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2. DESIGN ANALYSIS TITLE

3rd WP Probabilistic Criticality Analysis: Methodology for Basket Degradation with Application to Commercial SNF

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4. Revision No.	5. Description of Revision
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1. Purpose

This analysis is prepared by the Mined Geologic Disposal System (MGDS) Waste Package Development (WPD) department to describe the latest version of the probabilistic criticality analysis methodology and its application to the entire commercial waste stream of commercial pressurized water reactor (PWR) spent nuclear fuel (SNF) expected to be emplaced in the repository. The purpose of this particular application is to evaluate the 21 assembly PWR absorber plate waste package (WP) with respect to degraded mode criticality performance. The degradation of principal concern is the borated stainless steel absorber plates which are part of the waste package basket and which constitute a major part of the waste package criticality control. The degradation (corrosion, dissolution) of this material will result in the release of most of the boron from the waste package and increase the possibility of criticality. The results of this evaluation will be expressed in terms of the fraction of the PWR SNF which can exceed a given k_{eff}, as a function of time and the peak value of that fraction over a time period up to several hundred thousand years.

The ultimate purpose of this analysis is to support the waste package design which defines waste packages to cover a range of SNF characteristics. In particular, with respect to PWR criticality the current categories are: (1) no specific criticality control material, (2) borated stainless steel plates in the waste package basket, and (3) zirconium clad boron carbide control rods (Ref. 5.4). The results of this analysis will indicate the coverage provided by the first two categories. With these results, this study will provide the first quantitative estimate of the benefit expected from the control measure consisting of borated stainless steel plates.

This document is the third waste package probabilistic criticality analysis. The first two (Ref. 5.12 for the first and Ref. 5.15 for the second) analyses were based primarily on the waste package criticality of the design basis fuel with a limited extension to SNF with other characteristics, and that only in terms of an infinite array (k_∞ versus k_{eff}) for the other fuel types. The previous analyses were also limited in the coverage of the range of possible input parameter values (material corrosion rates and the rate of water into the waste package). This analysis will show the sensitivity of criticality performance with respect to variations in the distribution of these parameters.

2. Quality Assurance

The Quality Assurance (QA) program applies to this analysis. The work reported in this document is part of the preliminary WP design analysis that will eventually support the License Application Design phase. This activity, when appropriately confirmed, can impact the proper functioning of the Mined Geologic Disposal System waste package; the waste package has been identified as an MGDS Q-List item important to safety and waste isolation (pp. 4, 15, Ref. 5.1). The waste package is on the Q-List by direct inclusion by the Department of Energy (DOE), without conducting a QAP-2-3 evaluation. As determined by an evaluation performed in accordance with QAP-2-0, *Conduct of Activities*, the work performed for this analysis is subject to *Quality Assurance Requirements and Description* (QARD; Ref. 5.3) requirements. The applicable procedural controls for this activity are indicated in the QAP-2-0 work control activity evaluation entitled *Perform Probabilistic Waste Package Design Analyses* (Ref. 5.2).

Unless otherwise stated, parameters and assumptions which are identified in this document are for preliminary design and shall be treated as unqualified data; these design parameters and assumptions will require subsequent qualification (or superseding inputs) as the WP design proceeds. This document will not directly support any construction, fabrication or procurement activity and therefore is not required to be procedurally controlled as TBV (to be verified). In addition, the inputs associated with this analysis 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 the appropriate procedures.

3. Method

The following items indicate the methods used in this analysis, and the activities in which they are applied, in approximately the sequence indicated.

- A qualitative (general) discussion of the degradation scenario for the 21 PWR absorber plate waste package is provided.

- The general configuration generator (applicable to all waste forms and external, as well as internal criticality) is simplified and specialized to a configuration generator for a commercial SNF waste package with criticality evaluated for the entire expected PWR waste stream. For this purpose the specialized configuration generator incorporated the regressions developed in Reference 5.5 for k_{eff} as a function of the SNF burnup and initial enrichment, as well as the parameters of waste package degradation (most importantly thickness of borated stainless steel plate remaining).

- The nominal results and their sensitivities to the various parameters of waste package degradation parameters are discussed.

- The set of *n* input parameters to which the performance results will be most sensitive is identified, and a probability distribution (discrete with no more than 4 points per parameter) is developed for the values of each. These individual probability distributions are assumed to be independent and are combined into a joint probability distribution for the set of *n*-tuple input parameter values using a computer code which generates all possible n-tuple combinations of the values for each parameter. Each of the *n*-tuples, together with the associated joint probability derived by multiplying together the probabilities for the occurrence of each of the individual values is listed to define a set of input cases covering the range of parameters of interest. It should be noted that the values of the input parameters are taken to be consistent with TSPA-95 (Ref. 5.14) and the CDA (Ref. 5.13)

- Probability distributions for the output parameters (principally peak critical fraction of PWR SNF, and the time of occurrence of this peak) are computed by sorting the output parameter-probability pairs according to the value of each parameter of interest, using a computer code developed for this purpose.

4. Design Inputs

All design inputs are for preliminary design; these design inputs will require subsequent qualification (or superseding inputs) before this analysis can be used to support procurement, fabrication, or construction activities, unless otherwise noted.

4.1 Design Parameters

4.1.1 Waste package geometry

The intact waste package geometry parameters used in this analysis are listed in Table 4.1-1 below. Figure 4.1-1 depicts the 21 Pressurized Water Reactor (PWR) Advanced Uncanistered Fuel (AUCF) absorber plate WP, its internals, and the material specifications (Ref. 5.11). This is considered unqualified TBV information, as other WPD QAP-3-9 analyses being performed in parallel may result in design changes not reflected in this analysis.

Table 4.1-1. Intact WP Parameters

Parameter	Value	Reference
Outer barrier thickness	10 cm	5.10, p. I-18
Inner barrier thickness	2 cm	5.10, p. I-19
Inner barrier inner diameter	1.410 m	5.10, p. I-19
Inner barrier inner length	4.585 m	5.10, p. I-19
Empty (no fuel or basket) 21 PWR absorber plate WP internal volume	7.158 m^3	5.5, Att. III
Fuel cell tube thickness	0.5 cm	5.10, p. I-21
Total mass of Fe in single fuel cell tube	163.374 kg	5.5, Att. III
Total displaced volume of single fuel cell tube	0.02117 m^3	5.5, Att. III
Criticality control plate thickness	0.7 cm	5.10, pp. I-29 to -31
Total mass of Fe in all criticality control plates	1137.596 kg	5.5, Att. III
Total mass of natural Boron in all criticality control plates	30.11 kg	5.5, Att. III
Total displaced volume of all criticality control plates	0.243 m^3	5.5, Att. III
Guide and support plate thickness	1.0 cm	5.10, pp. I-22 to -28
Total mass of Fe in all guides and supports	1998.771 kg	5.5, Att. III
Total displaced volume of guides and supports	0.259 m^3	5.5, Att. III

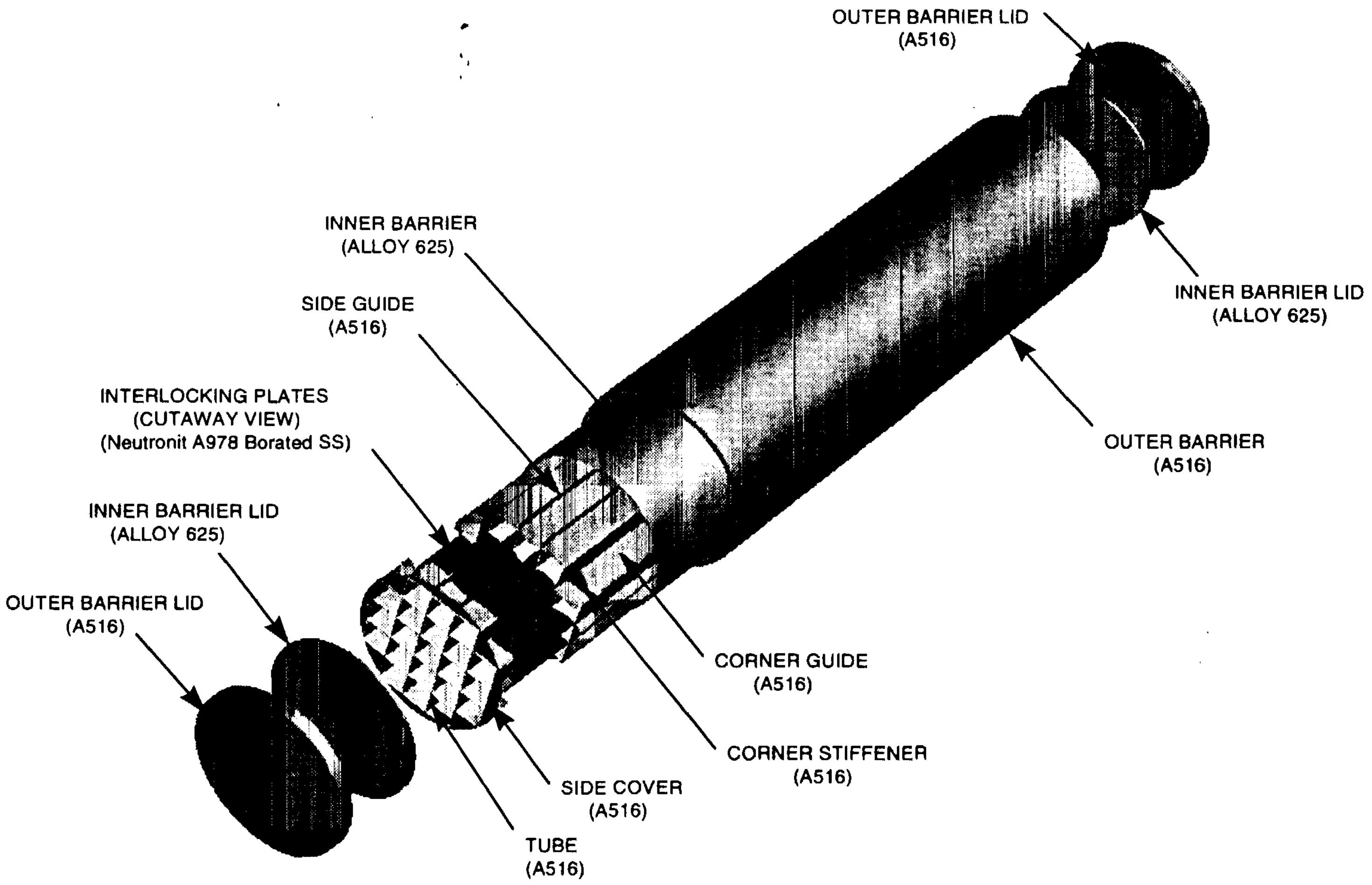

Figure 4.1-1. Advanced Uncanistered Fuel Waste Package with Internals Shown

4.1.2 Commercial PWR SNF properties

The fuel assembly upon which this calculation is based is the B&W Mark B 15 x 15 fuel assembly, with a cladding thickness of 0.06731 cm (Ref. 5.6, p. 2.1.2.2-6) and a displaced volume of 0.081 m^3 (Ref. 5.5, Att. III). Additional information on the criticality potential PWR SNF in degraded configurations, and fuel assembly degradation, is provided in the following subsections.

4.1.2.1 k_{eff} regressions for PWR SNF in degraded configurations

Reference 5.5 (Sect. 7.6) developed 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 4.1.2-1, and the form of the regression in both cases is as follows:

$$k_{eff}+2\sigma = C_0+C_1b+C_2b^2+C_3a+C_4a^2+C_5Ln(t)+C_6Ln(t)^2+C_7Ln(t)^3+C_8O+C_9T+C_{10}T^2+C_{11}T^3 \qquad (4\text{-}1)$$

where b is burnup in GWd/MTU, and 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. Reference 5.5 indicates that for the uniform case, the vol% of Fe_2O_3 uniformly distributed throughout the WP void space may be quickly obtained by multiplying the kg of Fe released by basket corrosion by a factor of 4.9998E-3.

Table 4.1.2-1. 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

Table 4.1.2-1. Regression Coefficients for Partially Degraded Basket WP $k_{eff}+2\sigma$

Regression Coefficients	Uniform Oxide	Settled Oxide
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 4.1.2-2, and the form of the regression in both cases is as follows:

$$k_{eff}+2\sigma = C_0+C_1Ln(t)+C_2b+C_3a+C_4Ln(t)^2+C_5Ln(t)^3+C_6b^2+C_7b^3+C_8a^2+C_9a^3+C_{10}Ln(t)b+C_{11}Ln(t)a+C_{12}O \qquad (4\text{-}2)$$

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 4.1.2-2. Regression Coefficients for Fully Degraded Basket WP $k_{eff}+2\sigma$

Regression Coefficients	33% 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 5.5 also developed 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 still an effective neutron absorber until it is removed from the WP. The corrected k_{eff} is obtained using:

$$Corrected\ k_{eff} = k_{eff} + \Delta k_{eff} = k_{eff}(1+\frac{\Delta k_{eff}}{k_{eff}}) \qquad (4\text{-}3)$$

The coefficients of the regression are provided in Table 4.1.2-3, and the form of the regression is as follows:

$$\Delta k_{eff}/k_{eff} = C_0+C_1\ln(B)+C_2\ln(B)^2+C_3\ln(B)^3+C_4T+C_5O \qquad (4\text{-}4)$$

where b is burnup in GWd/MTU, and 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 4.1.2-3. Regression Coefficients for $\Delta k/k_{eff}$ as a Function of Dissolved ^{10}B for the 58 vol% Settled Oxide Partially Degraded Basket Configuration

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 5.5 also developed 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 4.1.2-4, and the form of the regression is as follows:

$$\Delta k_{eff}/k_{eff} = C_0+C_1\ln(B)+C_2\ln(B)^2+C_3\ln(B)^3 \qquad (4\text{-}5)$$

where b is burnup in GWd/MTU, and B is the total grams of ^{10}B in solution in the fully flooded WP.

Table 4.1.2-4. Regression Coefficients for $\Delta k/k_{eff}$ as a Function of Dissolved ^{10}B for the 58 vol% 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 5.5 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 4.1.2-5, and the form of the regression equation is as follows:

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

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

Table 4.1.2-5. Regression Coefficients for 58 Vol% Settled Peak k_{eff} as a Function of Burnup and Enrichment

Regression Coefficients	First Fit (Sect. 7.4 Data Only)	Second Fit (Sect. 7.4 + new cases)
C_0	6.08171e-01	6.40653e-01
C_1	-1.05737e-02	-1.02912e-02
C_2	3.46934e-01	3.00169e-01
C_3	1.40880e-07	-2.54581e-05
C_4	-6.71155e-02	-4.90929e-02
C_5	5.80601e-07	9.92035e-07
C_6	5.66667e-03	3.64521e-03

4.1.2.2 Fuel assembly degradation

Section 7.5 of Reference 5.5 has shown that events or processes which lead to a reduction in fuel rod clearance will significantly reduce the k_{eff} of the degraded configuration. Mechanisms which might lead to such a reduction include corrosion of the fuel rods or spacer grids, or crushing of the assemblies by mechanical loading.

Reference 5.28 (p. 40), indicates that at the below boiling temperatures that would be expected in the time frames considered for WP breach, studies have found no localized corrosion of zircaloy in aqueous environments across a pH range of 1 to 12, and in the presence of a variety of ions including lithium, sodium, potassium, ammonium, nitrate, sulfate, chloride, and fluoride. Furthermore, localized corrosion would produce small pinholes and cracks, not significant changes in the assembly geometry. At general corrosion rates, the zircaloy components of the fuel assembly would be expected to last much longer than any other internal components of the WP. Garzarolli has indicated (Ref. 5.29) that the post-transition phase of zircaloy corrosion (the phase following initial oxidation layer formation) prior to irradiation is characterized by the typical Arrhenius equation: corrosion rate = $(5.38 \times 10^{10}\ \mu m/yr)e^{-(14199\ K)/T}$. At 100°C, this yields a corrosion rate of $1.58 \times 10^{-6}\ \mu m/yr$. This is a significantly lower corrosion rate than the corrosion rates for the other basket materials discussed in Section 4.1.3, indicating that zircaloy clad commercial SNF would be expected to resist corrosion and remain intact much longer (following WP breach) than the WP basket componenents. It should be noted that this anlaysis ignores the possible early clad failure mode (called cald unzip) which can release the SNF pellets. There has been no definitive analysis on failure mode, and it is believed to be unlikely. The omission of this failure mode is conservative, since the released pellets would form a more dense configuration, which has been shown to be less reactive with respect to criticality (Ref. 5.5, Section 7.5).

Reference 5.27 evaluated possible static load mechanisms for denting or crushing zircaloy clad Westinghouse 17x17 fuel assemblies such that they no longer provide an optimum geometry for criticality. It was concluded that denting of the fuel rods is not likely to occur because there is sufficient void space for expansion of the corroding basket materials, thus preventing them from causing any load on the fuel assemblies. Furthermore, it was determined that the bottom-most fuel assemblies would be capable of supporting the static load from the entire degraded basket structure, and all fuel assemblies above them, without being crushed. Reference 5.28 (Section 7.8) has performed further structural analysis to demonstrate that other vendors assemblies are at least as robust as the Westinghouse 17x17 assembly, and that the top assembly can support the load of 2.5 m of tuff rubble. However, while the zircaloy fuel rods are relatively robust under static loads, they are not capable of withstanding significant dynamic loads. For example, 100 kg rock falling 2 m will have sufficient energy to break some of the rods on the top row of fuel assemblies (Ref. 5.28, p. 47). Reference 5.27 (p. 64) indicates that at times > 100,000 years, sufficient corrosion of the WP barriers will have occurred such that rocks of that mass or greater will be capable of causing dynamic loads on the fuel if they impact the WP.

As PWR SNF k_{eff} is relatively insensitive to time at fuel ages > 100,000 years (see Ref. 5.5, Sections 7.3 and 7.4), and corrosion or mechanical loading is expected to cause rod consolidation at times > 100,000 years (thus further reducing k_{eff}), internal criticality risk will be evaluated out to 200,000 years.

4.1.3 Basket material properties

Carbon Steel

Reference 5.27 indicates that the 10 mm thick carbon steel side guides required only 60 to 340 years following WP breach to generally corrode to a thickness of 2.9 mm, using a simplification of the TSPA-95 corrosion model for carbon steel and the relative humidity and temperatures indicated for an 83 MTU/acre repository (5.14). Since corrosion occurs on both sides of the guides, this calculation yields a general corrosion rate of 10 to 50 μm/yr.

Neutronit A978 Borated Stainless Steel Corrosion

Several researchers have investigated the general corrosion rates of Types 304 and 316 stainless steels (SS) in J-13 well water environments which roughly bound the range of conditions indicated in assumption 4.3.8. A summary of this corrosion data for temperatures in the 28 - 100°C range is given in Table 4.1-5. These temperatures cover the range expected for the WP internals (Ref. 5.14) for times later than 3,000 years in a repository with a thermal loading of 83 MTU/acre, which is when the majority of WPs will begin to fail and release the He fill gas (Ref. 5.11) which previously maintained an inert environment within the WP. While the specified criticality control material is Neutronit A978 (Ref. 5.11) (with a composition similar to the conceptual borated 316 stainless steel in Ref. 5.31), much of the stainless steel corrosion data collected in repository relevant environments is for 304 stainless steels. This data has been included in Table 4.1-5 because 304 stainless steels have performed similarly to 316 stainless steel in repository relevant tests which included both materials, and they are generally recognized as being less corrosion resistant than 316 stainless steels in harsher environments.

Based on the short term (relative to the time frames being considered) corrosion information in 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 (see assumption 4.3.14). 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 typical corrosion rate for 304/316 stainless steel for this analysis. At a pH slightly below that of the bottom range given in assumption 4.3.8, or Cl^- concentrations (a significant influence on SS corrosion per Ref. 5.33, p. 148) ≈2500x that of J-13, the corrosion rates of 304/316 stainless steels were 1 to 2 orders of magnitude higher than in the typical environment. At a pH near the top of assumption 4.3.8, and Cl^- concentration ≈150x J-13, the corrosion rates were only slightly to one order of magnitude higher than the typical range. Therefore, a rate of 1 μm/yr (one order of magnitude higher than typical) will be used as the upper bound for the 304/316 stainless steel corrosion rate. The lower bound of the 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 occurred during the relatively short duration tests.

Most of the tests reported in Table 4.1-5 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 had a corrosion rate that was 4x that of the unborated material. Reference 5.32 (pp. 3-22 to 3-27) also indicates that borated stainless steels with boron contents between 1-2 wt% show decreased resistance to general, pitting, crevice, and intergranular corrosion in harsh (boiling acidic and/or high Cl^-) environments as boron content increases. 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. 5.32, p. 3-22). Therefore, to more conservatively model the corrosion of Neutronit A978 with the available data, a factor of 4 will be applied to the lower bound, typical, and upper bound corrosion rates defined for unborated 304/316 stainless steels.

4.1.4 Expected waste stream of commercial PWR SNF repository deliveries

Figure 4.1.4-1 shows the distribution of PWR fuel assemblies with $k_\infty \geq 1.0$. Each box in the figure represents a number of assemblies, according to the legend given in the figure. The information used to develop this figure is provided in the BURNRICH.OUT file created in Reference 5.5 (Sect.7.2) from the waste stream data discussed in assumption 4.3.13.

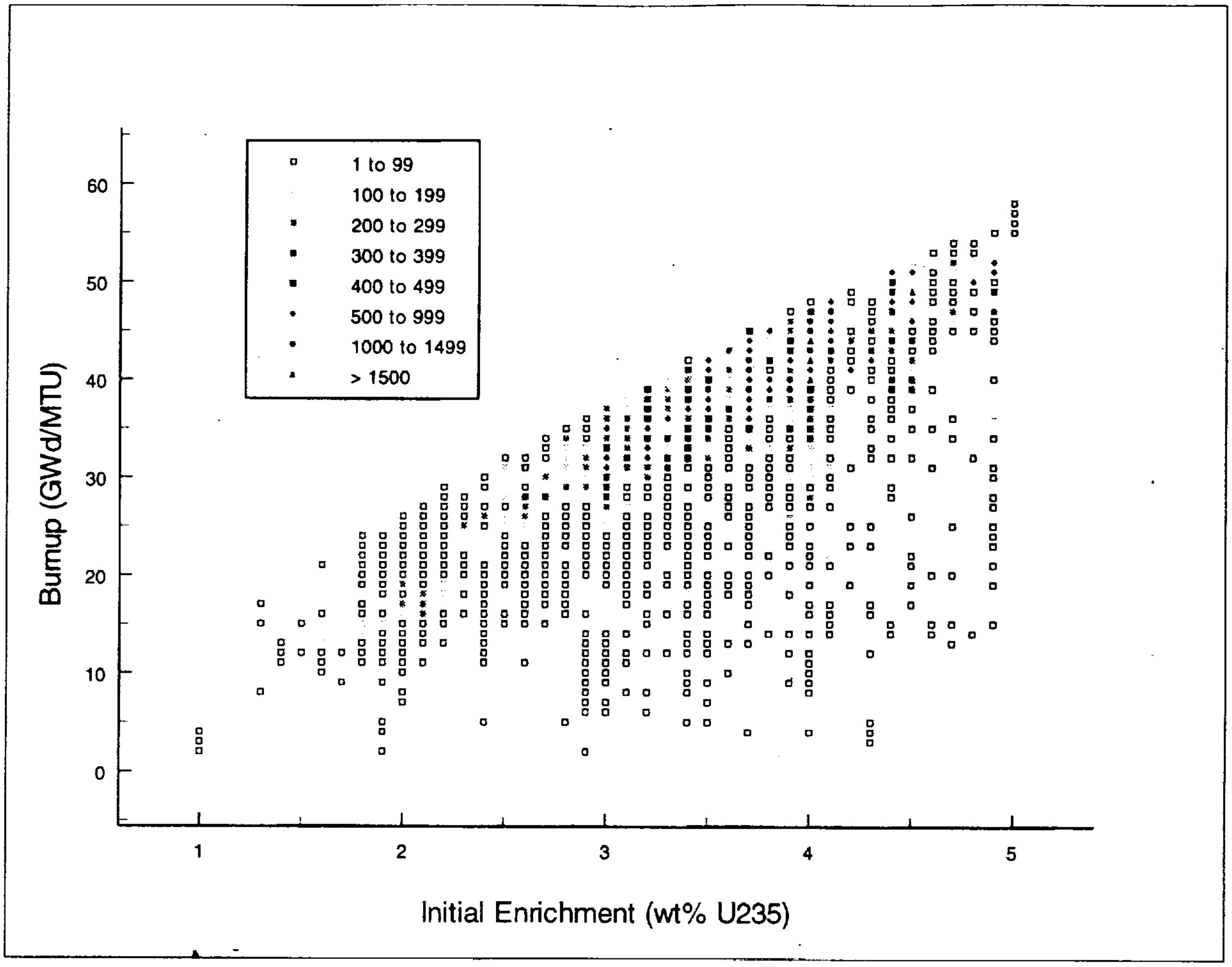

Figure 4.1.4-1. Distribution of Historical and Projected PWR Fuel Assemblies with $k_\infty \geq 1.0$

Table 4.1-5. Type 304 and 316 SS General Corrosion Data

SS Material	Environment	pH	Cl- (ppm)	Test Type	Test Duration (hours)	Test Temp(s) (°C)	Corrosion Rate (μm/yr)	Reference
304L	J-13	7.6[2]	6.9[2]	weight loss	10.4-11.5k	50-100	0.07-0.13	5.21, p. 24
304L	J-13	7.6[2]	6.9[2]	weight loss	3.5-5.0k	50-100	0.03-0.23	5.24, p. 24
304L	J-13	7.6[2]	6.9[2]	weight loss	8.8k	28	0.14-0.45	5.21, p. 26
304L	J-13 w/ crushed tuff	7.6[2]	6.9[2]	weight loss	1k	100	0.25	5.23, p. 79
304L	Simulated J-13 w/ alloy 825 galv. couple	7[2]	6.4[2]	electrochem.	0-1k	90	0.08-0.37	5.22, p. 108
304L	Simulated J-13 w/ alloy 825 galv. couple	7[2]	6.4[2]	electrochem	1-2k	90	0.04-0.07	5.22, p. 108
304L	Simulated J-13	7[2]	6.4[2]	electrochem.	0-2k	90	0.02-0.14	5.23, p. 35
304L	Simulated J-13	7[2]	6.4[2]	weight loss	2k	90	0.57	5.22, p. 117
316L	J-13	7.6[2]	6.9[2]	weight loss	10.4-11.5k	50-100	0.04-0.15	5.21, p. 24
316L	J-13	7.6[2]	6.9[2]	weight loss	3.5-5.0k	50-100	0.10-0.28	5.24, p. 24
316L	J-13 w/ crushed tuff	7.6[2]	6.9[2]	weight loss	1k	100	0.51	5.23, p. 79
304L	Sim. J-13 Sol. 20 (vapor/liq./alternating)	10[2]	1000[2]	weight loss	2.9k	90	0.03/0.29/0.43	5.23, p. 54
304L	Sim. J-13 Sol. 20 (vapor/liq./alternating)	10[2]	1000[2]	electrochem.	0-2.5k	90	0.04-0.18	5.23, p. 56
304L	Sim. J-13 Sol. 20	10[2]	1000[2]	electrochem.	0-1k	90	0.46-1.3	5.22, p. 114
304L	Sim. J-13 Sol. 20	10[2]	1000[2]	electrochem.	1-2k	90	0.04-0.25	5.22, p. 114
304L	Sim. J-13 Sol. 20	10[2]	1000[2]	weight loss	2k	90	1.57	5.22, p. 114
304	Ocean Surface	8[3]	19k[3]	weight loss	9.3k	17.6	14.6	5.20, p. 40
316	Seawater, Kure Beach, NC	8[3]	19k[3]	weight loss	11.5k	0-40[3]	6.11	5.25, p. 21
316	Seawater, Panama Canal	8[3]	19k[3]	weight loss	8.8k/70k/140k	0-40[3]	14.99/6.4/1.25	5.25, p. 21
304L	See Note 1 below	3.8	0.4	weight loss	96	90	10	5.26, p. 14
B-304L	See Note 1 below	3.8	0.4	weight loss	96	90	41	5.26, p. 14

Note 1: 0.01M formic acid, 0.01M sodium formate, 0.02M sodium oxalate, 0.01M nitric acid, 0.01M sodium chloride, 0.01M hydrogen peroxide in dist. water.

