPA-VA basecase rev 01.

ou18305.zip

Don't hesistate to call if you need more info,
Kevin

Load in PWR waste stream data $A := \mathrm{READPRN}(\text{"pwr.prn"})$ $totalpwrassy := \Sigma A^{<0>}$ $\mu m := 10^{-6} \cdot m$

Define keff Regression Parameters for Fully Degraded Basket with Uniform Corrosion Product:

$$F := \begin{bmatrix} -5.12955 \\ 1.65615 \\ -0.00852852 \\ 0.292660 \\ -0.153971 \\ 0.00467070 \\ 0.000068964 \\ -0.000000163227 \\ -0.0671372 \\ 0.00536083 \\ -0.000408151 \\ 0.00723708 \\ -0.00525978 \end{bmatrix}$$

k_{eff} Regression Equations

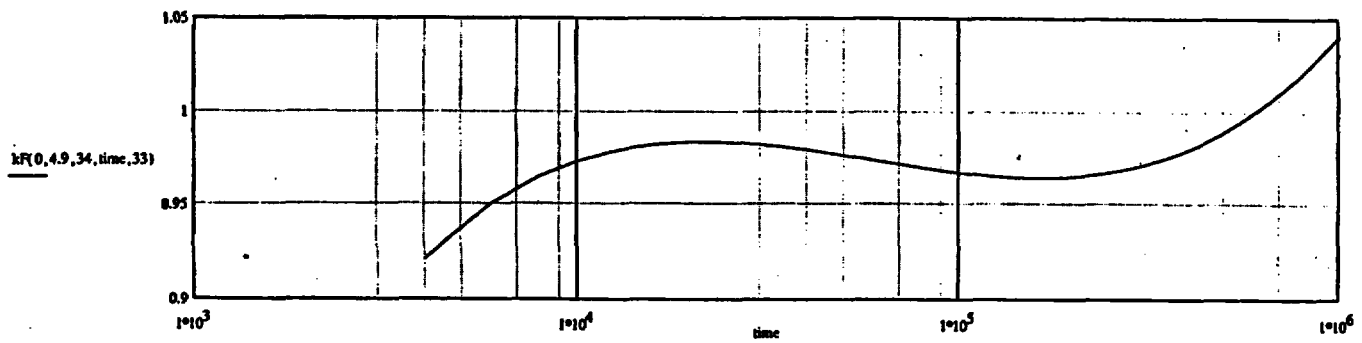
(Note that for both regressions d=0 is for uniform oxide distribution)

Fully Degraded Basket Regression

$time := 4000, 6000 .. 1000000$

$$kF(d,a,b,t,O) := F_{0,d} + F_{1,d} \cdot \ln(t) + F_{2,d} \cdot b + F_{3,d} \cdot a + F_{4,d} \cdot \ln(t)^2 + F_{5,d} \cdot \ln(t)^3 + F_{6,d} \cdot b^2 + F_{7,d} \cdot b^3 + F_{8,d} \cdot a^2 + F_{9,d} \cdot a^3 + F_{10,d} \cdot \ln(t) \cdot b + F_{11,d} \cdot \ln(t) \cdot a + F_{12,d} \cdot O$$

Example Fully Degraded Basket keff Regression Results for 4.9% enrich. 34 GWd/MTU fuel in 33 vol% uniform oxide



Define functions for calculating fraction of PWR population that exceeds a given k_{eff} limit based on degraded configuration parameters

$$\mathrm{Fcfrac}(d,t,O,B,l) := \left| \begin{array}{l} \mathrm{totcrit} \leftarrow 0 \\ \text{for } i \in 0..(\mathrm{rows}(A)-1) \\ \quad \left| \begin{array}{l} k \leftarrow kF\left(d, A_{i,1}, \frac{A_{i,2}}{1000}, t, O\right) \\ \mathrm{totcrit} \leftarrow \mathrm{totcrit} + A_{i,0} \ \text{ if } k \geq l \end{array} \right. \\ \dfrac{\mathrm{totcrit}}{\mathrm{totalpwrassy}} \end{array} \right.$$

Initialize total exceeding limit bin to zero.
Begin steping through PWR assembly batch records in matrix A.