Note 2: J-13 and Simulated J-13 composition based on Reference 5.23, Table 2.3. Simulated J-13 Solution 20 composition from Reference 5.23, Table B.3.

Note 3: Seawater composition based on Reference 5.20, Table 28. Temperature based on natural range if not given in reference.

4.1.5 Distribution of environmental parameters

- Infiltration rate (percolation flux at the repository): The present day net infiltration rate is taken to be 5 mm/yr, which is close to the results (6.2 mm/yr)of the most authoritative current Yucca Mountain hydrological model (Ref. 5.35 and assumption 4.3.7). In contrast, the current CDA (Ref. 5.13; see assumption 4.3.7) specifies long-term (up to 20,000 years) WP drip rates of 0.5 m^3/yr (fully mediated; equivalent to 50 mm/yr), with 20 m^3/yr flows occuring once every 40 years (focused flow). This yields an average long term infiltration rate of $\approx$100 mm/yr. Accounting for the maximum factor of 5 due to spatial variations in flux across the repository footprint (see assumption 4.3.7), yields an upper bound of 500 mm/yr for this analysis.

- Fe solubility: The solubility of iron in J-13 well water for various pH and oxidizing/reducing conditions was investigated in Attachment IV of Reference 5.15. Under oxidizing conditions, the solubility of iron was 3.45×10^{-10} molar for neutral J-13 (pH 7), and 2.47×10^{-4} molar for acidic J-13 (pH 2.13). Attachment VI of Reference 5.15 demonstrated that even the small amount of heat produced by the low burnup fuel (20 GWd/MTU evaluated) that is of concern for postclosure criticality is sufficient to drive a small amount of natural circulation and maintain an oxygenated environment in a flooded WP. Therefore, the solubilities for oxidizing conditions will be used for this analysis. Since assumption 4.3.7 indicates that the lowest expected pH is 4.5, an iron solubility of $\approx 3.5\times10^{-7}$ molar (obtained by linearly interpolating between the log of the above solubilities) will be used for conservatism. Multiplying by the molecular weight of iron yields 2×10^{-5} kg/m^3.

4.1.6 Other parameters

The following parameters are taken from standard references and will not change in subsequent analyses. They are, therefore, exempt from the general disclaimer of Section 2 and are considered qualified inputs.

Density of water (Ref. 5.38, p. 665): 995.8 kg/m^3 at 26.67°C
Viscosity of water (Ref. 5.38, p. 665): 8.6×10^{-4} kg/(m*s) at 26.67°C
Density of air at atm. pressure (Ref. 5.38, p. 661): 1.1774 kg/m^3 at 27°C
Diffusion coefficient in water for Cl_2: 1.22×10^{-5} cm^2/s
(all from Ref. 5.37, p. 950) O_2: 1.80×10^{-5} cm^2/s
HNO_3: 2.64×10^{-5} cm^2/s

4.2 Criteria

The *Engineered Barrier Design Requirements Document* (EBDRD; Ref. 5.7) contains several criteria which relate to criticality control. The "TBD" (to be determined) items identified in these criteria will not be carried to the conclusions of this analysis based on the rationale that the conclusions are for preliminary design, and will not be used as input in design documents supporting construction, fabrication, or procurement. A review of the EBDRD and CDA extensions to the EBDRD identified the following requirements pertaining to this analysis:

- The EBDRD requirements 3.2.2.6 and 3.7.1.3.A both indicate that a WP criticality shall not be possible unless at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety. These requirements also indicate that the design must provide for criticality safety under normal and accident conditions, and, that the calculated effective multiplication factor (k_{eff}) must be sufficiently below unity to show at least a five percent margin after allowance for the bias in the method of calculation and the uncertainty in the experiments used to validate the methods of calculation. The latter requirement contains a "TBD" at the end.

- CDA Assumption EBDRD 3.7.1.3.A (Ref. 5.13, p. 4-32) clarifies that the above requirement is applicable to only the preclosure phase of the MGDS, in accordance with the current DOE position on postclosure criticality. This assumption also indicates that for postclosure, the probability and consequences of a criticality provide reasonable assurance that the performance objective of 10CFR60.112 is met. While the Nuclear Regulatory Commission (NRC) has not yet endorsed any specific change for postclosure, they have indicated that they agree that one is necessary.

- Finally, EBDRD 3.3.1.G indicates that "The Engineered Barrier Segment design shall meet all relevant requirements imposed by 10CFR60." The NRC has recently revised several parts of 10CFR60 which relate to the identification and analysis of design basis events (Ref. 5.9) including the criticality control requirement, which was moved to 60.131(h). These changes are not reflected in the current versions of the EBDRD or the CDA. The change to the criticality requirement simply replaces the phrase "criticality safety under normal and accident conditions" with "criticality safety assuming design basis events."

These criteria can be summarized as: (1) Demonstration of the prevention of criticality, (2) Demonstration that the consequences of criticality (even if one did occur) are insignificant. This analysis is part of a continuing sequence which individually contribute to satisfying these criteria in the following manner:

- The occurrence of criticality is shown to be impossible, or extremely unlikely, for some significant period of time, under a range of conditions which could arise in the repository.

- The probability/statistical distribution of criticality occurrence, and time of occurrence, and severity of consequence (particularly increase in radionuclide inventory which is computed in a study closely related to this) will be used as input to the Total System Performance Assessment (TSPA) - Viability Assessment (VA) which, in turn, will demonstrate compliance with the performance objective of §60.112 (as specified in CDA Key assumption 60).

- The sensitivity of criticality performance to design parameters can be used to suggest additional design features which will provide evidence of defense in depth (above and beyond simple compliance with requirements) which provides additional likelihood of regulatory acceptance.

4.3 Assumptions

4.3.1 The *n* individual input parameters associated with single case are assumed to have independent probability distributions, so that probability of their joint occurrence with the particular values manifested in that case is simply the product of the probabilities of the occurrence of these particular values. This assumption is used in Section 6.2.3, and Attachment III.

4.3.2 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 CDA Key 009 (Ref. 5.13). This assumption is used throughout Section 7.

4.3.3 The reference PWR fuel physical assembly selected for preliminary design is the B&W Mark B 15 x 15 fuel type, which has been established as one of the more reactive PWR fuel designs under intact fuel assembly and fixed basket geometry conditions (Ref. 5.19, p. II.6-6). This assumption is used throughout Section 7.

4.3.4 It is assumed that, for the low enriched fuel discharged from a commercial PWR reactor, there can be no fast criticality, and silica moderation is not sufficient to cause criticality (Ref. 5.8, Fig. 7.8-1, which shows $k_{eff} < 0.93$ for 8% UO_2 and water < 14%, for a 150 cm sphere). Furthermore, the analysis of Reference 5.5, Table 7.4-10, showed that keff is significantly depressed when the water level in the waste package drops below the top of the upper layer/row of assemblies. This assumption is used throughout Section 7.

4.3.5 It is assumed that the diffusion coefficient for boric acid (HBO_3) in water is comparible to that of compounds which are similar in size (such as Cl_2, O_2, and HNO_3). The basis for this assumption is engineering judgement. This assumption is used in Attachment VI.

4.3.6 Reserved

4.3.7 The long-term (300 - 20,000 years after emplacement) design-basis ambient (naturally existing) flow conditions are provided by CDA Assumption TDSS 026 (Ref. 5.13, p. 10-22) and are grouped into three categories: Fully Mediated (steady in time and uniform in space), Steady Focused (steady in time and focused in space), and Episodic Focused (episodic in time and focused in space). The flow rates of water onto the WP, and the frequency of occurrence for each category are as follows:

Category	Flow Rate	Frequency
Fully Mediated	0.5 m^3/year	Nominal
Steady Focused	20 m^3 /year	Once per 40 years
Episodic Focused	20 m^3 /year, occurring over one week	Once per 40 years

Furthermore, the Rationale section of TDSS 026 also indicates that the above-mentioned ambient flow assumptions do not consider the spatial variation of average flux across the repository footprint, which is estimated to be between near zero to a factor of five times the average infiltration flux. Finally, TDSS 026 gives the present-day net infiltration rate as 5 mm/yr. This assumption is used in Sections 4.1.5 and 7.4.

4.3.8 The composition of seeping water that enters the excavated volume of the repository per CDA Assumption TDSS 025 (Ref. 5.13, p. 10-20) is assumed to be:

Typical: pH 7.4 (J-13)
Variability: pH 4.5 to 10.5
Concentration factor of 0.1 to 10 times the nominal J-13

These variabilities of the water chemistry are applicable to the water influx at the edge of the excavated volume. The basis for this assumption is given in TDSS 025. For this analysis, the above composition is also taken to be the composition of the water entering the WP. This assumption is used in Section 7.4.

4.3.9 It is assumed, per the WP barrier design goal in CDA Assumption Key 074 (Ref. 5.13), that no more than 10 waste packages will breach within 3,000 years after repository closure when exposed to the near-field environment based on assumptions 4.3.7 and 4.3.8 as modified by the engineered barrier system. Breaching of the waste package is defined as an opening through the wall of the waste package through which advective or diffusive transport of gas or radionuclides can occur. The basis for this assumption is given in CDA Assumption Key 074 (Ref. 5.13, p. 3-64). This assumption is used in Section 7.4.

4.3.10 It is assumed that the repository thermal loading will be within the range of 80-100 MTU/acre. The basis for this assumption is provided in CDA Assumption Key 019 (Ref. 5.13, p. 3-64). This assumption is used in Section 4.1.3.

4.3.11 The following equation obtained from Reference 5.34, page 7, is assumed to provide representative, but slightly conservative values for PWR 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 U235 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 5.34. The basis for using this equation is that it was used in defining the WP design configurations in Reference 5.4, and is used in this analysis only to identify the range of burnups and enrichments of fuels currently intended for a specific WP design. This assumption is used in the computer code described in Section 6.2.5 and Attachment V. The calculation with this formula is used in Section 7.5.7 for comparison with the criticality control threshold used in Reference 5.4; the value c=10 years was used for consistency with that reference.

4.3.12 Reserved

4.3.13 Reserved

4.3.14 It is assumed that the 304/316 stainless steel general corrosion data from immersion in J-13-like environments can be used to represent the bulk corrosion of Neutronit A978 borated stainless steel in repository environments, when increased by a factor of 4. The basis for this assumption is that Neutronit A978 is similar in composition to 316 stainless steel, and corrosion data in repository relevant environments is only available for 304/316 stainless steels. Furthermore, a borated 304 stainless steel was found to have a corrosion rate 4 times that of unborated stainless steel in a short term corrosion test in a harsh environment (see Section 4.1.4). This assumption is used in Section 4.1.

4.4 Codes and Standards

Not Applicable.

5. References

5.1 *Q-List*, YMP/90-55Q, REV 4, Yucca Mountain Site Characterization Project.

5.2 *Perform Probabilistic Waste Package Design Analyses*, QAP 2-0 Evaluation WP-25, 8/03/97, Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O).

5.3 *Quality Assurance Requirements and Description*, DOE/RW-0333P, REV 7, Department of Energy (DOE) Office of Civilian Radioactive Waste Management (OCRWM).

5.4 *Determination of WP Design Configurations*, Document Identifier Number (DI#): BBAA00000-01717-0200-00017 REV 00, Civilian Radioactive Waste Management System (CRWMS) Management and Operating Contractor (M&O).

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

5.6 *Preliminary Waste Form Characteristics Report Version 1.0*, UCRL-ID-108314 Rev 1, Lawrence Livermore National Laboratory, December 1994.

5.7 *Engineered Barrier Design Requirements Document*, YMP/CM-0024, REV 0, ICN 1, Yucca Mountain Site Characterization Project.

5.8 *Probabilistic External Criticality Evaluation*, DI#: BB0000000-01717-2200-00037 REV 00, CRWMS M&O.

5.9 *10CFR Part 60; Disposal of High-Level Radioactive Wastes in Geologic Repositories; Design Basis Events; Final Rule*, U.S. Nuclear Regulatory Commission, Federal Register, Volume 61, Number 234, pp. 64257-64270, December 4, 1996.

5.10 *Waste Package Design Basis Events*, DI#: BBA000000-01717-0200-00037 REV 00, CRWMS M&O.

5.11 *Waste Package Materials Selection Analysis*, DI#: BBA000000-01717-0200-00020 REV 00, CRWMS M&O.

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

5.13 *Controlled Design Assumptions Document*, DI#: B00000000-01717-4600-0032 REV 04, ICN 02, CRWMS M&O.

5.14 *Total System Performance Assessment - 1995, An Evaluation of the Potential Yucca Mountain Repository*, DI#: B00000000-01717-2200-00136 REV 01, CRWMS M&O.

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

5.16 *Input Files and Models Used in the Waste Quantity, Mix and Throughput Study*, Interoffice Correspondence (IOC) #: VA.SAI.MF.03/97.007, CRWMS M&O, March 21, 1997.

5.17 *Probabilistic Criticality Consequence Evaluation*, DI#: BBA000000-01717-0200-00021 REV 00, CRWMS M&O.

5.18 *Characteristics of Potential Repository Wastes*, DOE/RW-0184-R1, Volume 1, USDOE OCRWM, July 1992.

5.19 *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.

5.20 *Survey of Degradation Modes of Four Nickel-Chromium-Molybdenum Alloys*, UCRL-ID-108330, Lawrence Livermore National Laboratory, March 1991.

5.21 *Progress Report on the Results of Testing Advanced Conceptual Design Metal Barrier Materials Under Relevant Environmental Conditions For A Tuff Repository*, UCID-21044, Lawrence Livermore National Laboratory, December 1987.

5.22 *Pitting, Galvanic, and Long-term Corrosion Studies on Candidate Container Alloys for the Tuff Repository*, NUREG/CR-5709, U.S. Nuclear Regulatory Commission, January 1992.

5.23 *Immersion Studies on Candidate Container Alloys for the Tuff Repository*, NUREG/CR-5598, U.S. Nuclear Regulatory Commission, May, 1991.

5.24 *Electrochemical Determination of the Corrosion Behavior of Candidate Alloys Proposed for Containment of High Level Nuclear Waste in Tuff*, UCID-20174, Lawrence Livermore National Laboratory, June 1984.

5.25 *Survey of Degradation Modes of Candidate Materials for High-Level Radioactive-Waste Disposal Containers, Volume 2 - Oxidation and Corrosion*, UCID-21362 Vol. 2, Lawrence Livermore National Laboratory, August 1988.

5.26 Van Konynenburg, R.A., Curtis, P.G., "Scoping Corrosion tests on Candidate Waste Package Basket Materials for the Yucca Mountain Project", *High Level Radioactive Waste Management - Proceedings of the Seventh Annual International Conference*, American Nuclear Society, pp. 464-467, April 29 - May 3, 1996.

5.27 *Emplaced Waste Package Structural Capability Through Time Report*, DI#: BBAA00000-01717-5705-00001 REV 00, CRWMS M&O.

5.28 *Design Basis Cladding Analysis*, DI#: BBA000000-01717-0200-00054 REV 00, CRWMS M&O.

5.29 *Review of PWR Fuel Rod Waterside Corrosion Behavior*, EPRI NP-1472, Electric Power Research Institute (EPRI), August 1980.

5.30 Stehle H., Garzarolli, F., Garde, A. M., Smerd, P. G., "Characterization of ZrO_2 Films Formed In-Reactor and Ex-Reactor to Study the Factors Contributing to the In-Reactor Waterside Corrosion of Zircaloy", *Zirconium in the Nuclear Industry*, ASTM STP 824, American Society of Testing and Materials (ASTM), 1984.

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

5.32 *Borated Stainless Steel Application in Spent-Fuel Storage Racks*, EPRI TR-100784, EPRI, June 1992.

5.33 Sedriks, A. John, *Corrosion of Stainless Steels,* John Wiley & Sons, Inc., 1996.

5.34 *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.

5.35 Flint, A. L., Hevesi, J. A., Flint L. E., *Conceptual and Numerical Model of Infiltration for the Yucca Mountain Area*, U. S. Geological Survey, 3GUT623M, September 20, 1996.

5.36 Fox, R. W., McDonald, A. T., *Introduction to Fluid Mechanics*, 3rd Edition, John Wiley & Sons, New York, 1985.

5.37 Gebhart, B., et al, *Buoyancy-Induced Flow and Transport,* Hemisphere Publishing Corporation, New York, 1988.

5.38 Holman, J. P., *Heat Transfer,* 7th Edition, McGraw-Hill Publishing Company, New York, 1990.

6. Use of Computer Software

6.1 Scientific and Engineering Software

None Used.

6.2 Software Routines

The first two programs described in this section (generate.c and snfpkg.c) were written specifically for the evaluation of degraded mode waste package criticality (either internal or external to the waste package). They represent an evolution from previous versions which were used in prior degraded mode waste package criticality analyses. It is expected that they will be expanded for further use in subsequent analyses of this type. For this reason they are to be considered software routines according to QAP-SI-0/Rev. 2, Section 5.3. As such, they have been tested by visual inspection by individuals who have had no role in the development of the software. They are presently compiled and run on both a PC using Windows 95 (using Microsoft Visual C++) and on a UNIX workstation (using the ANSI Standard C).

The remaining three programs described in this section (preproc.c, postprc.c, and loadcurv.c) were developed to support the use of the first two programs, so their qualification and use will satisfy the same set of requirements.

The versions of these software routines are all September 8, 1997, as shown in Attachments I-V.

6.2.1 generate.c

This program is the general configuration generator, which is the basic implementation of the probabilistic methodology. It is described more fully in Section 7.1 and is listed in Attachment I. The program tracks the values of parameters which characterize the state of the system, particularly those which relate to the amount of fissile material in locations. These locations are of two types: ponds and paths. The ponds are characterized by being able to support some form of retained water which can serve as moderator; the waste package is the zeroth pond. The paths support the flow between ponds.

The parameters are of two types: those with initial values read from the input file, and those with initial values specified in the source code. At the present time there are only 4 parameters read from the input file: infrate (infiltration over the package), pkgwout0 (the nominal outflow from the package), dissrate[0] (dissolution rate of form 0, in this case representing the immobilized Pu waste form), and prob (the probability of the configuration); pkgwout0 is are in cubic meters/yr; dissrate[0] is in gm/sqm/yr; infrate is in mm/yr. The source code parameters are mostly initialized in the subroutine setupv(), except for the arrays pkgin (concentrations in the water infiltrating to the package), issolchanger (elements set to 1 for species which have a strong effect on the pH, such as chromate), issolvar (elements set to 1 for species whose solubility is strongly determied by pH, such as U or Gd). M-K-S units are used throughout, except for infiltration rates, which are mm/yr to conform to common usage.

The infiltration and outflow rates (infrate, pkgwout0) are constant in this version, but may be made time dependent in the future. The concentrations in these flows in the waste package are pkgin[SPECIES], which is presently initialized in the global declaration and pkgout[SPECIES], or cout[SPECIES] for any type of pond. There are two types of change of species mass or concentration: those which proceed at a some determined rate, so that the amounts are multiplied by the timestep (inflow, outflow, dissolution, and radioactive decay); and those which are assumed to be completed at each timestep, no matter how short (transferring among dissolution product, in solution, and in precipitate), so that the changes are not multiplied by the length of the timestep.

The global variable cout[SPECIES] (in kg/cubic meter)is used to transfer from one location to the next. It is used as input for each update subroutine and then reset for use by the next in the sequence. The only exception is package, which takes input from the initialized pkgin[SPECIES]. If more than one object will feed another object (such as both the drift and the package feeding the invert) then the two feeds will be combined in a special subroutine, such as backfill(TIMESTEP). It should be noted that several of the arrays used to record amounts in locations and/or of species will be sparse because for many of the locations only a limited subset of SPECIES will be used; furthermore, the density of elements in these arrays is further decreased because many of the characteristics of ponds and paths are so different that array elements which are nonzero for paths will be zero for ponds and vice-versa.

6.2.2 snfpkg.c

This program is the specialization of the configuration generator to the waste package interior. This specialization is done for the following reasons:

- Avoid large memory requirement associated with path-delayed transport (several megabytes for retarded matrix flow)
- Add specialized capability to process the waste stream database (10 megabytes)

The program tracks the kg of boron and iron in a PWR WP, as they are oxidized from the steel into scale deposits, solution, and ultimately flushed from the package by the water either flowing through the package or overflowing. As with generate.c, the program numerically integrates a set of first order linear differential rate equations defining the corrosion processes. The program also computes the fraction of the expected commercial SNF (from the waste stream database) which will be critical at time, as a function of: borated stainless (basket) thickness, iron oxide remaining in the package, and boron remaining in the package after complete degradation of the borated stainless, as well as the individual SNF batch characteristics (burnup and initial enrichment). This program and the inputs and outputs for this analysis are listed in Attachment II.

6.2.3 preproc(*n*).c

This program generates sets of *n*-tuples of input parameters and the associated probability for the *n*-tuples (each of which forms a case to be run by generate.c or snfpkg.c. There are different versions of the program for each value of *n*, the number of input parameters. This program is listed in Attachment III.

6.2.4 postprc(*n*).c

This program analyzes output parameters and probabilities for each case to generate probability distributions for key output parameters by sorting output parameter-probability pairs according to the value of the parameter, where *n* is the number of output parameters to be analyzed. This program is listed in Attachment IV.

6.2.5 loadcurv.c

This program evaluates a k_{eff} regression against the waste stream of expected repository receipts (as given in the data transmission with Ref. 5.16). For comparison purposes, it also calculates k_∞ against the same waste stream using the k_∞ regression given in Reference 5.34. This comparison is expressed as the fraction of PWR SNF having k_∞ below some limit (e.g., 1.13) which will have k_{eff} above some regulatory limit (e.g., 0.93). This program is listed in Attachment V.

7. Design Analysis

7.1 Criticality Control Measures and Degradation Scenarios

The commercial SNF waste package criticality control measures are designed to prevent criticality when intact and when degraded. Since the commercial SNF exhibits a broad range of reactivities, the waste package criticality control measures are grouped into separate designs to cover this range of reactivities in three segments, as defined in Reference 5.4. For the least reactive SNF, little or no neutron absorber is necessary to prevent criticality, so the iron in the carbon steel which forms the basket structure will be sufficient. For the moderately reactive commercial SNF, a stronger neutron absorber is required; this function is provided by borated stainless steel plates which are inserted into the waste package basket structure between adjacent assemblies, where their neutron absorption can be the most effective. For that small fraction of the commercial SNF which is the most reactive, a third design is required. This third design provides very strong neutron absorption by means of control rods (placed within the assembly guide tubes) made of zircaloy clad boron carbide (B_4C).

However, the effectiveness of the criticality control measures will be reduced by eventual degradation of the neutron absorber material. Of the three general waste package designs for PWR commercial SNF, the one with borated stainless steel plates (to be used for the moderately reactive fuel) is most appropriate for extensive analysis at the present time for the following reasons: (1) it covers most of the commercial SNF for which criticality could be a possibility; (2) it is the one most susceptible to aqueous degradation; and (3) it is the only one for which there is presently an established design.

The waste package degradation scenarios used in this analysis are similar to those used in the previous evaluations of References 5.12 and 5.15, but are characterized in greater detail and over a greater range of the principal parameters, in order to support the detailed evaluation of the entire spectrum of commercial PWR SNF. As with these previous analyses, the degradation scenarios leading to criticality begin with breach of the waste package barriers by aqueous corrosion, followed by corrosion of the carbon steel of the basket structure and then the degradation of the borated stainless steel plates.

From Sections 4.1.2 and 4.1.3, it is seen that the corrosion rate of the zircaloy cladding of the SNF is much slower than the corrosion rates of the two principal materials which make up the basket (carbon steel and borated stainless steel). Therefore, the basket materials will degrade while the SNF is still mostly intact. What is not known is the exact disposition of the basket material after it has degraded. The iron oxide is very insoluble and will tend to precipitate, but the distribution of the precipitate could range from: (1) collecting equally on all the available surfaces, to (2) settling into the configuration with the lowest gravitational energy, limited only by the maximum density of hydrated iron oxide. The parameters for these two alternatives, called the uniform and settled distributions, respectively, are described in some detail in Reference 5.5.

The uniform distribution means that the iron oxide is distributed throughout the waste package wherever there is water. The settled distribution has two different manifestations, depending on whether the basket is partially degraded or fully degraded. The settled distribution for the partial basket will fill the lower portion of each assembly cell with 1/21 of the total oxide formed thus far from the degradation of the carbon steel in the assembly tube basket structure and from the degradation of the borated stainless steel, but not from the carbon steel guides and supports. For the fully degraded basket, the settled distribution will fill the lower portion of the waste package with all of the iron oxide from the complete degradation of the basket, so that some of the assemblies are completely covered by iron oxide while others see no iron oxide at all. These two alternative configurations are described more fully in Reference 5.5, where they serve as the basis for MCNP evaluations of criticality which were used to develop the regressions for k_{eff} in that document, which are repeated in this document in Section 4.1.2.1 for reference.

7.2 General Configuration Generator

7.2.1 Background

Previous evaluations of the possibility of degraded waste package criticality have used computer codes to track the concentrations of fissile and neutron absorber species and estimate k_{eff} for the most likely geometric configurations. Specifically, two general codes were developed: one for commercial SNF in a waste package with partly or completely degraded basket, and the other for degraded immobilized plutonium waste forms (glass or ceramic) with fissile material collected in clay precipitate in the lower portion of the waste package. It is now desired to combine and extend these codes to be able to cover the four general categories of waste form expected at the repository which have significant criticality potential: (1) commercial SNF, (2) DOE owned SNF, (3) immobilized plutonium waste forms, and (4) mixed oxide (MOX) SNF containing plutonium from decommissioned weapons. This program is also intended to be able to track all the successive stages of waste form degradation and the resulting possible criticality locations: internal, near-field external, and far-field external.

For this purpose, the locations are divided into two categories: paths and ponds. Paths represent vertical flow through a geologic layer of the repository. Ponds represent locations where fissile material can be concentrated in a critical mass and where there can be sufficient water as moderator to cause a criticality. The waste package itself is designated as pond number 0, but its concentrations are computed by a unique subroutine, which is initially driven by the dissolution rates of the waste forms and the basket materials, and by the concentrations in the water dripping or infiltrating into the waste package. The other ponds, and all the paths, are driven only by the concentrations in the inflowing water (solution). Ponds are nominally connected by one or more paths (in series), although ponds may be directly linked without any intervening path (e.g., the package outflow feeding a possible pond in the invert). The algorithms used to model these two regime categories are described in the following sections.

7.2.2 Technical approach

Algorithms are constructed to model the physical and chemical processes, which include the following:

- Trace movements of fissile and absorber elements between entities (ponds and paths between) from initial concentrations/locations (which are also entities). For most waste forms there will be no ponds within the waste package, but only the waste package pond and the possibility of external ponds. The paths will have the capability for retardation of the fissile material, particularly U. Ultimately, retarded fissile material may be remobilized. The relative importance of retardation and remobilization will be determined by whether significant remobilization can occur within the time horizon which could be as high as 1,000,000 years.

- Account for water buildup as a function of time (both to transport key elements and to provide moderator for criticality).

- Determine criticality potential as a function of time at individual locations, which are defined as either ponds or localized water supersaturations (e.g., moist clay, or porous region in the saturated zone).

- Probability evaluated by the joint occurrence of individual selections.

The principal features of the current implementation are as follows:

- Species tracked, and their indices: (0) U235, (1) U238, (2) Pu, (3) Gd, (4) Cr, (5) Fe, (6) Carbonate, (7) Boron

- Forms which could be tracked and their indices: (0) Non-SNF waste form (glass or ceramic), (1) SS containing Cr, (2) depleted uranium (DU) invert backfill (in the space between WP support piers), (3) DU filler in the waste package (not presently used), (4) Carbon steel (containing Fe), (5) SNF. Note: Since this document reports no calculations with this code, no specific assumptions for the masses of these forms are made.

- Locations (pond and path) tracked and their indices: (0) Waste package [pond], (1) Invert [pond], (2) Path through 10 meters of host rock beneath the waste package.

- DU backfill is evaluated in the backfill() subroutine which gets the DU from the backfill form[dduid], with dduid=2. The drift is a special location which is neither pond or path, since it is averaged together with the waste package in feeding the invert.

- The timestep interval is TINT years. Each case continues until it reaches the specified time limit (maxyrs) or runs out of iron.

- When the concentration of either type of steel reaches zero, it may overshoot to a negative value. The steel concentration is easily corrected to zero, but a special takeout accounting must correct for the extra addition into the oxide pool caused by the fictitious negative steel removed.

- The program reads case specific parameters from the input file "generate.in" which can contain any number of cases, with one input line per case.

- Output is printed to 3 files: "generate.out" which provides a detailed listing of the amounts of iron at each 1,000 year time interval, "generate.log" which lists the relevant parameters at the completion of each case, and "summary.out" which gives only one line of output for each case, with that line including the probability (see discussion of preproc.c and postprc.c).

7.2.3 Probabilistic selections

The following parameters influence the occurrence of a configuration capable of criticality. The specific values to be used will be determined probabilistically, as appropriate.

- Acidification of water within the waste package by oxidation of Cr atoms in the corrosion of SS. This process will enhance removal of some absorbers, e.g., Gd. It may also enhance the removal of U and Pu from the waste package (which acts as a source term for the external environment). If bacteria can be demonstrated to produce a quantifiable acidification, then such acidification will also be considered in the model.

- Infiltration rate.

- Whether there is standing water in the package ("bathtub").

7.2.4 General rules for ponds and paths

- Paths can connect between only 2 ponds.

- Paths can go in only one direction.

- Paths are characterized by flow velocities which imply transit times. The velocity and any retardation, filtering or addition of suspended or dissolved material is determined by the abstraction from hydraulic transport calculations.

- Ponds can have volumes and masses which can support criticality. Paths will only have the capability to track entering and exiting concentrations and will not have the concentrations to support criticality. If preliminary analysis shows that some portion of a path can have concentrations which would support a k_{eff} greater than 0.9, there is an implication that the path is acting as a pond, and it will be reevaluated to determine if it should be partitioned so that one, or more, pond(s) is created. In each pond, there will be bookkeeping by species in solution, species in precipitate, and total amounts of forms (for which the individual species are fixed by the input).

- Ponds are connected to 2 paths, one input path and one output path, except for the waste package which is a pond, but is connected directly to the next pond, the invert. It should be noted that both the package and the invert are only ponds under the conditions in which they can hold water.

7.2.5 Properties of ponds (including the waste package as a pond)

- The fundamental bookkeeping variables of a pond are the water volume, and the masses of each species in solution and in precipitate. The concentrations in solution and in the outflow are then determined from the water volume and the masses in solution.

- The concentration of each element in solution is equal to the solubility limit of that element or the total mass of that element divided by the water volume, whichever is smaller.

- Balance of species in solution and precipitate will be tracked with the variables msltn[pondid][speciesid], precip[pondid][speciesid], for mass in solution and in precipitate, respectively. For the waste package, these are specialized to pkginsltn[speciesid], and pkginprecip[speciesid], respectively. They are simply updated at each timestep, and not recorded as a function of time (since that would impose too great a memory requirement). The update is according to chemical reactions in the pond, and the amounts of each species being transported in and out of the pond, which are specified by pkgin[speciesid] and cout[speciesid] for the input to the waste package, and the output from the previous upstream location for all subsequent ponds.

- For species, i, which are solubility limited, the kg of species i in solution in the waste package will be, pkginsltn[i] = (water/1,000) pkgsol[i] (solubility of species i in the package solution), where variable water is expressed in m^3. The 1,000 factor adjusts for the fact that pkginsltn[i] is in kg, while pkgsol[i] is in ppm which is approximately the same as g/m^3.

- Any mass of an element in excess of the solubility limit will be assumed to be in the precipitate (or adsorbed, for those cases in which an adsorber, and associated distribution coefficient, is identified). The only exception is the waste package (which is also a pond) for which there is also element mass in the initial solid forms, which will be dissolved according to some dissolution rate which may vary with solution characteristics.

- The effects of circulation within a pond are modeled. The timestep is always chosen to be at least a few thermally driven circulation times, to assure that the species concentrations will be uniform throughout the solution over the timestep.

- For packages which contain SNF only, there will be only a single pond for the entire package. If such ponds contained significant amounts of stainless steel they would present an important possibility for production of acid. The concentration of chromate ion could build up to a steady state; for such situations it may be useful to use the steady state concentration:

$$\text{Concentration} = 365 r_0 A_s/(ex*i*A_i) \ (\text{kg/m}^3 \text{ or g/liter})$$

where:

r_0 dissolution rate in $g/m^2/day$,
i infiltration rate in mm/yr,
ex is the exchange (flushing) factor which is always less than 1; the range of numerical values is estimated in Attachment VI,
A_s surface area of the degrading material (in this case, stainless steel),
A_i waste package, or pond, cross section area transverse to the direction of infiltrating flow.

In general the surface area of the degrading material within a pond is expected to be comparable to the surface area of the pond itself. For some materials, A_s may be considerably enhanced by internal fracturing, although this is not expected for stainless steel.

- The solubility limit of an element is either a constant throughout the run or a variable determined as a function of pH and/or other solution characteristics. For the variable case, the chemistry used to develop the formula(s) will reflect the alternative ionic species available for each element. To reflect this complexity, there will be bookkeeping of all the species which can significantly effect the pH, or otherwise influence the solubility of the neutronicaly active elements. Those species which have their solubilities computed have their indices specified by ones in the array issolvar[SPECIES]. Solubility calculations will override any input solubility values, so all species could initially be given nominal constant solubilities without raising any conflicts.

- For computing pH to use in the solubility calculation, the concentration of H ions is accumulated by adding the concentrations of the negative ionic species which are matched with hydrogen ions in acidic solutions (e.g., chromate).

- For each variable solubility species, the solubility is abstracted into a piecewise log-linear function of pH with up to 4 segments. The variable array to record which species change pH is issolchanger[SPECIES]. The formula for pH is:

  $pH= -\log_{10}(x)$, where x=sum over i {phcoef[i]*csltn[i]/pkgwater}.

  The log-linear formula for the solubility of each species and for each segment of the pH range is:

  Log slblty[speciesid][segmentid] = alpha[speciesid][segmentid]*pH +
  beta[speciesid][segmentid],

  where the parameter, segmentid, identifies the discrete range (or bin) of pH values into which the particular pH happens to fall.

- For very shallow ponds, and/or at times greater than 100,000 years, there may be insufficient temperature difference to drive thermal circulation. Nevertheless, preliminary calculations indicate that there will still be sufficient mixing driven by: (1) molecular diffusion, and (2) mechanical mixing driven by the impulse and momentum of infiltrating drops or films.

- It will generally be assumed that dissolution is congruent so that each element in the dissolving solid will be released at a fraction of the entire dissolution rate, which is given by the ratio of the element mass remaining in the solid to the total mass of the solid (which should be equal to the initial mass fraction of the element in the solid). In considering the dissolution, the designation "waste form", or simply "form", is used for all initial solids in the package which dissolve and release species of tracking interest. This is the most convenient way to assure the accounting of all sources for each species; however, the matrix formfrac[FORMS][SPECIES] may be sparse.

7.2.6 Calculations at each time step for each pond

- Decay of isotopes (for the present this is only ^{239}Pu).
- Solubility of species whose solubility depends on ion concentrations or pH.
- Amounts of solids dissolved (waste form, basket).
- Amounts of species precipitating at this time step (amount dissolving at this time step minus the amount in solution being removed from the waste package).
- Amounts in solution (balance of the above 2 amounts plus the net flow of all the connected paths, through the interfaces).
- Criticality (k_{eff}) at each of the potentially critical locations (based on regression at each of those locations, developed from several hundred MCNP calculations using the environmental parameters appropriate to that location, accounting for isotopic decay by specifying ranges of time over which the effect of time variation of isotope decay will be small. At the present time, the general code contains only the regression developed for some configurations which may result from the immobilized Pu waste form. However, the specialized waste package code (snfpkg.c) incorporates regressions covering the entire range of concentrations of neutronically active species expected to be encountered in the degradation of the basket of a commercial SNF waste package. The specialized waste package code also restricts k_{eff} computation to specified time intervals, because it must be calculated for every commercial SNF expected at the repository, which would require excessive time. These special conditions for snfpkg.c are explained fully in Section 7.3, below.

7.2.7 Properties of paths

- Flow into a path is nominally assumed to be equal to the flow out of the pond for which it serves as exit. There is also the possibility of mixing with water already in the path, or infiltrating from immediately adjacent regions of the drift (possibly influenced by backfill). The outflow from the path defines the inflow to the subsequent pond or path. The water flow rate out of a path is equal to the water flow rate into the path.
- The fraction, *f*, of the flow which is in the fractures; the rest is in the matrix. No specific values are assumed at this time.
- The fundamental bookkeeping variables of a path are the mean infiltration velocity, and the concentration of each species in that water.
- Species concentration in the fracture fraction of a path outflow is the same as the concentration in the inflow. [The path from the waste package may have this initial concentration diluted by mixing, as mentioned in the first bullet, above.]

- Species concentration in the matrix fraction of the outflow is reduced, from that in the inflow, according to the retardation equation, given below.

- The matrix flow in the path is modeled by the retardation equation given in TSPA-95 (Ref. 5.14, Eqs. 7.4-13 and 7.4-15):

$$\frac{\partial c_i}{\partial t} + \frac{u_w}{R_{di}\phi S_w}\frac{\partial c_i}{\partial x} = 0$$

  where c_i is the concentration of species i at time t and position x, ϕ is the porosity of the rock, R_{di} is the retardation coefficient of species i, S_w is the groundwater saturation, and u_w is the infiltration rate, assumed to be uniform over the penetration area of interest (typically the footprint of a single waste package).

- The concentrations in the flow out of the path depend on the time from the first appearance of a fissile bearing solution at the entrance to a path. The three functional forms for this dependence are as follows:

  (1) **$t<t_1$** $(t_1=L\phi_f/u_w)$, where

  L is the length of the path (or thickness of the layer);

  ϕ_f is the fracture porosity, defined in TSPA-95, where it is assumed to be 0.001;

  t_1 is the earliest time for fracture flow through the path, or layer, and is, therefore, called the breakthrough time for fracture flow. Preceding this time, the flow out of the path is not yet influenced by the concentrations flowing in.

  (2) **$t_1<t<t_{2i}$** $(t_{2i}=R_{di}\phi S_w L/u_w)$

  Before the earliest of the t_{2i} (called the matrix breakthrough time for species i) all the outflow is due to the fracture flow, and the concentrations are given by: $c_{i,out}=fc_{i,in}(t-t_1)$, for all species i.

  (3) **$t_{2i}<t$**

  After the time exceeds the breakthrough time for a species, its concentration in the outflow is given by: $c_{i,out}=fc_{i,in}(t-t_1)+(1-f)c_{i,in}(t-t_{2i})$

- The above derivation incorporates the tacit assumption that flow through a layer can transfer between fracture and matrix only at the interface between layers (or paths). In fact, the frequency of this transfer process is not known so it is appropriate to evaluate alternatives such as 3 transfers during the flow through a path (or layer). The resulting expression for the concentration of species i in the outflow is:

$$c_{i,out}=f^3c_{i,in}(t-t_1)+3f^2(1-f)c_{i,in}(t-(2t_1+t_{2i})/3)+3f(1-f)^2c_{i,in}(t-(t_1+2t_{2i})/3)+(1-f)^3c_{i,in}(t-t_{2i}),$$

  where the function $c_{i,in}(t) = 0$ for $t<0$. The code will have the option to incorporate several alternative transfer schemes as part of a probability distribution.

- The derivation of the retardation equation given in TSPA-95 appears to assume that the concentration of each species in the solid will immediately equilibrate to its steady state value of K_i times the concentration of the same species in solution (where K_i is the distribution coefficient for species i). In actual fact, the concentration cannot propagate through the layer until concentration is brought up to the equilibrium steady state value. This would appear to make a significant difference, particularly if $K_i>>1$. However, the form of the retardation equation actually accounts for this fact, as can be seen for the case of $K_i>>1$, where the retardation coefficient becomes $\rho K_i/(\phi S_w)$, which gives $t_{2i}=\rho K_i L/u_w$, which is just ρK_i times the matrix propagation time. For uranium in zeolite, the K_i could be as high as 500. If the very conservative value of $K_i=50$, $u_w=4$mm/yr, $\rho=2.5$, $L=10$ meters (for a conservative estimate of zeolite layer effective thickness, which accounts for the fact that zeolite is only 50% of the rock), then the breakthrough time for uranium is $t_{2i}=600{,}000$ years. In contrast, with these same parameters (including $\phi_f=0.001$), a typical breakthrough time for fracture flow is $t_1=2.5$ years.

- For large values of t_{2i}, storage provision must be made for values of $c_{i,in}$ for timesteps from t_e to $T-t_{2i}$ (where t_e is the time of first entry of species i into the path, and T is the time period covered by the run).

- In any single path (or layer) there is assumed to be no mixing between fracture and matrix flow, but between two successive paths (or layers) there is assumed to be complete mixing. Within a path, this is physically equivalent to the maximum possible amount of unhindered fracture flow, and is, therefore, conservative. This is also the assumption used in TSPA-95.

7.2.8 Calculations at each time step for each path

- Delayed time at which parcel of water now leaving path initially entered the path, for fracture travel, matrix travel, and up to a specified number of switchings, which are a simplified way to model the interactions, between the two (3 in the present version).

- Output concentrations from inputs at delayed times, including up to 3 switchings between fracture and matrix.

7.2.9 Parameters fixed for all cases

- Isotope decay rates (principle isotopes for burnup credit).

- Solubilities for a few species.

- Waste package characteristics, including materials, materials performance, geometry, void space.

- Characteristics for each of the waste forms to be analyzed.

7.2.10 Variable Inputs

These are specified in an input file, which may change at each case, and parameters which are specified in the source code and cannot be changed without recompiling. Since the compilation takes only a few seconds, these source code parameters can be changed fairly easily, as well. Only the input parameters can be varied over statistical distributions, which variation is provide by preproc(x).c, described in Section 6.2.4, and in Attachment III. However, only trivial modifications of the program can exchange one, or more, of the true input parameters with some of the source code parameters, so all can eventually be subject to statistical analysis. Note that values for all of these input parameters are not included in Section 4 because the generate.c code was not specifically used for this analysis.

- Start and end time (initial significant waste package penetration).
- Initial concentrations.
- Form geometry. These forms will eventually include several categories such as sphere and plate, which represent the two extremes of corrosion rate as a function of mass remaining. The sphere (which will be used for most of the external criticality concentrations) has a remaining surface area proportional to the 2/3 power of the mass remaining (as the degradation process proceeds) and the plate (which will be used for the canisters, which contain glass, and for the basket plates) having surface area approximately independent of mass remaining. Geometry factors influencing the effective corrosion rate are also manifested in the fracture factor (ratio of total surface area to outer surface area).
- Dissolution rates (per unit area).
- Pond definitions (location and size) (not yet implemented).
- Path definitions (from and to ponds) and the corresponding fracture flow factors (flow in fractures)/(flow in fractures + flow in matrix).
- Environmental parameters (including infiltration rates to individual ponds which result from concentration factors, temperature as a function of time, and transport properties of the rock which forms the paths.

7.2.11 Database

These are source code parameters which are not considered for change.

- Names of elements of interest:

Strongly neutronically active:	Pu, U, Gd, Hf, B
Little neutronically active:	Mn, Fe (in 2 types of steel), Fe_2O_3
No neutron activity:	oxygen, but may effect the solubility and chemistry of neutronically active species, e.g., Cr.

- Solubility for each element (expressed in ppm and based on known mineral species and pH).

- Names and dissolution rates of initial solids (steel, waste form), as a function of pH or other parameter which might characterize an individual pond.

- Proportion of each species in the initial solids (to give release rate for elements from dissolution rate of the containing species).

- Names and location/geometry of solid/mineral precipitate forms (within the waste package, e.g., clay).

7.2.12 Future extensions

- High alkalinity of entering water from the concrete liner, or from glass (e.g., immobilized Pu waste form, codisposal of high enriched SNF) or other alkaline material within the waste package. This increases the solubility of U or Pu from the waste form, but is only important after significant degradation of the waste form has begun (which might be as small as 5,000 years for the immobilized Pu or aluminum clad/matrix SNF waste forms, but is expected to be upwards of 20,000 years for commercial SNF).

- Water level categories (up to 5 to develop separate families of k_{eff} regression).

- For codisposal of DOE-SNF and for immobilized Pu waste forms, there can be significant amounts of clay formed in the bottom of the package, and this clay could have several ponds formed in pockets on the surface. [at the present time, multiple ponds within a waste package are not implemented.] Each of these several ponds could have its own source of dripping water, and all but the highest could also be fed from other ponds. This is the only case in which one pond could feed several paths, and several paths could feed one pond.

- Processes which increase water in the repository: (1) increased infiltration rate, (2) plugging of holes, and/or (3) buildup of hygroscopic mass. At the present time the water infiltration rate is fixed at a constant value throughout the run.

- Processes to decrease water: (1) creation of new holes (corrosion), and/or (2) opposite of increasing processes (previous item). At the present time the water infiltration rate is fixed at a constant value throughout the run.

- Circulation and diffusion to reoxygenate, spread acidification (or basification), to verify homogenization within a timestep. This capability has not yet been implemented.

- Change in pH and other ionic concentration changes, which can arise from dissolution and oxidation, and which can lead to changes in solubility.

7.3 Specialized configuration generator

The computer code snfpkg.c is a specialization of the genera l configuration generator code (generate.c), and all the description of that code in Section 7.2 applies here, except for those features which deal with tracking material outside the waste package. The specialization is to evaluate the entire inventory of commercial PWR SNF expected for emplacement at the repository. For this purpose, the following are additional features provided by this specialized code:

- The k_{eff} regressions developed in Reference 5.5, and restated in Section 4.1.2.1 are incorporated into the code. In keeping with the qualitative discussion of scenarios given in Section 7.1, there are two basic forms of the regression: partially degraded basket and the fully degraded configuration, which are repeated in this document in Section 4.1.2.1 as equations 4-1 and 4-2, with regression coefficients given in Tables 4.1.2-1 and 4.1.2-2, respectively. The computer code calculates the time to dissolve the borated stainless steel plate, as a function of the corrosion rate of the borated stainless steel, and switches from the partially degraded basket regression to the fully degraded configuration regression at this time. This lifetime of the basket is named tbskt, and is used for the discussion of results in Section 7.5. If the infiltration rate is low, the effect of boron in solution may be significant while the borated stainless steel is degrading, and for some time thereafter. This is accounted for by the correction shown in equation 4-3, which uses the regressions of equations 4-4 and 4-5 for the partially degraded basket and the fully degraded configuration, respectively. At the present time, this correction factor has only been developed for the settled oxide distribution. This limitation is acceptable because the uniform oxide distribution is less conservative than the settled distribution, so omitting the correction for boron in solution is conservative.

- The k_{eff} regressions from Reference 5.5 are applied to each batch of commercial SNF assemblies (typically 10 to 20 assemblies having identical in-core histories) as read from the input file "data.in" which is prepared by the Waste Stream Management program (WSM), and which contains upwards of 20,000 individual batch records, approximately 15,000 of which are for PWR SNF. Because of the large amount of computation involved, the k_{eff} calculations are not done at each timestep, but only at intervals specified by the parameter "tabint" which are sufficiently frequent to capture the main features of the time dependent behavior. At each of these tabulation intervals, the result of calculating k_{eff} for all the assembly batches is expressed in terms of the fraction of the assemblies which show k_{eff} to be greater than a threshold value which is generally taken to be significantly less than 1, according to regulatory requirements. This fraction is called the potentially critical fraction (PCF), and the maximum value of this fraction is called the peak potentially critical fraction (PPCF).

  It should be noted that Reference 5.5 states ranges of applicability of the regressions, with respect to SNF and basket characteristics, based on the range of parameters in the cases used to develop the regressions. The range of basket thicknesses used for this study fall within the range specified in Reference 5.5. A significant fraction of the SNF does, however, fall outside the parameter range for the partial basket regression, both on the more critical and the less critical side (i.e., parameters which would lead to a higher k_{eff} and a lower k_{eff} than those which would be calculated for parameter values within the specified ranges). For SNF which falls outside on the more critical side, the Reference 5.5, Table 7.6-3, shows that for typical cases the regression gives a slightly higher k_{eff} than actual MCNP calculations. Therefore, the only possible error in applying the regression to SNF on the more critical side will be conservative, i.e., the k_{eff}, and consequently the PCF, will be overestimated. This conclusion also holds for fuel which falls on the less critical side of the regression parameter range specified in Reference 5.5, because the only way to misclassify such SNF would be to include it in the PCF.

- For each individual input case, the numerical integration in time is continued until a maximum time (the parameter "maxyrs") is reached or until a peak in the potentially critical fraction is reached, whichever comes first. This peak fraction occurs because the reactivity of the assemblies reaches a peak between 10,000 and 25,000 years. If there is still significant boron in the package at this time, the time of peak potentially critical fraction (TPPCF) will be shifted to longer time when nearly all the boron is removed. If this time is delayed beyond 200,000 years, the peak may not occur because the individual k_{eff} curves for each pair burnup-enrichment pair in the commercial PWR SNF inventory will not decreases with time beyond 200,000 years (Ref. 5.5). It should be noted that the methodology for computing the TPPCF will take the earliest time for a flat peak (which k_{eff} turns out to have).

- When the concentration of either steel reaches zero it may overshoot to a negative value. The steel concentration is easily corrected to zero, but a special takeout accounting must correct for the extra addition into the oxide pool caused by the fictitious negative steel removed.

- The program reads input from a file "snfpkg.in" which can contain any number of cases, with one input line per case.

- Output is printed to 2 files: "snfpkg.out" which provides a detailed listing of the amounts of iron at each 1,000 year time interval, and "snfpkg.log" which lists the relevant parameters at the completion of each case. To facilitate the statistical (probabilistic) analysis of these results, a further reduced output is produced, with one line per case that has the probability at the end.

- The possible retention of small amounts of the highly soluble boron in the waste package after complete dissolution of the stainless steel basket is represented by a fraction which adheres to, or is trapped by, the iron oxide precipitate. At the present time, this fraction is thought to be so small as to be insignificant, so it was not used in the analyses of the current document.

This program is listed in Attachment II.

7.4 Input parameters

7.4.1 Nominal values

The following are brief justifications for the nominal values of material and environmental parameters. More detailed justifications are given in Section 4.1. Many of these parameters are still under intensive investigation in hopes of narrowing the large range of uncertainty in their present values.

- Infiltration rate: The current infiltration rate of 5 mm/yr will be used as the nominal value (see Section 4.1.5 and assumption 4.3.7).

- Threshold k_{eff}: 0.93: 0.95 (10CFR60.131(h), Ref. 5.9) - 0.01 (maximum difference when comparing MCNP results and the measured reactor parameters) - 0.015 (maximum bias) + 0.004 (reverse bias between single node and 18 node calculations). The last term is applied because the MCNP cases for reactor comparison are 18 node while the MCNP calculations in Reference 5.5 were single node. While the latter is certainly less of a precise model of reality, it has been found to be more conservative than the 18 node calculation by at least 0.004. Considering the uncertainty in this entire process it is appropriate to round the nominal value of the criticality threshold to 0.93.

- Borated stainless steel corrosion rate: 0.4 microns/yr. This is the median of values from the most relevant experimental studies (see Section 4.1.3).

- Borated stainless thickness: 7mm. This is the thickness in the current design (see Section 4.1.1).

- Waste package penetration time: 3,000 yrs. This is the most conservative value consistent with the design goals of the CDA (Ref. 5.13, see assumption 4.3.9).

- Exchange fraction: 0.1. This is the fraction of water entering the waste package which gets mixed with the water standing in the waste package before it flows out of the waste package. It is also the fraction of the water in the waste package which gets removed during the time it would take to fill the waste package with water entering the waste package at the infiltration rate. The nominal value is at one end of the range of possible values derived in Section 7.4.2, below.

- Fe solubility of 2×10^{-5} kg/m^3. This value is consistent with the low end of the pH range given in assumption 4.3.8 (see Section 4.1.5).