For each batch record determine k_{eff} using fully degraded basket regression.

If k_{eff} for batch is greater than limit then increment bin by number of assemblies in batch.

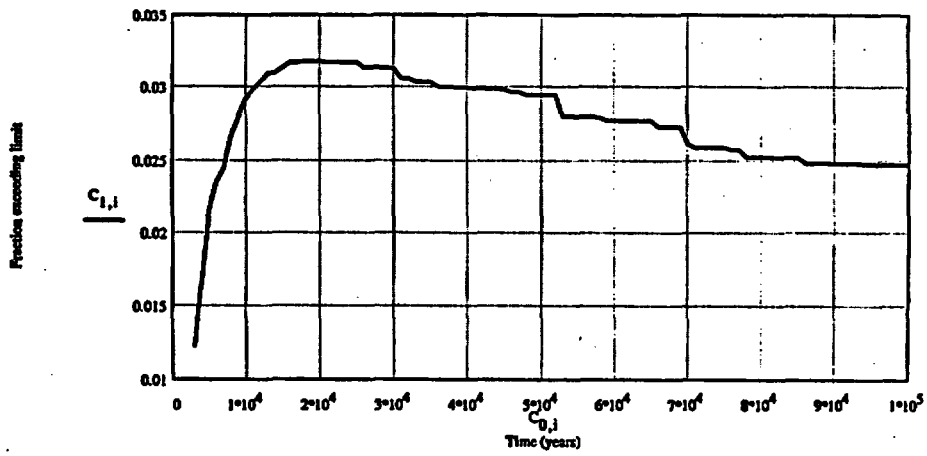
Once all records have been processed, determine fraction of PWR assemblies exceeding limit by dividing total number in bin by the total number of PWR assemblies in waste stream.

Calculate fraction exceeding 0.98 as a function of time for a flooded fully degraded basket with 33% uniform oxide starting at 3000 years

$i := 0..97$

$C_{0,i} := 3000 + i \cdot 1000$

$C_{1,i} := \mathrm{Fcfrac}(0, C_{0,i}, 33, 0, 0.98)$



Check of cumulative per package probability of exceeding 0.98 by 100,000 years

Mean percolation rate for long term average climate is 38.8 mm/yr (from Section 5.1.1)

Mean probability that a package gets dripped on at this percolation rate based on the info in Table 5.1.2-1 is:

$$Pdrip := .167 + \left[\left[(38.8 - 14.6)\frac{(.403 - .167)}{(73.2 - 14.6)}\right]\right] \qquad Pdrip = 0.26446$$

Probability that a package under a drip is breached by 100,000 years based on Figure 5.1.4-1 is: $Pbreach := 0.4$

Probability that breached WP under drip will accumulate water for any length of time based on info in Section 5.1.5 is: $Pbath := .4775$

Mean SS corrosion rate from Figure 5.1.6-1 is: $SS := 1 \cdot 10^{-4} \frac{mm}{yr}$

Mean boron factor from Section 5.1.6 is: $Bfac := 2.5$

Mean time to corrode 7mm of B-SS from both sides is: $\frac{7 \cdot mm}{2 \cdot Bfac \cdot SS} = 1.4 \cdot 10^{4}\ yr$

Probability that WP flooding lasts longer than mean time required to corrode B-SS based on Figure 5.1.5-1 is: $Pdur := 0.65$

Probability that WP contains fuel which will exceed the 0.98 limit based on the above graph is: $Pcrit := 0.025$

Simple estimate of probability that WP will exceed 0.98 by 100,000 years is : $Pdrip \cdot Pbreach \cdot Pbath \cdot Pdur \cdot Pcrit = 8.2082 \cdot 10^{-4}$

This value is close to that estimated using the Monte Carlo simulation for the no-loadcurve case in Figure 6-1