7.4.2 Variations from nominal values

The ranges of parameter values used in the probability distributions and in the sensitivity studies reflect the range of uncertainty in the values of the material and environmental parameters. The following are brief justifications of these ranges. More detailed justifications are given in Section 4.1.

- Infiltration rate: 0.1 mm/yr to 500 mm/yr. The low end of the range is a value that was recently thought to be the current average [TSPA-95; Ref. 5.14]; as explained in Section 4.1.5, this average is now thought to be in the range of 1 to 10 mm/yr. The high end of the range is the upper bound specified by CDA Assumption TDSS 026 (see Section 4.1.5 and assumption 4.3.7).

- Threshold k_{eff}: 0.91 to 1.0. The low end of the range is equal to the value which would be found by subtracting the current assumed bias and uncertainty (0.04) from the 0.95 limit from 10CFR60.131(h). This is very conservative because the extensive benchmark comparisons of MCNP calculations with benchmark commercial reactor criticals currently in progress are expected to lower the bias and uncertainty to no more than 0.02 (as explained in Section 7.4.1, above). The high end of the range is the actual physical threshold k_{eff} which would be required to produce a criticality. Any lower threshold represents some significant degree of conservatism.

- Borated stainless steel corrosion rate: 0.08 to 4 microns/yr. This is the range of values found in the most relevant experiments/tests (see Section 4.1.3).

- Thickness of borated stainless steel plates used for criticality control: 7-10 mm. The lower end of the range is the current design value. The high end represents the largest thickness which had ever been considered for a waste package (Ref. 5.12).

- Waste package penetration time: 3,000-10,000 yrs. The lower end of the range is based on the design goal defined by the CDA (Ref. 5.39, Key Assumption 074) that no more than 10 waste packages breach before 3,000 years (see assumption 4.3.9). The upper end of the range was chosen based on TSPA-95 results for the 83 MTU/acre repository, which shows the majority of waste packages experiencing first pit penetration prior to 10,000 years for both the high and low infiltration scenarios (Ref. 5.14, pp. 5-65 to 5-69). It is expected that TSPA-VA (1998) will provide a more refined estimate of pit penetration times, which will also reflect the current estimate of higher infiltration rates, so future evaluatoins with this parameter may have a different range and probability distribution within that range.

- Exchange fraction: 0.1 to 0.5. Buoyant circulation will tend to be in the plane transverse to the waste package axis. The circulation will be well mixed with the inflow in this plane (or disk having a thickness equal to the diameter of the hole letting in the water near the top of the waste package) for the following reasons: (1) the buoyant circulation velocity will be approximately 4 meters/day for a package without any basket remnants to obstruct the circulatory flow, even for the small temperature gradient remaining after 100,000 years, as was shown in Reference 5.15, attachment VI, pp. VI-4, -5, -6 (circulation times within a cell 4 cm high above the topmost row of assemblies ranging from 2,700 sec to 5,500 sec, or 0.75 to 1.5 hours, for typical PWR SNF at ages ranging from 5,000 to 100,000 years; an approximate one hour circulation time implies a velocity of 4sides*0.04meters/hour or 3.8 meters/day); and (2) a drop falling 2 meters onto the waste package will penetrate between 10 cm and 1 meter below the surface of water standing in the waste package, as shown by the analysis in Attachment VI. With this relatively rapid mixing in the plane (or disk) of the hole, the factor limiting the exchange for the waste package as a whole, is the diffusion of the solute, generally along the axis of the waste package, to the one, or few, such exchanging disk(s). In the waste package with borated stainless steel plates (called BSSWP), the principal removal concern is with boron in solution. Analysis in Attachment VI indicates that the diffusion time for boron in water will be between 22 and 48 years for a distance of approximately 2.3 meters along the waste package axis, which is the direction of largest density gradient if the removal is controlled by circulation in planes (or disks) perpendicular to the waste package longitudinal axis and diffusion along a gradient parallel to the waste package longitudinal axis. The exchange fraction, ex, is estimated as the ratio of the waste package filling time to this diffusion time, with a maximum of 1. This calculation is given in Attachment VI with the resulting range of 0.1 to 1.0. For this analysis, only the lower portion of this range is used, since the results are insensitive to changes in such high values of ex (as explained in Section 7.5, below).

7.5 Results

The potentially critical fraction of the entire family of commercial PWR SNF is a useful parameter for summarizing the long-term criticality performance capability of the borated stainless steel as the principal criticality control material. This fraction is not a measure of any criticalities which are expected to occur, but rather an indication of the SNF which cannot be emplaced in the BSSWP, and will, therefore, require additional criticality control measures (e.g., zircaloy clad boron carbide control rods, or a much smaller capacity).

Since this package relies primarily on borated stainless steel for criticality control, and since most of the neutron absorbing boron is released from the waste package within a few thousand years of the borated stainless steel corrosion (depending, of course, on the infiltration rate and the exchange fraction), the long-term criticality performance is most sensitive to the rate of corrosion of this material. For this reason most of the results are presented for a range of corrosion rates. It would be expected that the PCF would also be dependent on the thickness of the borated stainless steel plates, so this sensitivity is discussed, but only in Section 7.5.4, since it turns out not to be as strong as the sensitivity to borated stainless steel corrosion rate.

Sensitivity to exchange fraction (ex) was examined, and the results are summarized in the file ex.sum, which is reproduced in Attachment II These results are not presented here for the following reasons:

- The results were found to be insensitive to changes over the range chosen (0.1 to 0.5).
- The derivation of the range for exchange rate (given in Section 7.4.2 and in Attachment VI) indicates that the exchange rate is strongly correlated with the infiltration rate, so that the sensitivity to decreasing the exchange rate is already represented by decreasing the infiltration rate.
- The omission of this sensitivity analysis is consistent with the uncertainty connected with estimating the exchange fraction.

7.5.1 General time dependent behavior of potentially critical fraction

The general time dependent behavior is summarized in 2 figures (7.5.1-1, -2): one for the settled oxide distribution, and one for uniform. Each has three graphs: (1) nus (SS corrosion rate in microns/year) =0.08, dr (drip rate in mm/year) =5, (2) nus=0.40, dr=5, and (3) nus=0.40, dr=50; nominal values are used for all the other parameters. The original data on which the graphs are based are contained in the output file time.log. The following are the principal observations from these results.

- Progression from cases 1 to 3 reflects increasing environmental stress (higher dr) and decreasing material performance (higher SS corrosion rate). Going from 1 to 2 shifts the PPCF forward drastically in time and increases its value. Going from 2 to 3 eliminates the early minimum (because the high infiltration rate reduces the boron in solution to below the threshold of minimum effectiveness, 30 grams, and thus no k_{eff} correction is performed; Ref. 5.5, Sect. 7.4) and significantly increases the PCF just before the complete basket dissolution (0.0101 versus 0.0145 at 8,000 years which is just before the tbskt=8,646 years).

- Shows fraction of the fuel which should go into packages with greater criticality control (control rods or drastically reduced capacity).

- After the PPCF which immediately follows tbskt, there is a monotonic decline with time because of the decay of ^{239}Pu into ^{235}U, since the latter is less reactive in this configuration.

- Comparison between figures shows dominance (conservativeness) of the settled oxide configuration, so it will be used for the sensitivity studies.

- The general time dependence shown in Figures 7.5.1-1 and -2 holds for the range of parameters considered in this document, so it will not be repeated in the following presentation of the results of the sensitivity studies and the generated probability distributions. Instead, the following results are presented in terms of the summary statistics, the peak potentially critical fraction (PPCF), and time to peak potentially critical fraction (TPPCF).

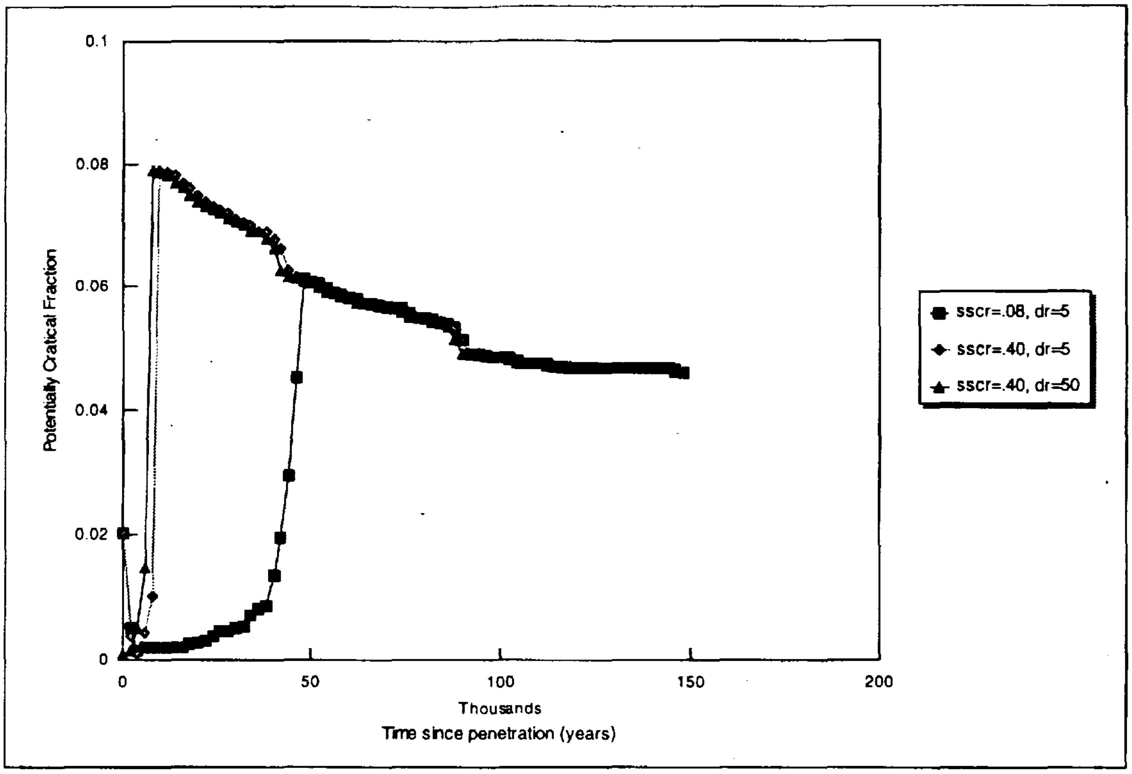

Figure 7.5.1-1. Time Dependence of Potentially Critical Fraction - Settled Oxide, WP Penetration = 3,000 years

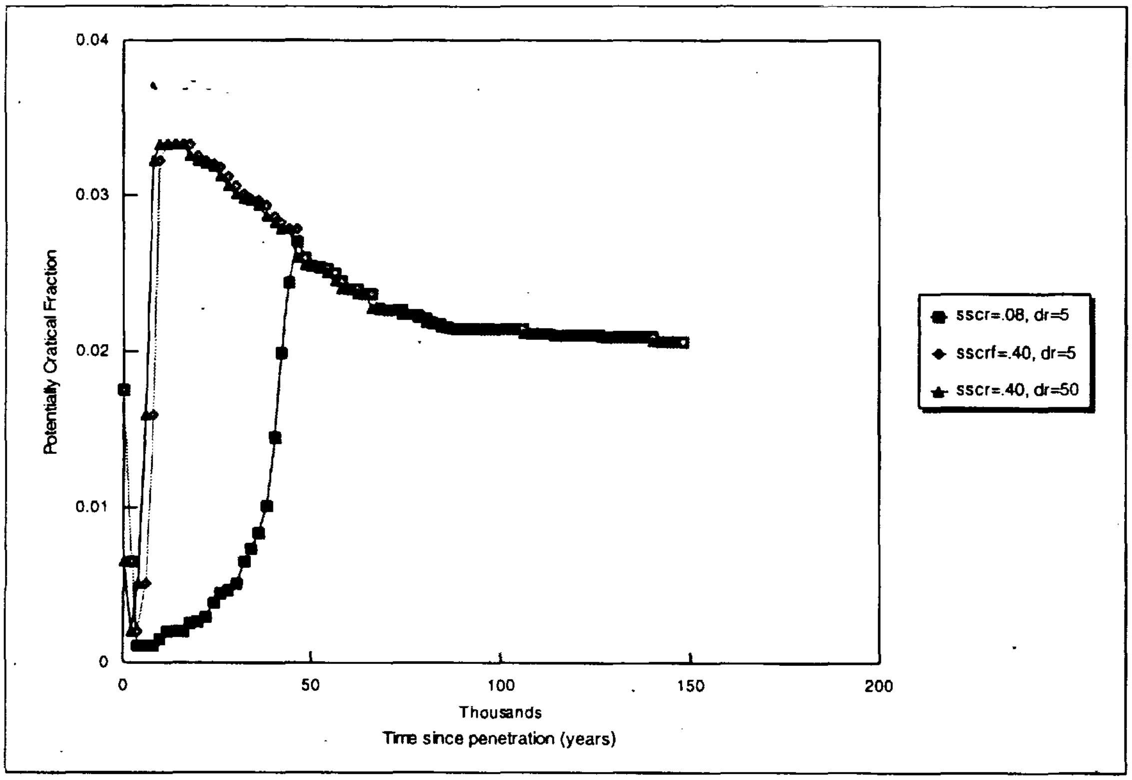

Figure 7.5.1-2. Time Dependence of Potentially Critical Fraction - Uniform Oxide, WP Penetration Time = 3,000 years

7.5.2 Sensitivity to k_{eff} threshold

The sensitivity of PPCF to threshold k_{eff} is shown in Figure 7.5.2-1, and the corresponding TPPCF in Figure 7.5.2-2. These results are for the settled oxide distribution and for the range of borated stainless steel corrosion rates from 0.08 microns/year to 0.40 microns/year. More complete results covering even higher corrosion rates, and also giving corresponding data for the uniform distribution of oxide, are given in Table 7.5.2-1, from which the figures are derived. The original data on which the graphs are based are given in the output file keff.sum.

- As would be expected, the PPCF declines with increasing k_{eff} threshold, and also with decreasing corrosion rate of borated stainless steel, as can be seen from both Figure 7.5.2-1 and Table 7.5.2-1.

- From Table 7.5.2-1 it is also seen that, for the settled oxide distribution, the PPCF and TPPCF are insensitive to increases in the stainless steel corrosion rate above 0.4 microns/ yr. This is because the boron has been removed so fast as to have no effect at all, leaving the time of occurrence of the peak to be determined solely by the time-varying isotopic composition of the SNF, which would place the beginning of the peak at approximately 15,000 years. Table 7.5.2-1 shows the settled oxide TPPCF at 10,000 to 12,000 years for corrosion rates of 0.4 microns/year and greater, which is consistent with the 15,000 year start of peak after addition of the 3,000 year penetration time.

- It should be noted that the saturation of corrosion rate sensitivity for the uniform oxide distribution shows a similar behavior with two significant differences: (1) the saturation effect for the uniform oxide distribution does not begin until the corrosion rate has reached 2.0 microns/yr; and (2) the TPPCF for the uniform oxide distribution drops to 2,000 years. Both these differences are artifacts of the condition that the borated stainless steel corrosion time is less than 2,000 years for the corrosion rates of 2.0 and 4.0 microns/yr (1,729 and 864 years, respectively, which can be verified by hand calculation or as the parameter tbskt in the output file keff.log in Attachment II). After the borated stainless steel corrosion time, the basket is considered fully degraded and that regression is applied. However, the smallest time in the dataset used for the fully degraded basket regression in Reference 5.5 was 8,000 years. This is 3,000 years greater than the 2,000 years plus 3,000 years penetration time, so some anomalous behavior may be expected.

- It should be noted that the data of Figure 7.5.2-1 (or Table 7.5.2-1) can be used as the basis for estimating the cost to the program associated with any criticality threshold below 1.0. The difference between the highest PPCF at threshold = 1.0 (0.018) and the PPCF at a lower threshold, is the fraction of the commercial PWR SNF which will have to be accommodated in a more expensive waste package (e.g., a waste package with control rods as the primary criticality control measure or a greater number of smaller, but not correspondingly cheaper, waste packages).

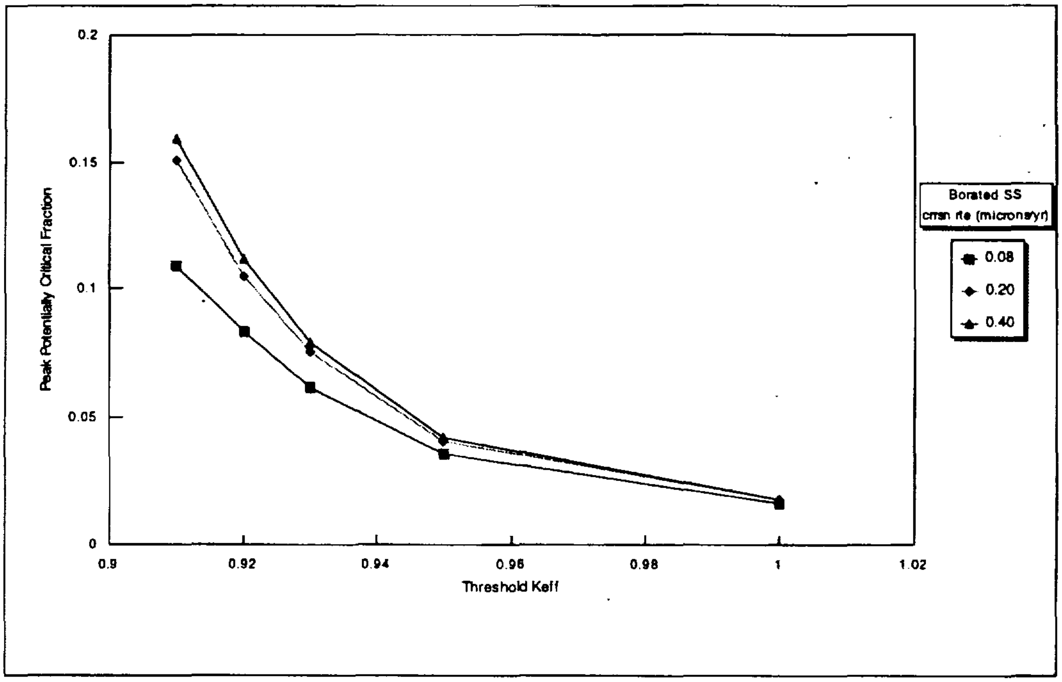

Figure 7.5.2-1. Effect of Threshold k_{eff} on Peak Potentially Critical Fraction for the Range of Borated Stainless Steel Corrosion Rates

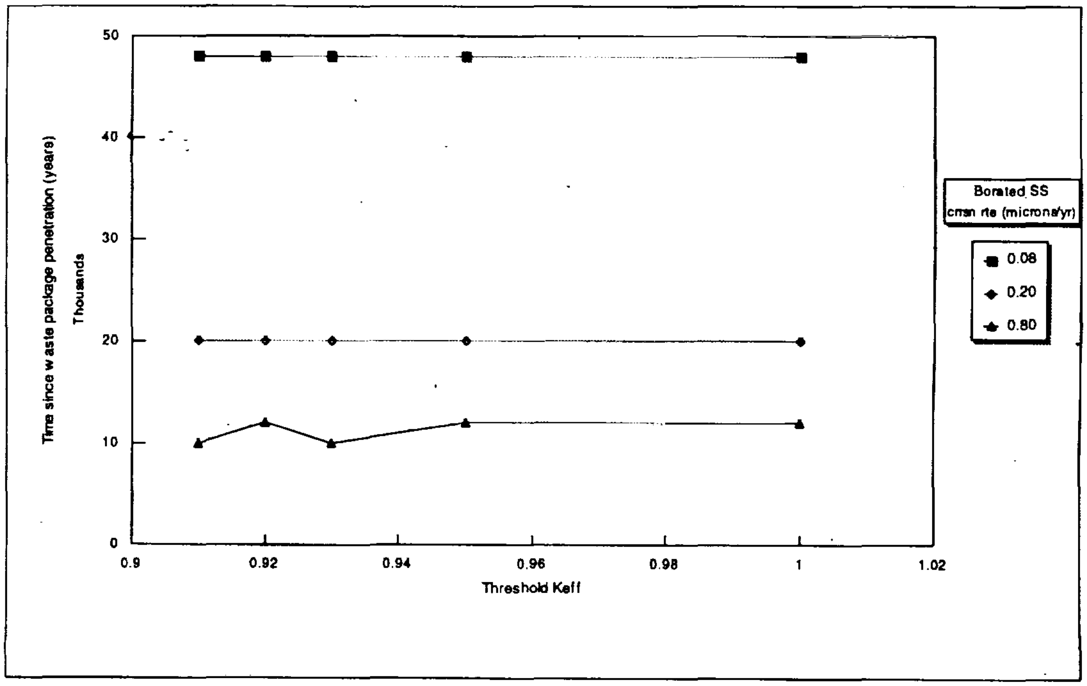

Figure 7.5.2-2.Effect of Threshold k_{eff} on Time of Peak Potentially Critical Fraction for the Range of Borated Stainless Steel Corrosion Rates

Table 7.5.2-1. Time of PPCF as a Function of BSS Corrosion Rate, Threshold k_{eff} and Oxide Distribution

BSS Corrosion Rate (μm/yr)	Threshold k_{eff}	Time of PPCF Uniform (years)	PPCF Uniform	Time of PPCF Settled (years)	PPCF Settled	Probability
0.08	0.91	44000	0.03567	48000	0.10914	1
0.08	0.92	46000	0.03196	48000	0.08337	1
0.08	0.93	46000	0.02717	48000	0.06145	1
0.08	0.95	46000	0.01906	48000	0.03576	1
0.08	1.00	48000	0.01195	48000	0.01578	1
0.2	0.91	20000	0.0452	20000	0.15074	1
0.2	0.92	20000	0.03669	20000	0.10488	1
0.2	0.93	20000	0.03254	20000	0.07499	1
0.2	0.95	20000	0.02325	20000	0.04052	1
0.2	1.00	20000	0.01263	20000	0.01782	1
0.4	0.91	12000	0.04569	10000	0.15949	1
0.4	0.92	14000	0.03744	12000	0.11182	1
0.4	0.93	14000	0.03322	10000	0.07891	1
0.4	0.95	16000	0.02355	12000	0.04176	1
0.4	1.00	14000	0.01263	12000	0.01785	1
0.8	0.91	12000	0.04569	10000	0.15949	1
0.8	0.92	14000	0.03744	12000	0.11182	1
0.8	0.93	14000	0.03322	10000	0.07891	1
0.8	0.95	16000	0.02355	12000	0.04176	1
0.8	1.00	14000	0.01263	12000	0.01785	1
2	0.91	2000	0.08461	10000	0.15949	1
2	0.92	2000	0.06294	12000	0.11182	1
2	0.93	2000	0.0453	10000	0.07891	1
2	0.95	2000	0.03311	12000	0.04176	1
2	1.00	2000	0.0148	12000	0.01785	1
4	0.91	2000	0.08461	10000	0.15949	1
4	0.92	2000	0.06294	12000	0.11182	1
4	0.93	2000	0.0453	10000	0.07891	1
4	0.95	2000	0.03311	12000	0.04176	1
4	1.00	2000	0.0148	12000	0.01785	1

7.5.3 Sensitivity to infiltration rate

A low infiltration rate permits some boron released from the stainless steel corrosion to remain in solution (since the flushing rate is slow), thereby lowering the k_{eff}, particularly since the boron in solution is somewhat more effective at absorbing neutrons than the boron in the spatially limited plates. The resulting reduction in PPCF and increase in TPPCF are shown in Figures 7.5.3-1 and 7.5.3-2, respectively. The data from which these graphs have been developed are given in the output file inf.log.

- The PPCF increases with increasing infiltration rate, but this effect saturates at 10 mm/yr. The TPPCF decreases with increasing infiltration rate, and, as with the PPCF, saturates at 10 mm/yr.

- The low values of PPCF for low values of infiltration rate are due to the fact that the low flushing rate permits the retention of a significant amount of boron in solution for a significant period of time after complete dissolution of the borated stainless steel. This delay results in a longer TPPCF which, in turn, assures a lower PPCF because of the inherent decrease in SNF reactivity with time (beyond the 15,000 - 25,000 year peak, of course).

- As with all the sensitivities, the PPCF decreases with increasing stainless steel corrosion rate, but this effect saturates at 0.4 microns/yr, which is the reason that the curves for higher values are not shown in these figures.

- The usually strong dependence of PPCF and TPPCF on borated stainless steel corrosion rate is weakened for very low infiltration rates. This is because the removal time for boron in solution becomes much longer than the corrosion time itself, so it no longer makes much difference how long the borated stainless steel lasts. It should, however, be noted that this boron retention effect is only significant for infiltration rates of 0.1mm/yr or lower. Unless further infiltration rate investigations show that such low infiltration rates are likely after all, the current high infiltration rates of the CDA will preclude any credit for benefit from potential boron retention after complete corrosion of borated stainless steel.

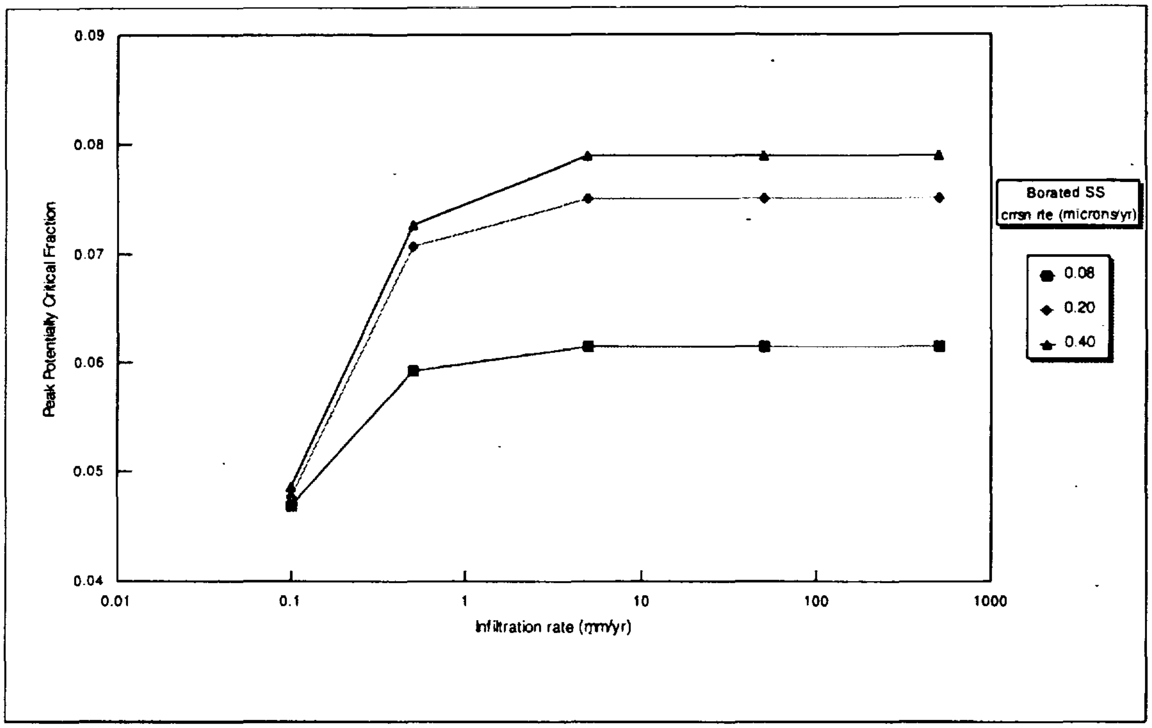

Figure 7.5.3-1. Peak Potentially Critical Fraction as a Function of Infiltration Rate (for a family of borated stainless steel corrosion rates)

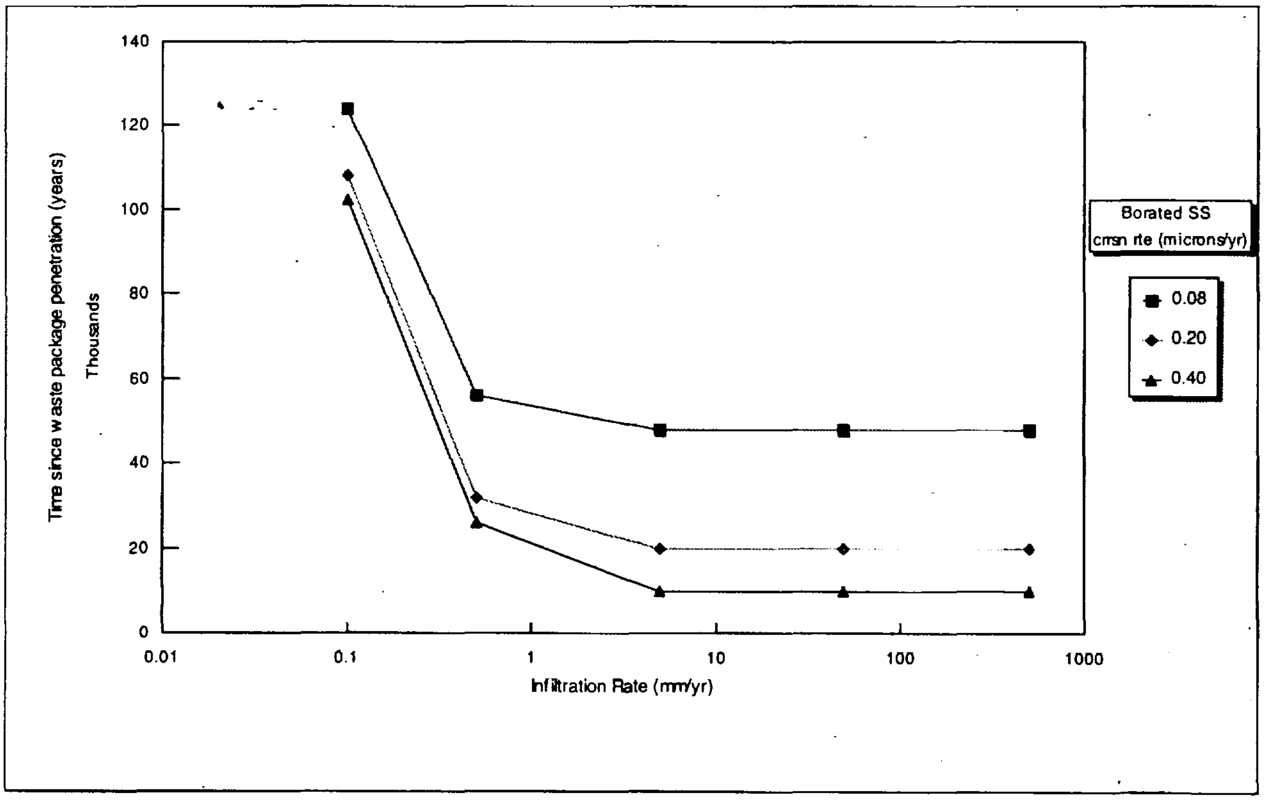

Figure 7.5.3-2. Time of Peak Potentially Critical Fraction as a Function of Infiltration Rate (for a family of borated SS corrosion rates)

7.5.4 Sensitivity to thickness of borated stainless steel plates

The principal effect of increasing borated stainless steel thickness is to increase the time to complete dissolution of the borated stainless steel, which increases the TPPCF, and correspondingly decreases the PPCF because monotonic decrease in reactivity with time. This effect is shown in Figures 7.5.4-2 and 7.5.4-1, respectively. However, the effect is not as strong as would be expected, particularly for the high borated stainless steel corrosion rates, for the following reasons:

- The variation in borated stainless steel thickness is dominated by the much larger range in corrosion rates (40% versus 400%).
- At the higher corrosion rates, even a 10 mm thickness does not prevent the high corrosion rate from dropping the corrosion time well below the time of the intrinsic k_{eff} peak, 15,000 to 25,000 years.

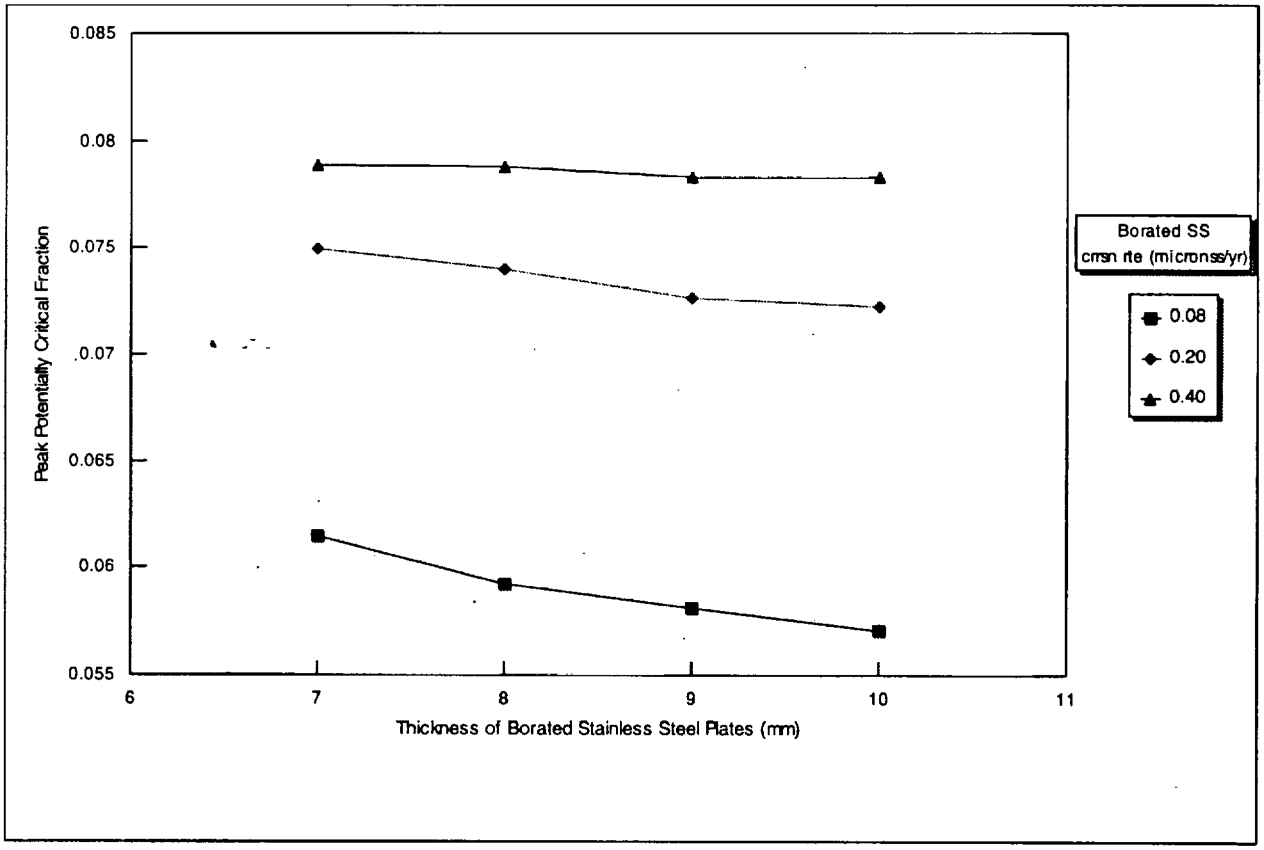

Figure 7.5.4-1. Effect of Borated SS Thickness on Peak Potentially Critical Fraction for the Range of Borated SS Corrosion Rates

The data from which these graphs have been developed are given in the output file thick.log.

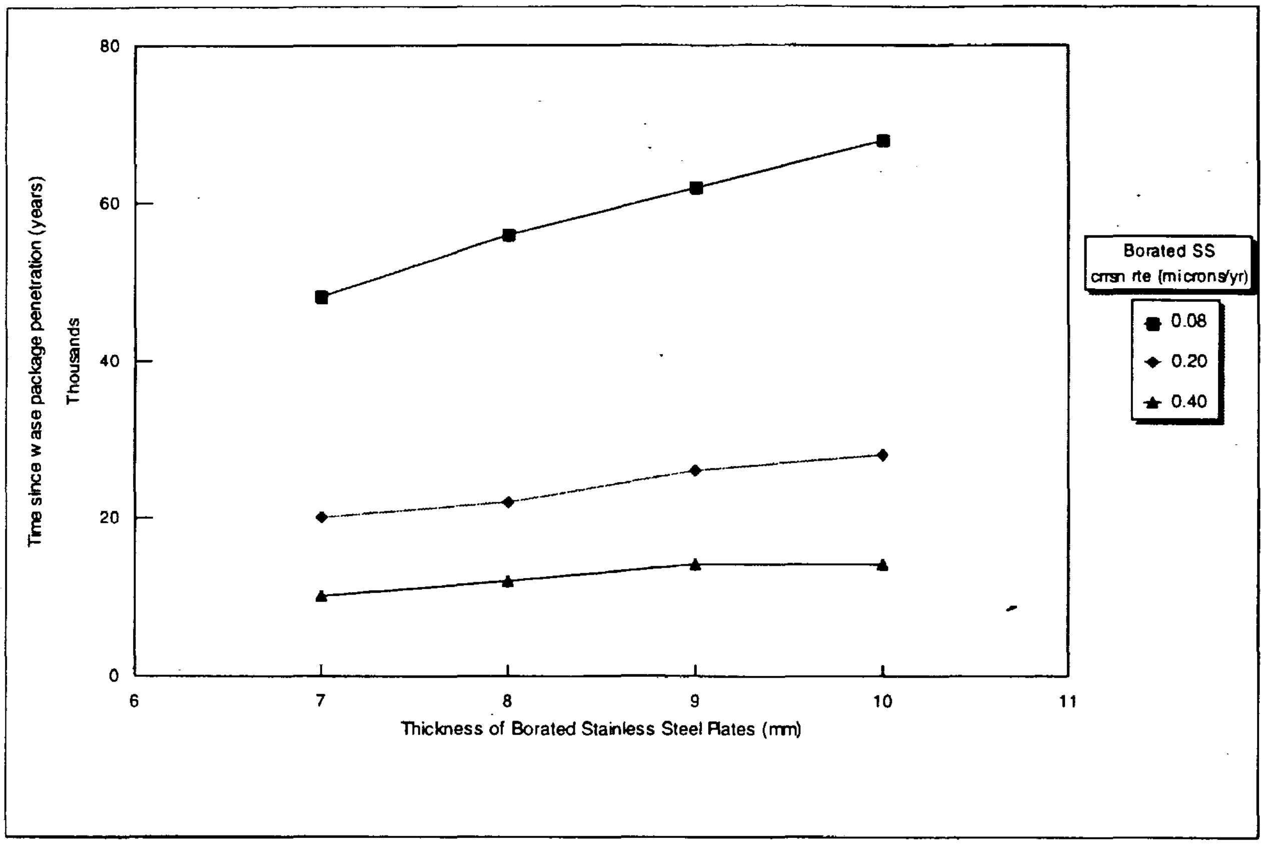

Figure 7.5.4-2. Effect of Borated SS Thickness on Time of Peak Potentially Critical Fraction for the Range of Borated SS Corrosion Rates

7.5.5 Sensitivity to time of package barrier penetration

A major goal of waste package design is to increase the penetration time (time to waste package breach by aqueous corrosion of the barriers). It is, therefore, useful to test the sensitivity of criticality performance to penetration time. The resulting PPCF and TPPCF are shown in Figures 7.5.5-1 and 7.5.5-2, respectively. The original data from which these graphs have been derived are given in the output file pentime.log.

- There is a small decrease in PPCF with increasing penetration time which reflects the decrease of reactivity with time (already discussed above).

- The TPPCF measured from the time of penetration changes very little with penetration time. If this time were measured from emplacement, it would, obviously, show an increase approximately equal to the increase in penetration time. Hence increasing penetration time does have a significant benefit with respect to criticality performance.

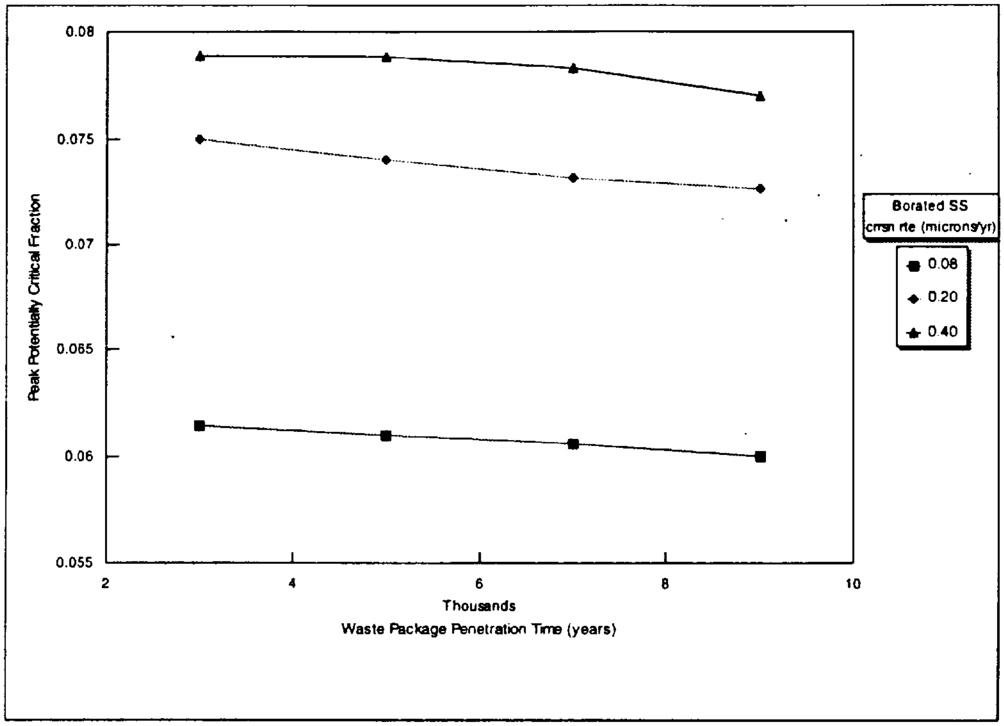

Figure 7.5.5-1. Effect of Waste Package Penetration Time on Peak Potentially Critical Fraction for the Range of Borated Stainless Steel Corrosion Rates

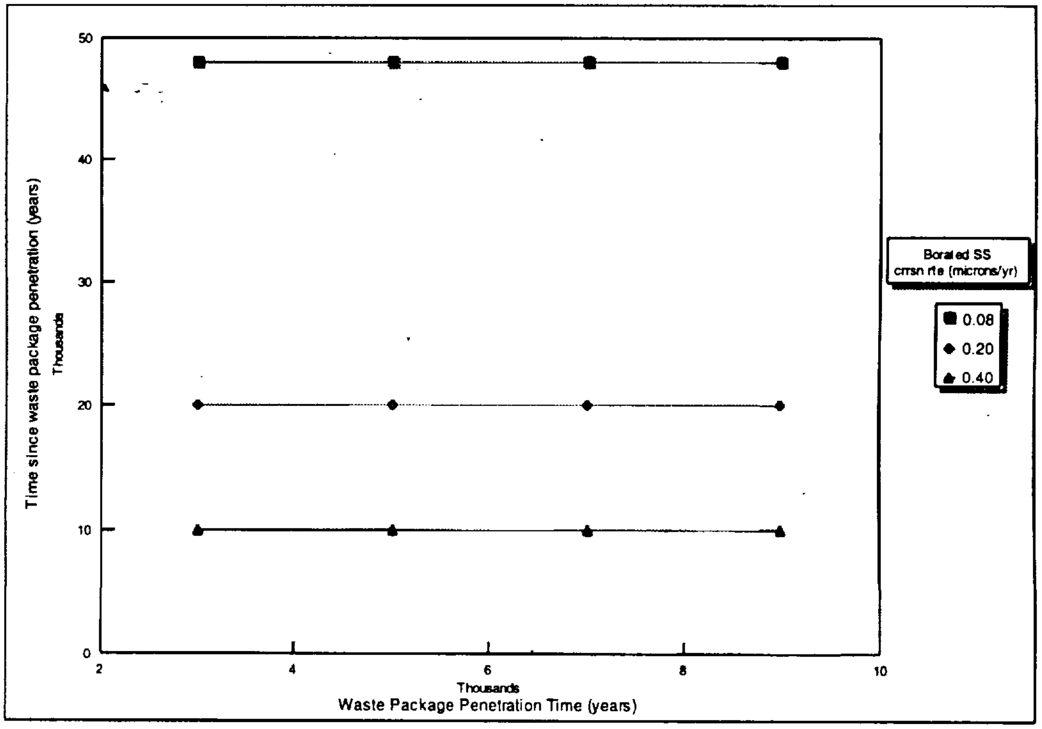

Figure 7.5.5-2. Effect of Waste Package Penetration Time on Time to Peak Potentially Critical Fraction for the Range of Borated Stainless Steel Corrosion Rates

7.5.6 Probability distributions of potentially critical fraction

The greatest uncertainty in the long-term criticality evaluation is associated with three parameters which cannot even be modeled quantitatively at this time: (1) the length of time for which there will be standing water in the waste package, (2) the number of assembly layers covered by such standing water, and (3) the distribution of iron oxide within the waste package (which can't even be modeled by a single parameter). It is expected that some quantitative modeling of these parameters will be developed to secure NRC approval for any probabilistic criticality evaluation methodology, and certainly for the license application. In the meantime, the probabilistic methodology will be applied to the three input parameters having the next greatest degree of uncertainty: infiltration rate, borated stainless steel corrosion rate, and waste package penetration time. For this purpose, the ranges of these parameters given in the Section 7.4.2, above, are truncated to somewhat more realistic values, and represented by the following discrete distributions (where the reasons for the truncation are indicated in parentheses):

- Stainless steel corrosion rate (microns/yr): 4 value, probability pairs: 0.08,0.25; 0.2,0.25; 0.4,0.25; 0.8,0.25 (where the highest values are omitted because they reflect extremely unlikely hostile environments, and because the PPCF is relatively insensitive to increase in corrosion rate above 0.8 microns/yr, as can be seen from table 7.5.2-1, particularly for the most conservative, and most realistic, settled oxide distribution).

- Infiltration rate (mm/yr): 3 value, probability pairs: 0.5,0.3; 5.0,0.4; 50.0,0.3 (where the highest value, 500 mm/yr is not included because it represents a peak expected to occur on average only once every 40 years, Ref. 5.13 and assumption 4.3.7)

- Penetration time (yrs): 3 value, probability pairs: 3000,0.4; 5000,0.4; 7000,0.2 (where the highest values were not included because the PPCF is relatively insensitive to penetration time (Table 7.5.5-1), and because the shorter times are more conservative).

These distributions were used to generate 36 combinations of the three parameters. These 36 combinations were input as cases to the specialized configuration generator, snfpkg.c, together with the associated probabilities. The resulting probability distributions for PPCF and TPPCF are shown in Figures 7.5.6-1, and 7.5.6-2, respectively. The original data from which these graphs have been derived are given in the output file distrib.out.

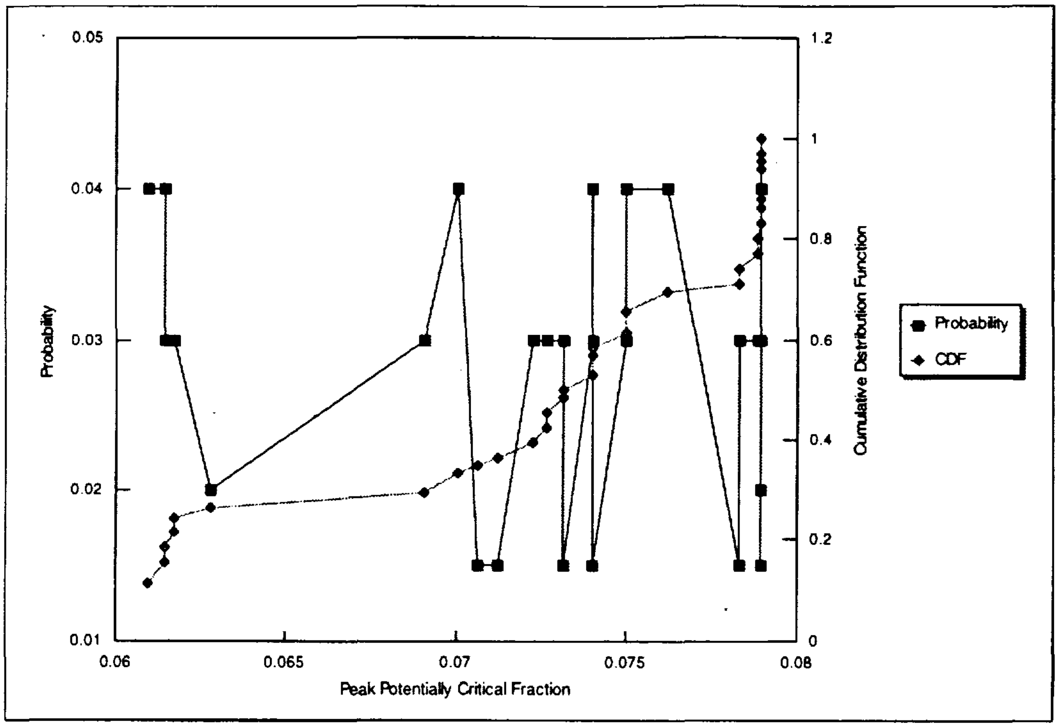

Figure 7.5.6-1. Probability Distribution of Peak Potentially Critical Fraction

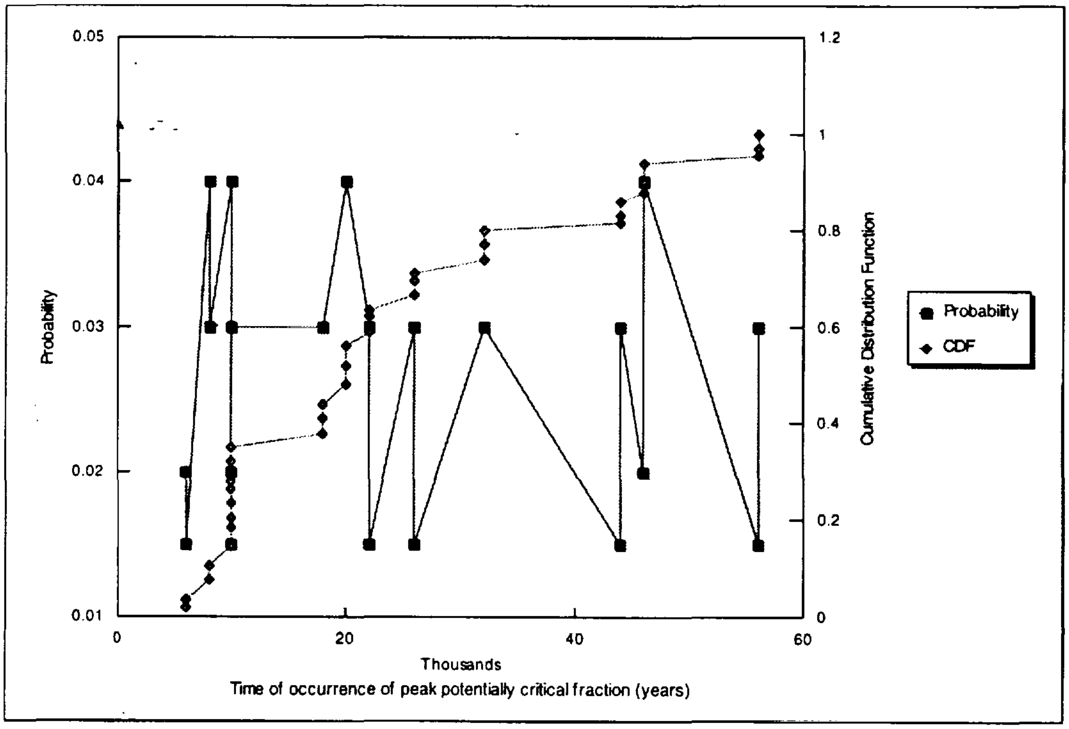

Figure 7.5.6-2. Probability Distribution for Time of Occurrence of Peak Potentially Critical Fraction Assuming Iron Oxide has Settled to the Bottom of the Waste Package

The following features of these figures should be noted:

- The probability functions (which can be interpreted as similar to the probability density function of a continuous distribution) show considerable fluctuation, reflecting the variations in probability within two of the three individual parameter distributions.

- The cumulative distribution function (CDF) in Figure 7.5.6-1 shows major jumps, or steps, at PPCF=0.061, 0.074, 0.078, which correspond to the PPCF levels for the borated stainless steel corrosion rates=0.08, 0.20 and 0.40 microns/yr illustrated in Figures 7.5.3-1 and 7.5.4-1, for the nominal parameter values infiltration rate = 5 mm/yr and borated stainless steel plate thickness = 7 mm, respectively.

- For the TPPCF distribution shown in Figure 7.5.6-2, the probability steps are at times=45,000, 20,000, and 10,000 years, which, again, correspond the times in Figures 7.5.3-2 and 7.5.4-2 for the borated stainless steel corrosion rates=0.08, 0.20 and 0.40 microns/yr. It should be noted that the CDF steps at 20,000 and 45,000 years are actually broken into substeps separated by a few thousand years. This substep behavior reflects the fact that the time of onset of the PPCF is a slightly more sensitive function of parameter variation than is the value of the PPCF itself.

7.5.7 Implementation of loading strategy

The results of this study will be used to establish preliminary rules for selecting the appropriate emplacement package for each batch of PWR SNF, and for determining the fraction of fuel which will have to be emplaced in the more expensive package with the greater criticality control. In particular, the results presented in Figure 7.5.2-1 show the fractions requiring the greater criticality control waste package for the range of stainless steel corrosion rates with the nominal assumptions for the other parameter values.

A more conservative approximation of peak potentially critical fraction can be developed from a worst case, time independent regression developed in Reference 5.5 (repeated as equation 4-6 and Table 4.1.2-5 of this document). That regression represents the peak k_{eff} values which would generally occur at the time of the intrinsic peak k_{eff}, between 15,000 and 25,000 years after discharge. In many cases, the borated stainless steel dissolution required to permit this k_{eff} would not be achieved with 15,000 to 25,000 years. If this conservative k_{eff} regression is applied to the range of characteristics of commercial PWR SNF, the results are as shown in Figure 7.5.7-1.

Also shown in this figure is the application of this conservative regression to the fraction of the commercial PWR SNF which has burnup and enrichment which would satisfy the criticality control threshold used in Reference 5.4 (k_∞<1.13). The degree to which the values of this second graph are all above zero, indicates the inadequacy of k_∞ as an effective parameter for measuring the amount of fuel which would require the greater criticality control waste package.

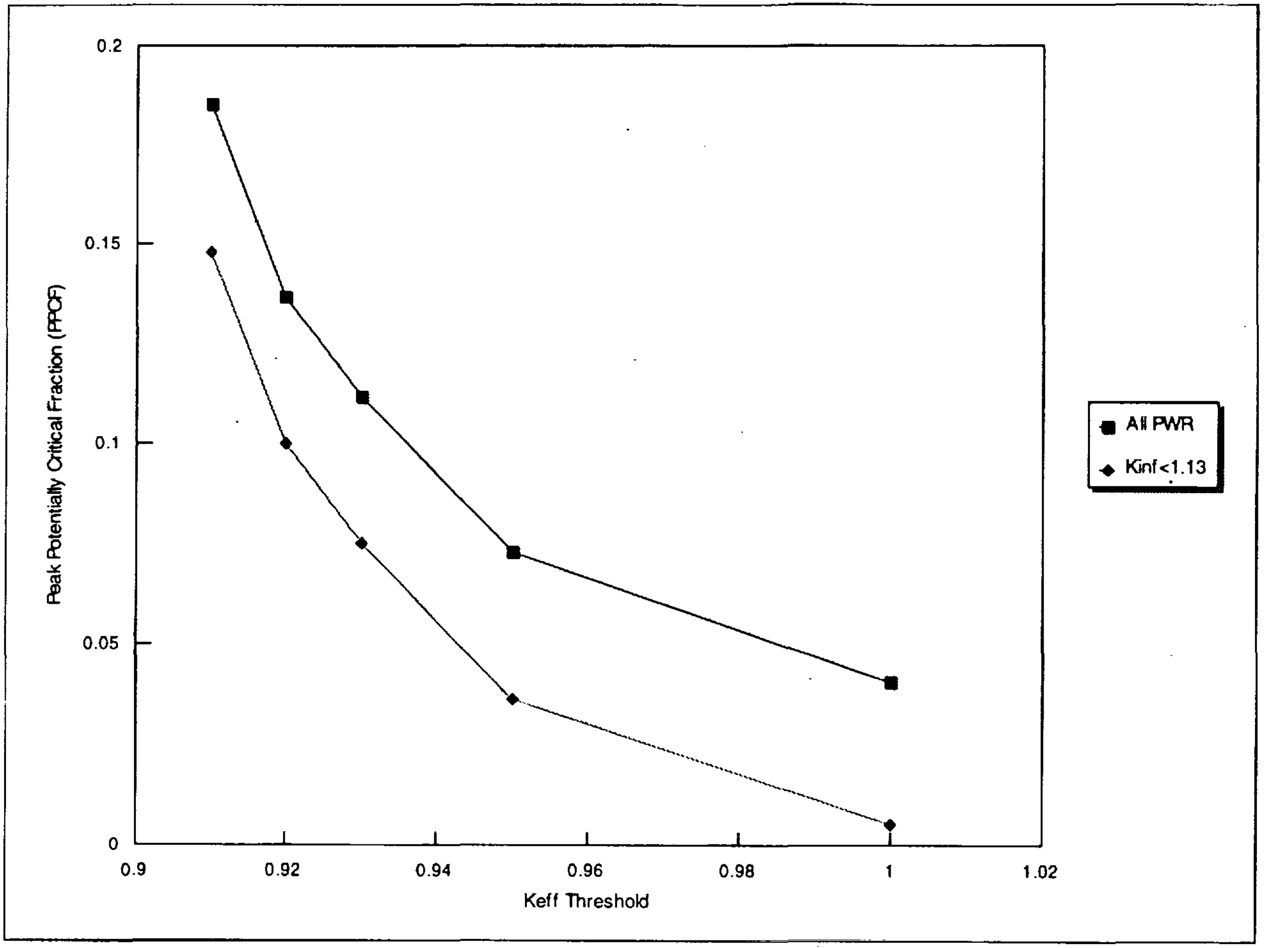

Figure 7.5.7-1. PPCF Before and After k_∞ Screening

8. Conclusions

- The factors which tend to maintain the pond required for criticality will also tend to retain boron in solution (very low ex, low infiltration rate) so that TPPCF is increased and PPCF is correspondingly decreased. Examples of these factors: low number of holes, small size of the holes, and mechanical obstacles to circulation.

- The TPPCF measured from the time of penetration changes very little with penetration time. If this time were measured from emplacement, it would, obviously, show an increase approximately equal to the increase in penetration time. Hence increasing penetration time does have a significant benefit with respect criticality performance.

- The results are rather insensitive to changes of infiltration rate above 5 mm/yr (the nominal value used in this study) to as high as 500 mm/yr. Therefore, if the long-term average infiltration turns out to be closer to the CDA predictions of 50 mm/yr (CDA fully mediated case) or even 100 mm/yr (the average between the fully mediated, 0.5 m^3/yr and the steady focused or episodic focused, 20 m^3/yr, which are projected to occur 0.025% of the years) the analyses presented here will still be valid.

- The possibility of internal criticality for waste packages containing commercial SNF requires the confinement of water within the waste package, as with previous M&O studies on this subject (References 5.12 and 5.15). This fact enhances the importance of delaying the earliest possible time of criticality (discussed in Ref. 5.15) or the time of peak potentially critical fraction (discussed in this document) to a time when ponding becomes very unlikely (because the bottom would have already been penetrated by some aqueous corrosion). The strictness of this ponding requirement is demonstrated by the number of assembly layers required to be covered for settled distribution. From Table 7.4-10 of Reference 5.5, it is found that out of 5 layers of assemblies in a waste package, 4.2 must be covered; after the entire collection of assemblies has settled to the bottom of the package, covering 4.2 layers is estimated from scaling figure 7.4-1 of Reference 5.5 as 8.5cm/12.5cm=0.68. It should be noted that this concept of layers of assemblies is only an approximation to the actual condition, in which the waste package is likely to be oriented so that the assembly layers are not horizontal.

- The k_{eff} regressions developed in Reference 5.5 are suitable for selecting between the BSSWP and the control rod WP when loading individual assemblies. In particular, the PPCF gives the fraction of the PWR SNF which will require the control rod WP. There is a range of values expected for PPCF, depending on the values of the various uncertain input parameters. The most conservative of these estimates is given in Section 7.5.7, as a function of the target k_{eff} threshold. The use of k_{eff} based selection criteria is expected to be much more accurate than the use of k_∞ based criteria, and certainly more conservative. The later fact is clearly demonstrated by estimating the PPCF for the set of PWR SNF which has already passed a k_∞ screening criterion, as shown in Figure 7.5.7-1.

Recommendations/future work

- Investigate criticality benefits which could result from loading single waste packages with assemblies having differing k_{eff} (blending for criticality) to minimize the number of packages having criticality potential. Such a strategy could result in reducing the peak potentially critical fraction to the point where the additional expense for providing the greater criticality control waste package for that fuel would be insignificant.

- Develop model for circulation and diffusion within the WP considering buoyant convection, obstructions to flow, molecular diffusion, viscous entrainment, to refine the estimate of the exchange fraction.

9. Attachments

Hardcopy attachments are listed in Table 9-1 below.

Table 9-1. List of Attachments

Attachment Number	Description	Pages	Date
I	Source Code for generate.c	9	9/8/97
II	Source Code, Input, and Output for snfpkg.c	57	9/8/97
III	Source Code, Input, and Output for preproc[x].c	3	8/26/97
IV	Source Code, Input, and Output for postprc[x].c	5	8/26/97
V	Source Code and Output for loadcurv.c	3	8/26/97
VI	Mathcad calculations associated with exchange efficiency	3	9/7/97

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/* generate.c Comprehensive configuration generator program
 * This code will test sensitivity and generate criticality performance
 * statistics based on a distribution of values of input parameters.  These
 * parameters are of two types: those read from the input file, and those
 * canned into the program.  At the present time there are only 4 read
 * from the input file: infrate (infiltration over the package), pkgwout0
 * (the nominal outflow from the package), dissrate[0], and prob; pkgwout0 is
 * in cubic meters/yr; dissrate[0] is in gm/sqm/yr; infrate is in mm/yr.
 * The canned parameters are mostly initialized in the subroutine setupv(),
 * except for the arrays pkgin (concentrations in the water infiltrating to
 * the package), issolchanger (elements set to 1 for species which have a
 * strong effect on the pH, such as chromate), issolvar (elements set to 1 for
 * species whose solubility is strongly determied by pH, such as U or Gd).
 * M-K-S units are used throughout, except for infiltration rates, which
 * are mm/yr to conform to common usage.  */

/*The infiltration and outflow rates (infrate, pkgwout0) are constant in this version, but may
* be made time dependent in the future.  The concentrations in these flows are pkgin[SPECIES],
* which is presently initialized in the global declaration and pkgout[SPECIES].  There
* are two types of change of species mass or concentration: those which procede at
* a some determined rate, so that the amounts are multiplied by the timestep
* (inflow, outflow, dissolution, and radioactive decay), and those which are
* assumed to be completed at each timestep, no matter how short (transferring among
* dissolution product, in solution, and in precipitate), so that the changes are
* not multiplied by the length of the timestep.

   Species assignments: (0) U235, (1) U238, (2) Pu, (3) Gd,  (4) Cr,  (5) Fe,
     (6) Carbonate,  (7) Boron
     Form assignments: (0) Waste form (glass or cer),  (1) SS containing Cr,
     (2) DU backfill, (3) DU filler in the waste package (not presently used),
      (4) Carbon steel (containing Fe), (5) SNF (presently not decayed)
     Path, layer, pond assignments (with index refering to LOCS)
     For this test use only
     0   Package   Pond
     1   Invert      Pond
     2   10 meters of host rock immediately below the waste package
     In addition, the drift may contain DU backfill to be handled by special subroutine;

 * The global variable cout[SPECIES] (in kg/cubic meter)is used to transfer from one object to the
 * next.  It is used as input for each update subroutine and then reset for use
 * by the next in the sequence.  The only exception is package, which takes
 * input from the initialized pkgin[SPECIES].  If more than one object will feed
 * another object (such as both the drift and the package feeding the invert)

 * then the two feeds will be combined in a special subroutine, such as
 * backfill(TIMESTEP).  It should be noted that several of the arrays used to record
 * amounts in locations and/or of species will be sparse because for many of the locations
 * only a limited subset of SPECIES will be used; furthermore, many of the characteristics
 * of ponds and paths are so different that arrays which apply to paths do not apply
 * and vice-versa.  */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>
#define PI 2*asin(1)
#define LOCS    5   /* Ponds and Paths */
#define SPECIES 10 /*total number of species in the database*/
#define FORMS 3   /* max number of initial forms in, and around, the package*/
#define TIMESTEPS 100000 /*max timesteps for retarded pass through path */
#define TIMESTEP 5 /*number of years per step */
#define MAXSOLINT 5 /*max number of linear pieces in the solubility formula */
```

```
void updatepo(int,int),updatepa(int,int,int),updatepkg(int),solubility(),
   setupc(),setupv(),backfill(int);
int step(float);
float kcalc3(float,float,float),kcalc4(float,float,float,float);
float precip[LOCS][SPECIES]={{0}},//kg of precipitate in a pond or path (of LOCS)
   slblty[SPECIES],   //Solubility (ppm); may be overridden by pH dependent algorithm
   inform[FORMS][SPECIES],//kg form i, species j, calc in setupv: massform[i]*formfrac[i][j]
   soludrift,/*Slblty of U in drift waters; constant throughout the run*/
   durich, //Enrichment of depleted uranium (used in drift or package)
   ddufrac, //fraction of DU in the form encapsulating it in the drift
   pkgdufrac, //fraction of DU in the form encapsulating it in the waste package
   mdduprecip, //kg DU precipitated in the drift (on a per/pkg basis)
   mpkgduprecip,//kg DU precipitated in the package
   driftarea; //horizontal cross-section to compute vol flow (per pkg) from infltrtn rate
float ph, //pH calculated (in solubility()) from certain ion concentrations
      infrate, //infiltration rate, input in mm.
      pkgwin,  //cubic meters/yr computed in setupv()
      pkgwater,//cubic meters initialized to zero in setupv()
      pkgwout, //either pkgwout0 or pkgwin if overflow
      dissrate[FORMS],pkginprecip[SPECIES],
      formfrac[FORMS][SPECIES]={{0}},massform[FORMS],
      phint[SPECIES][MAXSOLINT]={{0}},
      alpha[SPECIES][MAXSOLINT],beta[SPECIES][MAXSOLINT],cout[SPECIES],
      areaform[FORMS],areaform0[FORMS],pkginsltn[SPECIES]={{0}},
      phcoef[SPECIES],massform0[FORMS],pkgarea,
      radrate[SPECIES],pkgwatermax,pkgwout0,
      csltn[SPECIES], /*for current pond; used in solubility()*/
      msltn[LOCS][SPECIES],/*mass in solution for each pond location, not used for pkg*/
      matsat[LOCS], /*matrix saturation; used only for paths*/
      qin[LOCS], /* volumetric flow into each object */
      qout[LOCS], /*volumetric flow out of each object */
      qout0[LOCS], /*initial outflow from pond*/
      pkgin[]={0,0,0,0,0,0,10}, /*concentrations of infiltration to pkg; CO2 only */
      powater[LOCS]={0},powatermax[LOCS],infin,infout,invertarea,qnfin,qnfout,
      t1[LOCS],t2[LOCS][SPECIES],/*Used in updatepa(); calculated in setupv()*/
      len[LOCS],phim[LOCS],rd[LOCS][SPECIES],phif[LOCS],invertarea,
      cusol,ffrich,cint[2][TIMESTEPS],pamix[LOCS]={0};
int numspecies,numtforms,numpkgforms,numsolvar,isradtarget[SPECIES],pofrompa[LOCS],
      isvoldep[FORMS],formsleft,numsolint[SPECIES],numlocs,
      ispath[]={0,0,1,0,0},  /* Location 3 is a path*/
      dduid, pkgduid, /*id's for DU in drift and pkg*/
      driftmix,issolchanger[]={0,0,0,0,1,0,0},issolvar[]={1,1,1,1,0,0,0},
      numpaspecies,fineprint;
long int yr;
FILE *fin,*fout,*ferr,*fsmmry;

void main()
{long int i,j,k,maxyrs=100000,printyr=1000;/*length  of run and print interval*/
float keff,prob;
char dummy[121];
int nocrityet,casecount=0;
fin=fopen("generate.in","r");
fout=fopen("generate.out","w");
fsmmry=fopen("summary.out","w");
ferr=fopen("junk.out","w"); /* for debugging */
setupc();        /* initialize fixed parameters */
fgets(dummy,120,fin);  /*read through input file column headings*/
while(fscanf(fin,"%f %f %f %f\n",&infrate,&pkgwout0,&dissrate[0],
       &prob)!=EOF) /*WP infiltration, WP outflow,dissrate of Immob WF, prb this config*/
  {yr=0;   /*start each case at time 0*/
  nocrityet=1;  /*boolean to test for first criticality*/
  printf("starting %d\n",++casecount);
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  setupv();    /* initialize variables to restart each input case*/
  fprintf(fout,"\n\n%f %f %f %f\n",infrate,pkgwout0,dissrate[0],prob);
  fprintf(fout,"%7s%12s%12s%12s%12s%12s%12s%12s%12s%6s\n",
         "Kyrs","Water","U5precip","U8precip","Puprecip","U5sltn",
         "U8sltn","Pusltn","Gdprecip","Keff");/*heading for output table*/
  fprintf(ferr,"\n\n%7s%10s%10s%10s%10s\n",
   "KYr","U235conc","U238conc","Puconc","Gdconc");/*heading for diagnostice fl*/
  while(yr<maxyrs)
    {updatepkg(TIMESTEP);       /*update concentrations in WP  */
    if(yr%printyr==0)fprintf(ferr,"%7ld%10.2e%10.2e%10.2e%10.2e\n",
      yr,cout[0],cout[1],cout[2],cout[3]);
    for(i=1;i<numlocs;i++)
      {if(ispath[i]==0)
        {if((i==1)&&(driftmix==1)) /*is this the invert; is there DU backfill*/
          {backfill(TIMESTEP); /*calculates removal U from backfill, if any*/
          if(yr%printyr==0)fprintf(ferr,"%17.2e%10.2e%10.2e%10.2e\n",
          cout[0],cout[1],cout[2],cout[3]);}
        updatepo(i,TIMESTEP); /*only applied to the invert at this time*/
        if(yr%printyr==0)fprintf(ferr,"%17.2e%10.2e%10.2e%10.2e\n",
          cout[0],cout[1],cout[2],cout[3]);}
      else
        {updatepa(i,TIMESTEP,pamix[i]); /*presently only one path*/
        if(yr%printyr==0)fprintf(ferr,"%17.2e%10.2e%10.2e%10.2e\n",
           cout[0],cout[1],cout[2],cout[3]);}}
    keff=kcalc3(pkginprecip[3],pkginprecip[2],pkginprecip[0]);
    if((keff>1)&&(nocrityet==1))
      {fprintf(fsmmry,"%10d%10ld%15.5f\n",casecount,yr,prob);
      nocrityet=0;}
    if((yr<1000)&&(fineprint==1))        /*print every TIMESTEP for yr<1000*/
      {fprintf(fout,"%7ld%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e\n",
         yr,pkgwater,pkginprecip[0],pkginprecip[1],pkginprecip[2],
         pkginsltn[0],pkginsltn[1],pkginsltn[2]);
      fprintf(fout,"%19.2e%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e\n",
          powater[1],precip[1][0],precip[1][1],precip[1][2],
          msltn[1][0],msltn[1][1],msltn[1][2],precip[1][3]);}
    if((yr%printyr==0)&&((yr!=0)&&(fineprint==1))||(fineprint==0))/*print only at specified intervals*/
      {fprintf(fout,"%7ld%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e%6.2f\n",
          yr/1000,pkgwater,pkginprecip[0],pkginprecip[1],pkginprecip[2],
          pkginsltn[0],pkginsltn[1],pkginsltn[2],pkginprecip[3],keff);
      fprintf(fout,"%19.2e%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e%12.2e\n",
          powater[1],precip[1][0],precip[1][1],precip[1][2],
          msltn[1][0],msltn[1][1],msltn[1][2],precip[1][3]);}
    yr+=TIMESTEP;}
  printf("finished %d\n",casecount);
  if(nocrityet==1)    /*no criticality by max time*/
       fprintf(fsmmry,"%10d%10d%15.5f\n",casecount,TIMESTEPS,prob);}}

void solubility()  /* May overwrite constant solubilities specified in setupc()*/
{int i,j,k;
float x=0,eps=1e-14;
for(i=0;i<numspecies;i++)
  if(issolchanger[i]==1)
    x+=phcoef[i]*csltn[i];/*molality of H+ inducing ions*/
  /*Needs to be generalized to piecewise liner form?????*/
if(x<eps)x=eps;
ph=-(float)log10(x);                          /*calculate pH*/
if(ph<3) ph=3;                   /*  Estimate of floor, for realism  */
else if(ph>10) ph=10;        /*  Estimate of ceiling */
for(j=0;j<numspecies;j++) /* for species with variable solubility */
 if(issolvar[j]==1)
  for(k=0;k<numsolint[j];k++)  /* Assumed piecewise linear */
    if((phint[j][k]<ph)&&(ph<phint[j][k+1]))/* test for appropriate segment */
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      {slblty[j]=pow(10,alpha[j][k]*ph+beta[j][k]);
      break;}}

/*This routine uses the package specific variables, which are redundant with the
 *general pond arrays.  */
void updatepkg(int timest)
{int i,j,k,formcount=0;
float watern,newinsltn[SPECIES],del,fromform[SPECIES],dform[FORMS],
      newinprecip[SPECIES],fromtoform[FORMS][SPECIES],eps=1e-14,x,
      fromformt=0,delt=0,pkginprecipt=0,rf[2],rp[2],rs[2],mout[SPECIES];
pkgwout=(pkgwater<pkgwatermax?pkgwout0:pkgwin);/*pkg overflows at pkgwin rate*/
pkgwater+=timest*(pkgwin-pkgwout); /* increment water (zero in steady state*/
for(i=0;i<numspecies;i++)csltn[i]=pkginsltn[i];/*set global vars for use by solubility()*/
solubility();   /*now compute solubility for this timestep for package*/
if(pkgwater>pkgwatermax)pkgwater=pkgwatermax;/*pkg voidspace limits water*/
for(i=0;i<numspecies;i++)
    mout[i]=pkgwout*timest*pkginsltn[i]/pkgwater;/*species amounts to be removed*/
if(formsleft==1)
  for(j=0;j<numpkgforms;j++) /*this loop for 3-d area adjustments*/
    if(massform[j]>0) /*if there is any amount of this form*/
      {if(isvoldep[j]==1) /*area reduction for 3-d geometries  */
        areaform[j]=areaform0[j]*pow(massform[j]/massform0[j],.6667);
      else areaform[j]=areaform0[j];
      dform[j]= dissrate[j]*areaform[j]*timest*.001;}/*converts gm to kg*/
    else dform[j]=0; /*No decrement if form is already fully degraded*/
for(i=0;i<numspecies;i++)/*compute amounts released from forms for each species*/
 if(formsleft==1)            /*as long as there are solid forms left*/
  {fromform[i]=0;
  for(j=0;j<numpkgforms;j++)   /*species i released from form j*/
    {fromtoform[j][i]=(massform[j]>0?dform[j]*inform[j][i]/massform[j]:0);
    fromform[i]+=fromtoform[j][i];}}/*accumulate all the sources of species i*/
 or(i=2;i<numspecies;i++)  /*update all species except uranium isotopes*/
 {if(fromform[i]>0)   /*if any any of this species from a form*/
  {if(fromform[i]>(del=(slblty[i]/1000*pkgwater-pkginsltn[i])))/*always true if del<0*/
    {newinprecip[i]=pkginprecip[i]+fromform[i]-del;/*excess to precipitate*/
    newinsltn[i]=slblty[i]/1000*pkgwater;}
  else if(del>0)            /*else draw out of precipitate*/
    {if(pkginprecip[i]+fromform[i]<del) del=pkginprecip[i]+fromform[i];/*max avail for sln*/
    newinprecip[i]=pkginprecip[i]-(del-fromform[i]);/*decrement precipitate*/
    newinsltn[i]=pkginsltn[i]+del;}}      /*increment solution*/
 else                    /* no more of this species from forms */
  {newinsltn[i]=pkginsltn[i];
  newinprecip[i]=pkginprecip[i];
  if((pkginsltn[i]/pkgwater<slblty[i]/1000)&&(pkginprecip[i]>0)) /*Re-mobilize precipitate*/
    {del=slblty[i]/1000*pkgwater-pkginsltn[i];/*excess solution carrying capability*/
    if(del>pkginprecip[i])del=pkginprecip[i]; /*excess carrying capability takes all precip*/
    newinsltn[i]+=del;
    newinprecip[i]-=del;}
  if(newinsltn[i]/pkgwater>slblty[i]/1000) /*Add to precipitate if above sol lim*/
    {del=newinsltn[i]-pkgwater*slblty[i]/1000;
    newinsltn[i]-=del;                    /*and draw out of solution*/
    newinprecip[i]+=del;}}}
delt=slblty[0]/1000*pkgwater;   /*start with total solution capacity for U*/
for(i=0;i<2;i++)      /*Series of conditional operations for each uranium isotope*/
  {fromformt+=fromform[i]; /*combine amounts from form*/
    pkginprecipt+=pkginprecip[i]; /*combine amounts in precipitate*/
    delt+=-pkginsltn[i];}   /*decrement solution capacity by each isotope in sltn*/
for(i=0;i<2;i++)
  {rf[i]=(fromformt>0?fromform[i]/fromformt:0);/*combine solution inputs from form*/
   rp[i]=(pkginprecipt>0?pkginprecip[i]/pkginprecipt:0);}
if(fromformt>delt) /*fromform to solution, with excess to precip*/
  for(i=0;i<2;i++)
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    {newinsltn[i]=pkginsltn[i]+delt*rf[i];
     newinprecip[i]=pkginprecip[i]+fromform[i]-delt*rf[i];}
else if(delt>0)     /*excess solution capacity for uranium*/
  {if(delt>pkginprecipt+fromformt) /*fall short of net solution capacity*/
    for(i=0;i<2;i++)
      {newinsltn[i]=pkginsltn[i]+pkginprecipt*rp[i]+fromformt*rf[i];
      newinprecip[i]=0;}
  else if(fromformt==0)  /*take only from precip to go into solution*/
    for(i=0;i<2;i++)
      {newinsltn[i]=pkginsltn[i]+delt*rp[i];
      newinprecip[i]=pkginprecip[i]-delt*rp[i];}
  else    /*take from precip to make up deficiency in fromform*/
    for(i=0;i<2;i++)
      {newinsltn[i]=pkginsltn[i]+fromform[i]+rp[i]*(delt-fromformt);
      newinprecip[i]=pkginprecip[i]-rp[i]*(delt-fromformt);}}/*end uranium operations*/
for(i=0;i<numspecies;i++) /*now update all species for net from inflow and outflow*/
  newinsltn[i]+=timest*pkgwin*pkgin[i]-mout[i];
x=radrate[2]*timest*pkginsltn[2]; /*adjust for decay of Pu (species 2) in solution*/
newinsltn[0]+=x;
newinsltn[2]-=x;
x=radrate[2]*timest*pkginprecip[2];
newinprecip[0]+= x;
newinprecip[2]-=x;
if(formsleft==1)
 for(j=0;j<numpkgforms;j++) /*decrement form masses*/
  {if(massform[j]>0)
   for(i=0;i<numspecies;i++) inform[j][i]+= -fromtoform[j][i];
    if(inform[j][2]>0)  /*adjust for decay of Pu (species 2) in form*/
      {x=radrate[2]*timest*inform[j][2];
      inform[j][0]+=x;
      inform[j][2]-=x;}}
 or(i=0;i<numspecies;i++)  /*now update sltn and precip from temporary species variables*/
  {pkginsltn[i]=newinsltn[i];
    pkginprecip[i]=newinprecip[i];}
for(j=0;j<numpkgforms;j++) /*now update form masses and species fractions*/
  {massform[j]-=dform[j];
  for(i=0;i<numspecies;i++)
    if(inform[j][i]<0) inform[j][i]=0;
  if(massform[j]<0) massform[j]=0;
  if(massform[j]>0) formcount++;}
for(i=0;i<numspecies;i++) /*now compute species amounts removed to next location*/
  cout[i]=mout[i]/(pkgwout*timest);
if(formcount==0)formsleft=0;}

void updatepo(int poid, int timest) /*calculations parallel updatepkg()*/
{int i,j,k,formcount=0;
float watern,newinsltn[SPECIES],del,newinprecip[SPECIES],eps=1e-14,x,
     msltnt=0,delt=0,precipt=0,mint=0, /*for combined uranium isotopes*/
     rp[2],rs[2],mout[SPECIES];
qout[poid]=(powater[poid]<powatermax[poid]?qout0[poid]:qin[poid]);
powater[poid]+=timest*(qin[poid]-qout[poid]);
if(powater[poid]>powatermax[poid])
   powater[poid]=powatermax[poid];/*pond voidspace limits water*/
for(i=0;i<numspecies;i++)
  {csltn[i]=msltn[poid][i]/powater[poid]; /*to be used by solubility()*/
  mout[i]=qout[poid]*csltn[i]*timest;}/*to be removed from this pond*/
solubility();  /*now compute solubility limits for species in this pond*/
for(i=0;i<numspecies;i++)
 {newinsltn[i]=msltn[poid][i]-mout[i]+  /*decrement from outflow*/
      cout[i]*qin[poid]*timest;/*increment from inflow*/
  if(newinsltn[i]<0)newinsltn[i]=0;
  newinprecip[i]=precip[poid][i];}
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for(i=2;i<numspecies;i++)  /*adjust concntrtn to solubility; defer uranium*/
  {del= slblty[i]/1000*powater[poid]-msltn[poid][i];/*excess slblty this spcs*/
  if(del>precip[poid][i])del=precip[poid][i];
  newinsltn[i]+=del;
  newinprecip[i]-=del;}
delt=slblty[0]/1000*powater[poid];/*updates for uranium */
for(i=0;i<2;i++) /*combine uranium isotopes*/
  {precipt+=precip[poid][i];
  msltnt+=msltn[poid][i];
  delt+= -msltn[poid][i];}
for(i=0;i<2;i++)  /*record (store) U isotope fractions*/
  {rp[i]=(precipt>0?precip[poid][i]/precipt:0);
  rs[i]=(msltnt>0?msltn[poid][i]/msltnt:0);}
if(delt>precipt) delt=precipt; /*max available from precipitate*/
for(i=0;i<2;i++)
  {if(delt>0)
    {newinsltn[i]+=delt*rp[i];
    newinprecip[i]-=delt*rp[i];}
  else
    {newinsltn[i]+=delt*rs[i];
    newinprecip[i]=-delt*rs[i];}}
x=radrate[2]*timest*msltn[poid][2];
newinsltn[0]+=x;
newinsltn[2]-=x;
x=radrate[2]*timest*precip[poid][2];
newinprecip[0]+= x;
newinprecip[2]-=x;
for(i=0;i<numspecies;i++)
  {msltn[poid][i]=newinsltn[i];
  if(msltn[poid][i]<0)msltn[poid][i]=0;
  precip[poid][i]=newinprecip[i];
  cout[i]=newinsltn[i]*qout[poid]*timest;}/*outflow to next LOCS*/
if(poid==1)ffrich=cout[0]/(cout[0]+cout[1]);}/*constant enrichment for far-field*/

float kcalc3(float gdclay,float puclay,float uclay)
{if(gdclay>2.5) /*regression for immobilized Pu WF only, Feb 7, 1997 document*/
   return .7587-log(gdclay)*.11954+.00298*puclay+.00135*uclay;
else if (gdclay>1)
   return .67725-gdclay*.08524+.00478*puclay+.00205*uclay;
else if (gdclay>.2)
   return .62516-gdclay*.17972+.006578*puclay+.003005*uclay;
else return .448283597-gdclay*.36997+.010123*puclay+.004829*uclay;}

void setupv() /*initialization for each case (input data set)*/
{int i,j,k;
pkgwin=pkgarea*.001*infrate;  /* convert water mm/yr to cubic meters/yr */
qnfin=driftarea*.001*infin; /*convert drift-to-invert to volume flow*/
qnfout=invertarea*.001*infout;  /*convert invert-to-rock infrate to volume*/
qout0[0]=pkgwout0;/*redundant in the present formulation*/
qout0[1]=qnfout;/*redundant in the present formulation*/
mdduprecip=0;  /*initialize precipitated for each run.*/
mpkgduprecip=0;
cusol=0; /*concentration of uranium in drift waters, max solubility*/
for(i=0;i<numtforms;i++) /*reset mass variables to starting values*/
  {massform[i]=massform0[i];
  areaform[i]=areaform0[i];}
formsleft=1;/*Start with some form sources left*/
pkgwater=0; /*start dry*/
for(i=0;i<numspecies;i++)
  {pkginprecip[i]=0;
  pkginsltn[i]=0;
  for(j=0;j<numtforms;j++)
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```
     inform[j][i]+=formfrac[j][i]*massform0[j];}
 for(j=0;j<numlocs;j++)
    if(ispath[j]==1) /*compute transport times for each path*/
       {t1[j]=len[j]*phif[j]*1000/infrate; /*fracture flow time*/
       for(i=0;i<numpaspecies;i++) /*use the same infrate for all paths*/
          t2[j][i]=len[j]*rd[j][i]*matsat[j]*phim[j]*1000/infrate;})

 void setupc() /* mostly nominal constant values */
 {int i;
 fineprint=0; /*print every timestep for yr<1000*/
 infin=5; /*infiltration rate to the invert*/
 infout=1; /*infiltration rate out of the invert*/
 numlocs=3;  /*number of locations to coupled and evaluated*/
 dduid=2;   /*DU in drift form id*/
 driftmix=1;  /*DU from drift filler should mix with WP outflow*/
 pkgduid=0;/*fictitious at this time; no pkg DU*/
 durich=.002; /*DU enrichment*/
 ddufrac=.5; /*fraction of drift form which is DU?????*/
 pkgdufrac=0;  /*No pkg DU yet????*/
 pkgarea=3.9; /* sq meters, DHLW pkg area */
 driftarea=5.0; /* area for collecting drift for flow into invert */
 invertarea=2.0; /*area of collecting invert*/
 pkgwatermax=3;  /*pkg voidspace available for filling*/
 powatermax[0]=3;/*this is redundant with pkgwatermax, and may be revised*/
 powatermax[1]=1; /*invert voidspace*/
 numpkgforms=3;/*forms in the waste package*/
 numtforms=3;/*total forms, including DU backfill*/
 numspecies=8;/*same species for all LOCS,paths*/
 numpaspecies=2;/*only Pu and U to be tracked through a path*/
 /*the next 7 parameters are for the only current path, which is at location 2*/
 rd[2][0]=500;  /*retardation coefficient for uranium*/
 rd[2][1]=100;  /*retardation coefficient for plutonium*/
 phif[2]=0.001; /*fracture porosity */
 phim[2]=0.15;  /*matrix porosity */
 matsat[2]=0.85; /*matrix saturation */
 pamix[2]=.5; /*fraction of the flow in fractures*/
 len[2]=10;   /*length (m) of path*/
 for(i=0;i<numspecies;i++)
   pkgin[i]=0; /*set up default concentrations of pkg inflow*/
 isvoldep[0]=1;/*glass dsltn vol dependent (3-d)*/
 isvoldep[1]=0;/*SS dsltn not vol dependent (2-d)*/
 isvoldep[2]=1;/*backfill is volume dependent (3-d)*/
 dissrate[0]=.0005*365;/* glass gm/sqm/yr*/
 dissrate[1]= .78;/* SS, equivalent to .1micron/yr*/
 dissrate[2]=dissrate[0]; /*NEED A SPECIFIC ESTIMATE?????*/
 massform0[0]=2050; /* Total mass of Pu WF */
 massform0[1]=2000; /* Total mass of SS */
 massform0[2]=massform0[0]; /*NEED A SPECIFIC ESTIMATE?????*/
 areaform0[0]=15.5*10;/* area*fracfac */
 areaform0[1]=50.7;/*Total SS canister area inside + out*/
 areaform0[2]=areaform0[0];  /*NEED A SPECIFIC ESTIMATE?????*/
 slblty[4]=1000; /*default constant slblty for chromate ??? */
 slblty[5]=5.6; /*default constant slblty for Fe; may be overwritten in solubility()*/
 soludrift=1.0; /*conservative constant slblty for U in drift */
 numsolint[0]=3;/*3 intervals for U235 */
 phint[0][0]=0;
 phint[0][1]=5.31;
 phint[0][2]=8.34;
 phint[0][3]=14;
 alpha[0][0]= -1.9046;
 beta[0][0]=4.3714;
 alpha[0][1]=0;
```

```
beta[0][1]= -5.7424;
alpha[0][2]=4;
beta[0][2]= -39.1;
numsolint[1]=3;/*3 intervals for U238, identical with those for U235*/
phint[1][0]=0;
phint[1][1]=5.31;
phint[1][2]=8.34;
phint[1][3]=14;
alpha[1][0]= -1.9046;
beta[1][0]=4.3714;
alpha[1][1]=0;
beta[1][1]= -5.7424;
alpha[1][2]=4;
beta[1][2]= -39.1;
numsolint[2]=3; /* for Pu */
phint[2][0]=0;
phint[2][1]=4.3;
phint[2][2]=7.6;
phint[2][3]=14;
alpha[2][0]= -2;
beta[2][0]=1.362;
alpha[2][1]= -1;
beta[2][1]= -2.9343;
alpha[2][2]=3.997;
beta[2][2]= -41.6896;
numsolint[3]=2; /* for Gd */
phint[3][0]=0;
phint[3][1]=7.56;
phint[3][2]=14;
alpha[3][0]= -3.62;
beta[3][0]=21.1567;
alpha[3][1]=0.9758;
beta[3][1]=-13.5884;
phcoef[4]=(float)1/52; /*Cr is the only changer species*/
radrate[2]=.693/24100;/*Pu decay rate*/
formfrac[0][0]=0;/* fraction of [form] is [species]*/
formfrac[0][2]=0.1;
formfrac[0][3]=0.075;
formfrac[1][4]=0.2;
formfrac[1][5]=0.5;}

void updatepa(int paid, int timest,int mix)/*assumes no water loss in path*/
{int i,j,k,m,n[2],p[2],q[2];
float x,y,f;
f=pamix[paid]; /*fraction which flows in fractures*/
cint[0][yr/TIMESTEP]=cout[0]+cout[1];/*combine since far-field has const rich*/
cint[1][yr/TIMESTEP]=cout[2];/*shift Pu index down since U235 is combined with
* U238 to be re-separated at the end of the path; this limits the space used by
* cint[2][TIMESTEPS], which is the only large array in the current version.  */
m=(yr-t1[paid])/TIMESTEP;
m*=step(m);
for(i=0;i<2;i++)
  {n[i]=(yr-t2[paid][i])/TIMESTEP;
  n[i]*=step(n[i]);
  p[i]=(yr-(2*t1[paid]+t2[paid][i])/3)/TIMESTEP;
  p[i]*=step(p[i]);
  q[i]=(yr-(t1[paid]+2*t2[paid][i])/3)/TIMESTEP;
  q[i]*=step(q[i]);}
for(i=0;i<2;i++) /*current version tracks only uranium and plutonium*/
   {if(mix==0) cout[i]=f*cint[i][m]*step(yr-t1[paid])+  /*no transfer btwn matrix & frac*/
         (1-f)*cint[i][n[i]]*step(yr-t2[paid][i]);
    else cout[i]=pow(f,3)*cint[i][m]*step(yr-t1[paid])+ /*3 transfers btwn matrix & frac*/
```

```
        3*pow(f,2)*(1-f)*cint[i][p[i]]*step(yr-(2*t1[paid]+t2[paid][i])/3)+
        3*f*pow((1-f),2)*cint[i][q[i]]*step(yr-(t1[paid]+2*t2[paid][i])/3)+
         pow((1-f),3)*cint[i][n[i]]*step(yr-t2[paid][i]);}
cout[2]=cout[1];/*shift Pu back to nominal index*/
cout[1]=(1-ffrich)*cout[0];  /*ffrich determined in previous pond */
cout[0]=ffrich*cout[0];}  /* U235 */

int step(float x)  /*step function, for use in updatepa()*/
{if (x>0) return 1;
  else return 0;}

void backfill(int timest) /*tracks the uranium isotopes only*/
{int i,k;
float drform,musol,delduprecip,
   totalflow;
if(massform[dduid]>0) /*if there is any DU left)*/
    {areaform[dduid]=areaform0[dduid];
    if(isvoldep[dduid]==1) areaform[dduid]*=pow(massform[dduid]/massform0[dduid],.6667);
     drform= dissrate[dduid]*areaform[dduid]*timest*.001;/*converts gm to kg*/
     massform[dduid]-=drform;
     if(massform[dduid]<0) massform[dduid]=0;}
else drform=0;
musol=drform*ddufrac; /*uranium mass from dissolution, excess will precipitate*/
cusol=musol/(qnfin*timest);/*concentration in solution*/
if(cusol>soludrift)  /*compute excess U in sltn to precipitate*/
  {mdduprecip+=(cusol-soludrift)*qnfin*timest;
    cusol=soludrift;}
if((drform==0)&&(mdduprecip>0)) /*if no more DU form, re-mobilize precipitate*/
  {if((delduprecip=(mdduprecip-soludrift*qnfin*timest))>0)
      {mdduprecip-=delduprecip;
        cusol=soludrift;}
    else
      {cusol=mdduprecip/(qnfin*timest); /*take all the precipitate and still not sat*/
      mdduprecip=0;}}
totalflow=qout[0]+qnfin;
qin[1]=totalflow; /*totalflow into the invert*/
if(massform[ddid]+mdduprecip<=0)driftmix=0;//no more DU backfill remaining
/*In the following two lines, cout on the right side is the outgoing concentration
 *from the package, while cout on the left side is the combined concentration
 *which will go into the invert from the package and the drift.*/
cout[0]=(qout[0]*cout[0]+qnfin*cusol*durich)/totalflow; /*U235*/
cout[1]=(qout[0]*cout[1]+qnfin*cusol*(1-durich))/totalflow;}
```

```
/*snfpkg.c  This program tracks the kg of boron and Fe in a PWR WP, which are decreasing
with time as a result of corrosion processes and flushing of a waste package filled with water.
The program numerically integrates a set of first order linear differential rate equations
defining the corrosion processes. The timestep interval is TINT years.  The program also
computes the fraction of the expected commercial SNF (EIA database) which will be critical
at time intervals specified by tabint, as a function of borated stainless (basket)
thickness, iron oxide remaining in the package, and boron remaining in the package after
complete degradation of the borated stainless, as well as the individual SNF batch
characteristics (burnup and initial enrichment).  Each case continues until it reaches
the specified time limit (maxyrs) or until the peak criticality fraction.  This peak fraction
occurs because the reactivity of the assemblies reaches a peak between 10,000 and 25,000
years.  If there is still significant boron in the package at this time, the peak
critical fraction will be shifted out in time until nearly all the boron is removed.
If this time is  delayed beyond 200,000 years the peak may not occur because the
individual criticality curve no longer decreases with time.

When the concentration of either steel reaches zero it may overshoot to a negative value.
The steel concentration is easily corrected to zero, but a special takeout accounting
must correct for the extra addition into the oxide pool caused by the fictitious
negative steel removed.

The program has the capability to vary, from the input, the thickness of the borated
stainless steel plates.  The mass of boron10 is correspondingly varied automatically
by the program.

The program reads input from a file "snfpkg.in" which can contain any number of cases,
with one input line per case.  The SNF data is contained in the file "data.in" which
is the forecast of expected deliveries to the repository in accordance with the
forecast discharges (Energy Informatin Agencies) as processed by the M&O program,
Waste Stream Manager (WSM) which forecasts the fuel deliveries according to one
of several alternative utility selection strategies.

Output is printed to 4 files: "snfpkg.out" which provides a detailed listing of the
amounts of iron and boron in steel, and oxide, at selected time intervals,
(presently set to 1000 yrs),"snfpkg.log" which lists the Potentially Critical
Fraction (PCF) as a function of time (at the same interval as for snfpkg.out)
relevant parameters at the completion of each case.

The program nominally runs until peaks are reached in critical fraction
for both the uniform and settled distribution of the iron oxide, or until
maxyrs is reached, whichever occurs first.  It has the option to surpress the
testing for peak, and simply run for maxyrs, which is specified by pswitch=0 in the
input.*/


#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <string.h>
#define TINT 10    //Time step in years for numerical integration
#define TABYRS 100   //Maximum number of times at which crit fractions are evaluated
#define PI 2*asin(1) //Value of pi
#define BATCHES 20000 //Maximum number of PWR input batches to dimension data arrays

float getfloat(char*,int,int);
int getint(char*,int,int);
float mfec0=(float)5429.0,      //Initial mass of iron in carbon steel (kg)
     mfes00= (float)1137.0,//Iron mass (kg) in 7mm thick borated stainless steel
     mbs00= (float)30.11,//Boron mass (kg) in 7mm thick borated stainless steel
     mfes0,//Fe mass in BSS at the start of a case (computed from the input thickness)
     mbs0,//B mass in BSS at the start of a case (computed from the input thickness)
     mbtot,        //Total mass of boron as a function of time
```

```
     mfeo,            //Mass of iron oxide
     mfeon,        //Updated value of iron oxide mass
     mfetot,       //Total mass of iron
     nus, //Stainless steel corrosion rate (input as microns/yr converted to kg/yr; )
     nuc=1.65,   //Carbon steel corrosion rate (kg/yr), not normally input
     rho0,            //Initial flushing rate (computed directly from input, per year)
     rho,            //Actual flushing rate (computed from rho0 according to specified
    //time dependence, which is assumed constant in this study)
     s=.0001,//Iron solubility limit (input, kg); may be replaced by pH depndnt form
     cpb[2][13],  //partial basket criticality coefficients (uniform, settled)
     cfd[2][13],  //fully degraded bskt criticality coefficients (uniform, settled)
     dkpbs[10],  //partial  bskt boron dependence
     dkfds[10],  //fully degraded basket boron coeficients
     dkfdu[10],  //same as above, but uniform distributed oxide
     wcrit[2][TABYRS]={{0}}, //Array accumulates critical MTU (unfrm, stld)
     maxncrit[2], //current maximum num of critical assy (over tabulated yrs)
     maxwcrit[2], //current maximum MTU of critical (over tabulated yrs)
     wcritfrac[2][TABYRS]={{0}}, //MTU fractions critical
     arrb[BATCHES]={0},//burnup array for PWR assembly batches
     arra[BATCHES]={0},//initial enrichment array for PWR assembly batches
     arrw[BATCHES]={0},//MTU array for PWR assembly batches
     acritfrac[2][TABYRS]={{0}}; //assy fractions critical (uniform and settled)
int arrna[BATCHES]={0}, //Array of number of assemblies in PWR assembly batches
  tabndx;       //Index to array of times at which critical fractions are evaluated
long int ncrit[2][TABYRS]={{0}}, //Array accumulates num  critical assy
     tabint=2000;          //Years interval to tabulate critical fraction of SNF

void main()
{long int t,              //Basic time counting variable
     tt=0,             //Time to start flushing; zero in cases for this analysis
     ntotp=0,        //Total number of PWR assy counted, from WSM output
     finished,       //variable to test whether each case is finished
     tmax,           //Latest time for complete basket degradation
     tmin,           //Earliest time for complete basket degradation
     tbskt,          //Nominal complete bskd dgrdtn time (computed from ss crrsn rate)
     peaktime[2],    //Time at which maximum critical fraction occurs (for each case)
     maxyrs=150000,//Maximum integration time for each case: maxyrs<tabint*TABYRS
     tcyc=50000;          //Period for cyclic flushing time (not used in this analysis)
int i,j,k,n,          //Dummy variables for testing and looping
     count=0,        //Counts number of cases started
     na,             //number of assy in a batch from WSM file
     fined[2],       //boolean indicating whether (unfrm,stld) peak crit frac is reached
     npyr,           //emplacement year for EIA batch (not used)
     ndyr,           //discharge year for EIA batch (not used)
     pentime,        //time to penetrate package (shifting criticality peak)
     pswitch,  //=0 means run to maxyrs without stopping at maxncrit
     numbatches;//number of PWR SNF batches (max index to SNF property arrays)
float alph,               //Ratio of boron mass to total stainless steel mass
     x,z,             //Temporary variables for calculation efficiency
     ex,            //Exchange fraction for each entering water unit (value may be input)
     dr,            //Drip rate (input, mm/yr)
     mbcr,                //Total boron at time of criticality
     mfecr,               //Total iron at time of criticalityy
     keff,                //keff computed from linear regression function
     keffpb,        //keff computed by partial bskt regression
     kefffd,        //keff computed by fully degraded bskt regression
     dkpb,          //fractional delta keff from B-10 in solution, partial bskt
     dkfd,          //same as above for fully degraded
     udkfd,         //same as above, but for a uniform distribution of oxide
     sigma,         //overlapping factor surrounding  nominal degradation time
     mfec,                //mass of Fe remaining in carbon steel
     mfecn,               //Updated value of mass of carbon steel (Fe)
```

```
     mfes,                //mass of Fe remaining in stainless steel
     mfesn,               //Update value of mass of Fe (equivalent) remaining in stainless
     mbs,            //mass of boron remaining in stainless steel
     mbsn,                //Updated mass of boron remaining in stainless steel
     tf=0,        //Fraction of boron trapped in iron oxide, not presently used
     mbot,                //Mass of boron trapped in iron oxide as a function of time
     mbotn,          //Updated mass of boron trapped in iron oxide as a function of time
     mbosol,         //Mass of boron in solution as a function of time
     mbosolg,        //B-10 in solution in gm.
     mbosoln,        //Updated mass of boron in solution as a function of time
     w,              //MTU for this batch
     prob,//Probability of individual input case (simply passed to output processor)
     wtotp=0,         //Total PWR MTU read from WSM output
     b,              //burnup (MWD/MDU)
     a,              //enrichment (percent)
     rows,          //rows of fuel rodes covered by oxide in the uniform case
     ssthick0,     //Initial thickness of b-stainless (mm)
     keff0,        //keff threshold for detecting potentially critical waste package
     ssthick;     //Thickness of b-stainless remaining
FILE *fin,          //Input file pointer
     *fdata,      //WSM forecast of SNF deliveries to repository
     *fout,               //Detailed output file
     *flog,               //Log output file
     *ferr,               //File for reporting non-standard conditions
     *fsmmry;             //Summarize the results of stacked cases
char buff[100],           //Dummy variable for read-through of input
     buffer[300],  //Long buffer to read WSM output file
     type,          //'B' or 'P' from WSM output file
     labels[2][12]={"Uniform","Settled"}, //for output
     rname[20];   //Reactor name from WSM output (not used)
cpb[0][0]=2.354976e+000;     //Keff regression: Partial basket uniform
cpb[0][1]=-6.673711e-003;
cpb[0][2]=-1.809599e-005;
cpb[0][3]=1.417981e-001;
cpb[0][4]=-7.135429e-003;
cpb[0][5]=-5.193039e-001;
cpb[0][6]=5.947134e-002;
cpb[0][7]=-2.240619e-003;
cpb[0][8]=-5.088912e-003;
cpb[0][9]=-7.490603e-002;
cpb[0][10]=1.064620e-002;
cpb[0][11]=-5.233379e-004;
cpb[1][0]=1.720946e+000;    //Partial basket settled
cpb[1][1]=-6.723740e-003;
cpb[1][2]=-1.666736e-005;
cpb[1][3]=1.334764e-001;
cpb[1][4]=-6.049678e-003;
cpb[1][5]=-3.123208e-001;
cpb[1][6]=3.744225e-002;
cpb[1][7]=-1.471468e-003;
cpb[1][8]=-1.679677e-002;
cpb[1][9]=-6.631601e-002;
cpb[1][10]=9.403563e-003;
cpb[1][11]=-4.690478e-004;
cfd[0][0]=-5.129550e+000;    //Fully degraded uniform
cfd[0][1]=1.656154e+000;
cfd[0][2]=-8.528523e-003;
cfd[0][3]=2.926600e-001;
cfd[0][4]=-1.539711e-001;
cfd[0][5]=4.670704e-003;
cfd[0][6]=6.896402e-005;
cfd[0][7]=-1.632270e-007;
```

```
cfd[0][8]=-6.713724e-002;
cfd[0][9]=5.360828e-003;
cfd[0][10]=-4.081508e-004;
cfd[0][11]=7.237075e-003;
cfd[0][12]=-5.259776e-003;
cfd[1][0]=-1.251609e+000;  //Fully degraded settled
cfd[1][1]=6.831545e-001;
cfd[1][2]=-6.651329e-003;
cfd[1][3]=2.661446e-001;
cfd[1][4]=-6.402816e-002;
cfd[1][5]=1.926314e-003;
cfd[1][6]=-2.670409e-005;
cfd[1][7]=6.121968e-007;
cfd[1][8]=-6.182764e-002;
cfd[1][9]=5.203523e-003;
cfd[1][10]=-1.364971e-004;
cfd[1][11]=5.084904e-003;
cfd[1][12]=-1.409177e-001;
dkpbs[0]=6.3797e-003;  //Fractional change from distributed boron (part bskt)
dkpbs[1]=-6.0738e-002;
dkpbs[2]=2.0843e-002;
dkpbs[3]=-2.2156e-003;
dkpbs[4]=3.5971e-004;
dkpbs[5]=4.2369e-003;
dkfds[0]=2.3256e-002;  //Fractional change from distributed  boron (fully degraded)
dkfds[1]=-3.5638e-002;
dkfds[2]=1.4282e-002;
dkfds[3]=-1.9169e-003;
dkfdu[0]=-4.5159e-02;
dkfdu[1]=2.8222e-02;
dkfdu[2]=-4.7984e-03;
fin=fopen("snfpkg.in","r"); //Input one line for each case
fout=fopen("snfpkg.out","w"); //Nominal output, not presently used
flog =fopen("snfpkg.log","w"); //Criticality fractions at each tabint
ferr=fopen("junk.out","w");  //for miscellaneous debugging output
fdata=fopen("data.in","r"); //WSM input file of commercial SNF waste stream
fsmmry=fopen("summary.out","w");//peak critical fractions, occurrence time, probability
fprintf(fsmmry,"%12s%12s%12s%12s%12s\n",//heading for summary.out
       "Time Unfrm","Frac Unfrm","Time Stld","Frac Stld","Prob");
sigma=.1;//slight smearing between partial basket and fully degraded
//The following 7 parameters  are nominal values which are overridden by input values
nus=0.4; //Corrosion rate of borated stainless steel in microns/yr
ex=.1;    //Exchange fraction per incomming water unit
prob=1; //May be changed by input so that the total cases can build a prob distrbtn
dr=5.0;
pswitch=1;
ssthick0=7; //Initial thickness of b-stainless (mm)
keff0=.929;   //keff threshold; normally rounded to 0.93 by input
i=0;
//The following loop reads the characteristics of each SNF batch and stores them
//in arrays for repeated use in Keff calculations
while(fgets(buffer,300,fdata)!=NULL)
    {w=getfloat(buffer,21,10);  //Reading fields of the  WSM record
    b=getfloat(buffer,51,10);   //burnup (MWd/MTU)
    ndyr=getint(buffer,71,8);   //Discharge year
    npyr=getint(buffer,287,4);  //emplacement year
    type=tolower(buffer[123]);  //p or b for fuel type
    na=getint(buffer,31,10);    //number of assemblies in this batch
    a=getfloat(buffer,41,10);   //Initial enrichment
    strncpy(rname,buffer+1,11); //First 11 characters of reactor name
    rname[11]='\0';             //Make a proper string out of it
    if((type=='p')&&(npyr>0)) //Just use PWR SNF to be delivered
```

```
      {wtotp+=w;          //These two calcs will be redundant at each tabint,
      ntotp+=na;          //but the testing logic would take almost as much time
      b/=1000;       //Reduce to GWd/MTU for keff regression
      arrw[i]=w; //Loading 4 basic data arrays for use in repeated keff calculations
      arrna[i]=na;
      arrb[i]=b;
      arra[i]=a;
      i++;}}
numbatches=i;
fgets(buff,99,fin);    //Dummy read through data file header line
//Following instruction reads one input case and defines the start of the basic processing loop.
while((i=fscanf(fin, "%f %f %d %f %f %f %f %d",
      &nus,&dr,&pentime,&ssthick0,&ex,&keff0,&prob,&pswitch))!=EOF)
 {printf("read data %d \n",count++);      //Print case count on screen
 fprintf(fout,"nus=%f  nuc=%f  dr=%f  ex=%f  tf=%f\n",
                  nus,nuc,dr,ex,tf);    //print out input data in header for detailed listing
 fprintf(fout,"s=%f  var=%f  pentime=%d  ssthick0=%f\n",s,sigma,pentime,ssthick0);
 rho0=dr*ex*  //initial exchange rate (may be modified by cyclic infiltration)
      0.001*4*6.63/4.84; //(mm/m)*Concentration*PkgArea/PkgVoidSpace
 fprintf(fout,"%7s%8s%8s%8s%8s%8s%8s%8s\n","Time","B Stl","Tr B Ox",
       "B sltn","Tot B","Tot Fe","Cs Fe","Ss Fe","Oxide"); //Column headers for output file
 //The following are initializations based on input for each case
 mbs0=mbs00*ssthick0/7;//adjust for changes in ssthick0 by input
 mfes0=mfes00*ssthick0/7;
 alph=mbs0/(mfes0+mbs0);//Boron fraction in borated stainless steel
 nus=nus*7770*   //microns/yr to kg/yr (density of SS)*
       70*(1.e-6)*  //area*microns/meter*
       0.60445/(1-alph);//BSSFeFrac*(adj to Fe+B)
 tbskt=mfes0/nus;//time until complete degradation of borated stainless steel basket
 tmax=tbskt*(1+sigma); //Definition of latest time for complete SS bskt degrdtn
 tmin=tbskt*(1-sigma); //Definition of earliest time for complete SS bskt dgrdtn
 //The following initializations are identical for each case
 t=0;                 //Initialize starting time for this case
 tabndx=0;            //Inidialize index of critical fraction tabulation times
 for(i=0;i<2;i++)  //Initializations for both uniform and settled modes
   {fined[i]=0;
   maxwcrit[i]=0;
   maxncrit[i]=0;}
 for(i=0;i<2;i++)
   for(j=0;j<=maxyrs/tabint;j++)//Initializations for each crit frctn tabulation
     {wcritfrac[i][j]=0;
     acritfrac[i][j]=0;
     wcrit[i][j]=0;
     ncrit[i][j]=0;}
 finished=0;
 mbot=0;
 mbotn=0;
 mbosol=0;
 mbosoln=0;
 mfeo=0;
 mfeon=0;
 mbs=mbs0;
 mbsn=mbs;
 mfec=mfec0; //Set to starting carbon steel mass, to be decremented
 mfecn=mfec;
 mfes=mfes0; //Set to starting borated stainless mass
 mfesn=mfes;
 mfetot=mfec+mfes+mfeo;//Total iron n steel and oxide
 fprintf(flog,"nus=%f  nuc=%f  dr=%f ex=%f pentime=%d\n",nus,nuc,dr,ex,pentime);
 fprintf(flog,"f=%f  s=%f  Sigma=%f  tbskt=%ld  ssthick0=%.0f  keff0=%.3f\n",
                 tf,s,sigma,tbskt,ssthick0,keff0);
 fprintf(flog,"Criticality fraction for indicated times\n");
```

```
while((mfetot>rho*s*TINT) //While enough iron to be flushed in one timestep
    &&(t<maxyrs)     //As long as we haven't exceeded time limit
    &&(1-pswitch*(finished==1))) //Not passed the peak (when the switch is on)
 {if(t<tt) rho=0;      //No exchange before designated start; this study has only tt=0
 else   //rho=.1*rho0+.45*rho0*(1-cos(PI*t/tcyc)); //Used for cyclic flushing
   rho=rho0;     //constant rho for this study
 mfeon=mfeo+nus*TINT*(mfes>0?1:0)*(1-alph)+ //increment from ss crsn,
       nuc*TINT*(mfec>0?1:0)-                //increment from cs crrsn
       rho*s*TINT;                           //decrement from exchg flush
 x=rho*TINT;     //Fraction to be exchanged at each time step (TINT)
 if(x>1)mbosoln=0;    //All solution boron flushed in one TINT
 else
   mbosoln=mbosol*(1-x)+    //Decrement from exchange flushing
        (1-tf)*nus*TINT*alph*(mbs>0?1:0) //Incremented from ss corrosion
         +rho*s*tf*TINT*mbot/mfeon; //increment from release of trapped B
 mbotn=mbot+nus*TINT*alph*tf*(mbs>0?1:0) //Trapped B incremented from ss dgrdtn
              -rho*s*tf*TINT*mbot/mfeon; //Trapped B flushed with iron oxide
 if(mfec>0)mfecn=mfec-nuc*TINT;          //simple carbon steel corrosion
 if(mfes>0)mfesn=mfes-nus*TINT*(1-alph);//simple stainless steel corrosion
 if(mbs>0)mbsn=mbs-nus*TINT*alph;//Decrement B in ss congruently
 if(mfecn<0)                     //Correct for overshoot of zero
   {mfeon+=mfecn;
   mfecn=0;}
 if(mfesn<0)                     //Correct for overshoot of zero
   {mfeon+=mfesn;
   mfesn=0;}
 if(mbsn<0)                      //Correct for overshoot of zero
   {mbotn+=mbsn;
   mbsn=0;}
 if(mbotn<0)                     //Correct for overshoot of zero
   {mbosol+=mbotn;
   mbotn=0;}
 if(mbosol<0)mbosol=0;//Simply zero out since there are no more variables to correct
 mfec=mfecn;             //Adjust old values to start next integration step
 mfes=mfesn;
 mbs=mbsn;
 mbot=mbotn;
 mbosol=mbosoln;
 mfeo=mfeon;  //Don't bother testing for mfeo<0 since it can't happen
 ssthick=ssthick0*mfes/mfes0; //Remaining thickness proportional to remaining mass
 mfetot=mfec+mfes+mfeo+s/*always enough Fe for saturation*/; //Compute total iron
 mbtot=mbs+mbot+mbosol;      //Compute total boron
 if(t%tabint==0)             //Is this a criticality fraction tabulation year
   {tabndx=t/tabint;         //Compute index of this tabulation
   mbosolg=(mbosol)*1000*.199; //gm of B-10: (g/kg)*FracB10inNatBoron
   if(mbosolg>30)  //Threshold of effectiveness to avoid log divergence
     {x=log(mbosolg);//temporary variable
     rows=8*(1-mfec/mfec0)+2*(1-mfes/mfes0);  //Rows covered for settled
     dkpb=dkpbs[0]+dkpbs[4]*ssthick+dkpbs[5]*rows;//B frac chng, part bskt
     dkpb+=dkpbs[1]*x+dkpbs[2]*x*x+dkpbs[3]*x*x*x;
     dkfd=dkfds[0];         //Boron fractional change, fully degraded
     dkfd+=dkfds[1]*x+dkfds[2]*x*x+dkfds[3]*x*x*x;}
   else
     {dkpb=0;
     dkfd=0;}
   if((fabs(dkpb)>.75)||(fabs(dkfd)>.75)) //Sanity check on fractional change
     {printf("dkpb=%f  dkfd=%f\n",dkpb,dkfd);
     exit(0);}
   printf("Tabulating keff for %ld years\n",t);//To monitor progress of cases
   for(n=0;n<numbatches;n++)//Calculate keff for each batch
     {a=arra[n];
     b=arrb[n];
```

```
      w=arrw[n];
      na=arrna[n];
      z=log((double)(t+pentime));//Use total time since discharge
      for(i=0;i<2;i++)
           {keffpb=cpb[i][0]+cpb[i][8]*(i==0?mfeo*5.0e-3:rows);//Total oxide for uniform
           keffpb+=cpb[i][1]*b+cpb[i][2]*b*b;
           keffpb+=cpb[i][3]*a+cpb[i][4]*a*a;
           keffpb+=cpb[i][5]*z+cpb[i][6]*z*z+cpb[i][7]*z*z*z;
           keffpb+=cpb[i][9]*ssthick+cpb[i][10]*ssthick*ssthick+
                                       cpb[i][11]*ssthick*ssthick*ssthick;
           kefffd=cfd[i][0]+cfd[i][1]*z+cfd[i][2]*b+
                 cfd[i][3]*a+cfd[i][12]*(i==0?mfeo*5.0e-3:3.5);
           kefffd+=cfd[i][4]*z*z+cfd[i][5]*z*z*z;
           kefffd+=cfd[i][6]*b*b+cfd[i][7]*b*b*b;
           kefffd+=cfd[i][8]*a*a+cfd[i][9]*a*a*a;
           kefffd+=(cfd[i][10]*b+cfd[i][11]*a)*z;
          if(i==1)  //Boron in solution considered for settled config only
            {keffpb*=1+dkpb;
            kefffd*=1+dkfd;}
           if(t<tmin)keff=keffpb;//Partial basket only for this early time
           else if(t<tmax)keff= //Blending 2 keff's for intermediate times
               ((t-tmin)*kefffd+(tmax-t)*keffpb)/(tmax-tmin);
           else keff=kefffd; //Fully degraded only for t>tmax
          if(keff>keff0)
             {ncrit[i][tabndx]+=na;  //Accumulate number critical assy
             wcrit[i][tabndx]+=w;}}}//Accumulate critical MTU
       for(i=0;i<2;i++)
         if(ncrit[i][tabndx]>maxncrit[i])//New max in crit fraction?
           {maxncrit[i]=ncrit[i][tabndx];
           peaktime[i]=t;}
         else if((float)ncrit[i][tabndx]/ntotp<.001)maxncrit[i]=0;//Don't stop at early peak
         else if(t>tbskt+5*tabint)fined[i]=1;//Don't stop until well beyond tbskt
       if((fined[0]==1)&&(fined[1]==1))finished=1;//finish case if beyond max
      for(j=0;j<2;j++)    //Reduce numbers and weights to fractions
        {wcritfrac[j][tabndx]=wcrit[j][tabndx]/wtotp;
        acritfrac[j][tabndx]=(float)ncrit[j][tabndx]/ntotp;}
      fprintf(flog,"%12ld%12.4f%12.4f%4d%4d\n",t,acritfrac[0][tabndx],
                     acritfrac[1][tabndx],fined[0],fined[1]);}
  if(t%tabint==0)      //Print if time is multiple of tabulate interval
    fprintf(fout,"%7ld%8.2f%8.3f%8.2f%8.3f%8.1f%8.1f%8.1f%8.1f\n",
       t,mbs,mbot,mbosol,mbtot,mfetot,mfec,mfes,mfeo);
  t+=TINT;}                     //Increment t for next integration step
  fprintf(fsmmry,"%12ld%12.5f%12ld%12.5f%12.5f\n",
           peaktime[0],maxncrit[0]/ntotp,peaktime[1],maxncrit[1]/ntotp,prob);}}


float getfloat(char* string, int start, int length) //Get floating point from WSM rcrd
{char temp[20];
int i,j;
for(i=start;i<start+length;i++) temp[i-start]=string[i];
temp[length]='\0';
return(atof(temp));}

int getint(char* string, int start, int length) //Get integer from WSM record
{char temp[20];
int i,j;
for(i=start;i<start+length;i++) temp[i-start]=string[i];
temp[length]='\0';
return(atoi(temp));}
```

ex.in

```
  sscrsn    dr   pentime    ssthick0    ex    keff0    prob  pswitch
   0.08      5     3000        7        .1     .93       1       1
   0.08      5     3000        7        .2     .93       1       1
   0.08      5     3000        7        .3     .93       1       1
   0.08      5     3000        7        .4     .93       1       1
   0.08      5     3000        7        .5     .93       1       1
   0.20      5     3000        7        .1     .93       1       1
   0.20      5     3000        7        .2     .93       1       1
   0.20      5     3000        7        .3     .93       1       1
   0.20      5     3000        7        .4     .93       1       1
   0.20      5     3000        7        .5     .93       1       1
   0.40      5     3000        7        .1     .93       1       1
   0.40      5     3000        7        .2     .93       1       1
   0.40      5     3000        7        .3     .93       1       1
   0.40      5     3000        7        .4     .93       1       1
   0.40      5     3000        7        .5     .93       1       1
   0.80      5     3000        7        .1     .93       1       1
   0.80      5     3000        7        .2     .93       1       1
   0.80      5     3000        7        .3     .93       1       1
   0.80      5     3000        7        .4     .93       1       1
   0.80      5     3000        7        .5     .93       1       1
   2.00      5     3000        7        .1     .93       1       1
   2.00      5     3000        7        .2     .93       1       1
   2.00      5     3000        7        .3     .93       1       1
   2.00      5     3000        7        .4     .93       1       1
   2.00      5     3000        7        .5     .93       1       1
   4.00      5     3000        7        .1     .93       1       1
   4.00      5     3000        7        .2     .93       1       1
   4.00      5     3000        7        .3     .93       1       1
   4.00      5     3000        7        .4     .93       1       1
   4.00      5     3000        7        .5     .93       1       1
```

ex.log

```
nus=0.026997  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000   s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
        0      0.0175      0.0204   0    0
     2000      0.0065      0.0050   0    0
     4000      0.0011      0.0015   0    0
     6000      0.0011      0.0020   0    0
     8000      0.0011      0.0020   0    0
    10000      0.0015      0.0020   0    0
    12000      0.0020      0.0020   0    0
    14000      0.0020      0.0020   0    0
    16000      0.0020      0.0024   0    0
    18000      0.0025      0.0025   0    0
    20000      0.0028      0.0028   0    0
    22000      0.0032      0.0029   0    0
    24000      0.0044      0.0043   0    0
    26000      0.0046      0.0044   0    0
    28000      0.0049      0.0047   0    0
    30000      0.0053      0.0051   0    0
    32000      0.0070      0.0065   0    0
    34000      0.0081      0.0071   0    0
    36000      0.0086      0.0081   0    0
    38000      0.0120      0.0100   0    0
    40000      0.0168      0.0161   0    0
    42000      0.0222      0.0232   0    0
```

```
       44000      0.0267      0.0395   0    0
       46000      0.0272      0.0592   0    0
       48000      0.0260      0.0614   0    0
       50000      0.0255      0.0610   0    0
       52000      0.0254      0.0606   0    0
       54000      0.0253      0.0599   1    1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.200000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0    0
        2000      0.0065      0.0006   0    0
        4000      0.0011      0.0007   0    0
        6000      0.0011      0.0007   0    0
        8000      0.0011      0.0007   0    0
       10000      0.0015      0.0007   0    0
       12000      0.0020      0.0010   0    0
       14000      0.0020      0.0010   0    0
       16000      0.0020      0.0011   0    0
       18000      0.0025      0.0011   0    0
       20000      0.0028      0.0015   0    0
       22000      0.0032      0.0020   0    0
       24000      0.0044      0.0026   0    0
       26000      0.0046      0.0037   0    0
       28000      0.0049      0.0044   0    0
       30000      0.0053      0.0048   0    0
       32000      0.0070      0.0053   0    0
       34000      0.0081      0.0070   0    0
       36000      0.0086      0.0081   0    0
       38000      0.0120      0.0100   0    0
       40000      0.0168      0.0162   0    0
       42000      0.0222      0.0285   0    0
       44000      0.0267      0.0395   0    0
       46000      0.0272      0.0592   0    0
       48000      0.0260      0.0614   0    0
       50000      0.0255      0.0610   0    0
       52000      0.0254      0.0606   0    0
       54000      0.0253      0.0599   1    1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.300000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0    0
        2000      0.0065      0.0006   0    0
        4000      0.0011      0.0007   0    0
        6000      0.0011      0.0007   0    0
        8000      0.0011      0.0007   0    0
       10000      0.0015      0.0007   0    0
       12000      0.0020      0.0010   0    0
       14000      0.0020      0.0010   0    0
       16000      0.0020      0.0011   0    0
       18000      0.0025      0.0011   0    0
       20000      0.0028      0.0015   0    0
       22000      0.0032      0.0020   0    0
       24000      0.0044      0.0026   0    0
       26000      0.0046      0.0037   0    0
       28000      0.0049      0.0044   0    0
       30000      0.0053      0.0048   0    0
       32000      0.0070      0.0053   0    0
       34000      0.0081      0.0070   0    0
       36000      0.0086      0.0081   0    0
       38000      0.0120      0.0100   0    0
       40000      0.0168      0.0162   0    0
       42000      0.0222      0.0285   0    0
```

```
       44000      0.0267      0.0395   0   0
       46000      0.0272      0.0592   0   0
       48000      0.0260      0.0614   0   0
       50000      0.0255      0.0610   0   0
       52000      0.0254      0.0606   0   0
       54000      0.0253      0.0599   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.400000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0006   0   0
        4000      0.0011      0.0007   0   0
        6000      0.0011      0.0007   0   0
        8000      0.0011      0.0007   0   0
       10000      0.0015      0.0007   0   0
       12000      0.0020      0.0010   0   0
       14000      0.0020      0.0010   0   0
       16000      0.0020      0.0011   0   0
       18000      0.0025      0.0011   0   0
       20000      0.0028      0.0015   0   0
       22000      0.0032      0.0020   0   0
       24000      0.0044      0.0026   0   0
       26000      0.0046      0.0037   0   0
       28000      0.0049      0.0044   0   0
       30000      0.0053      0.0048   0   0
       32000      0.0070      0.0053   0   0
       34000      0.0081      0.0070   0   0
       36000      0.0086      0.0081   0   0
       38000      0.0120      0.0100   0   0
       40000      0.0168      0.0162   0   0
       42000      0.0222      0.0285   0   0
       44000      0.0267      0.0395   0   0
       46000      0.0272      0.0592   0   0
       48000      0.0260      0.0614   0   0
       50000      0.0255      0.0610   0   0
       52000      0.0254      0.0606   0   0
       54000      0.0253      0.0599   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.500000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0006   0   0
        4000      0.0011      0.0007   0   0
        6000      0.0011      0.0007   0   0
        8000      0.0011      0.0007   0   0
       10000      0.0015      0.0007   0   0
       12000      0.0020      0.0010   0   0
       14000      0.0020      0.0010   0   0
       16000      0.0020      0.0011   0   0
       18000      0.0025      0.0011   0   0
       20000      0.0028      0.0015   0   0
       22000      0.0032      0.0020   0   0
       24000      0.0044      0.0026   0   0
       26000      0.0046      0.0037   0   0
       28000      0.0049      0.0044   0   0
       30000      0.0053      0.0048   0   0
       32000      0.0070      0.0053   0   0
       34000      0.0081      0.0070   0   0
       36000      0.0086      0.0081   0   0
       38000      0.0120      0.0100   0   0
       40000      0.0168      0.0162   0   0
       42000      0.0222      0.0285   0   0
```

```
       44000      0.0267      0.0395   0   0
       46000      0.0272      0.0592   0   0
       48000      0.0260      0.0614   0   0
       50000      0.0255      0.0610   0   0
       52000      0.0254      0.0606   0   0
       54000      0.0253      0.0599   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0047   0   0
        4000      0.0011      0.0011   0   0
        6000      0.0020      0.0011   0   0
        8000      0.0026      0.0025   0   0
       10000      0.0044      0.0043   0   0
       12000      0.0064      0.0050   0   0
       14000      0.0085      0.0081   0   0
       16000      0.0189      0.0160   0   0
       18000      0.0324      0.0606   0   0
       20000      0.0325      0.0750   0   0
       22000      0.0322      0.0740   0   0
       24000      0.0320      0.0731   0   0
       26000      0.0318      0.0726   0   0
       28000      0.0312      0.0722   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.200000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0050   0   0
        4000      0.0011      0.0015   0   0
        6000      0.0020      0.0020   0   0
        8000      0.0026      0.0028   0   0
       10000      0.0044      0.0044   0   0
       12000      0.0064      0.0053   0   0
       14000      0.0085      0.0081   0   0
       16000      0.0189      0.0168   0   0
       18000      0.0324      0.0606   0   0
       20000      0.0325      0.0750   0   0
       22000      0.0322      0.0740   0   0
       24000      0.0320      0.0731   0   0
       26000      0.0318      0.0726   0   0
       28000      0.0312      0.0722   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.300000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0050   0   0
        4000      0.0011      0.0015   0   0
        6000      0.0020      0.0020   0   0
        8000      0.0026      0.0028   0   0
       10000      0.0044      0.0044   0   0
       12000      0.0064      0.0053   0   0
       14000      0.0085      0.0081   0   0
       16000      0.0189      0.0173   0   0
       18000      0.0324      0.0606   0   0
       20000      0.0325      0.0750   0   0
       22000      0.0322      0.0740   0   0
       24000      0.0320      0.0731   0   0
       26000      0.0318      0.0726   0   0
       28000      0.0312      0.0722   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.400000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
```

```
Criticality fraction for indicated times
          0       0.0175       0.0006    0    0
       2000       0.0065       0.0050    0    0
       4000       0.0011       0.0015    0    0
       6000       0.0020       0.0020    0    0
       8000       0.0026       0.0026    0    0
      10000       0.0044       0.0044    0    0
      12000       0.0064       0.0053    0    0
      14000       0.0085       0.0081    0    0
      16000       0.0189       0.0173    0    0
      18000       0.0324       0.0606    0    0
      20000       0.0325       0.0750    0    0
      22000       0.0322       0.0740    0    0
      24000       0.0320       0.0731    0    0
      26000       0.0318       0.0726    0    0
      28000       0.0312       0.0722    1    1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.500000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0       0.0175       0.0006    0    0
       2000       0.0065       0.0007    0    0
       4000       0.0011       0.0007    0    0
       6000       0.0020       0.0010    0    0
       8000       0.0026       0.0020    0    0
      10000       0.0044       0.0037    0    0
      12000       0.0064       0.0051    0    0
      14000       0.0085       0.0081    0    0
      16000       0.0189       0.0184    0    0
      18000       0.0324       0.0606    0    0
      20000       0.0325       0.0750    0    0
      22000       0.0322       0.0740    0    0
      24000       0.0320       0.0731    0    0
      26000       0.0318       0.0726    0    0
      28000       0.0312       0.0722    1    1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0       0.0175       0.0006    0    0
       2000       0.0065       0.0032    0    0
       4000       0.0025       0.0010    0    0
       6000       0.0053       0.0044    0    0
       8000       0.0181       0.0121    0    0
      10000       0.0322       0.0789    0    0
      12000       0.0332       0.0788    0    0
      14000       0.0332       0.0783    0    0
      16000       0.0332       0.0770    0    0
      18000       0.0332       0.0762    0    0
      20000       0.0325       0.0750    1    1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.200000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0       0.0175       0.0006    0    0
       2000       0.0065       0.0048    0    0
       4000       0.0025       0.0020    0    0
       6000       0.0053       0.0050    0    0
       8000       0.0181       0.0160    0    0
      10000       0.0322       0.0789    0    0
      12000       0.0332       0.0788    0    0
      14000       0.0332       0.0783    0    0
      16000       0.0332       0.0770    0    0
      18000       0.0332       0.0762    0    0
      20000       0.0325       0.0750    1    1
```

```
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.300000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0006   0   0
        2000       0.0065       0.0050   0   0
        4000       0.0025       0.0026   0   0
        6000       0.0053       0.0053   0   0
        8000       0.0181       0.0163   0   0
       10000       0.0322       0.0789   0   0
       12000       0.0332       0.0788   0   0
       14000       0.0332       0.0783   0   0
       16000       0.0332       0.0770   0   0
       18000       0.0332       0.0762   0   0
       20000       0.0325       0.0750   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.400000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0006   0   0
        2000       0.0065       0.0050   0   0
        4000       0.0025       0.0026   0   0
        6000       0.0053       0.0053   0   0
        8000       0.0181       0.0168   0   0
       10000       0.0322       0.0789   0   0
       12000       0.0332       0.0788   0   0
       14000       0.0332       0.0783   0   0
       16000       0.0332       0.0770   0   0
       18000       0.0332       0.0762   0   0
       20000       0.0325       0.0750   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.500000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0006   0   0
        2000       0.0065       0.0050   0   0
        4000       0.0025       0.0026   0   0
        6000       0.0053       0.0053   0   0
        8000       0.0181       0.0170   0   0
       10000       0.0322       0.0789   0   0
       12000       0.0332       0.0788   0   0
       14000       0.0332       0.0783   0   0
       16000       0.0332       0.0770   0   0
       18000       0.0332       0.0762   0   0
       20000       0.0325       0.0750   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0006   0   0
        2000       0.0071       0.0011   0   0
        4000       0.0164       0.0073   0   0
        6000       0.0289       0.0750   0   0
        8000       0.0312       0.0775   0   0
       10000       0.0322       0.0789   0   0
       12000       0.0332       0.0788   0   0
       14000       0.0332       0.0783   0   0
       16000       0.0332       0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.200000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0006   0   0
        2000       0.0071       0.0044   0   0
        4000       0.0164       0.0117   0   0
        6000       0.0289       0.0750   0   0
        8000       0.0312       0.0775   0   0
```

```
       10000     0.0322     0.0789   0   0
       12000     0.0332     0.0788   0   0
       14000     0.0332     0.0783   0   0
       16000     0.0332     0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.300000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0     0.0175     0.0006   0   0
        2000     0.0071     0.0050   0   0
        4000     0.0164     0.0143   0   0
        6000     0.0289     0.0750   0   0
        8000     0.0312     0.0775   0   0
       10000     0.0322     0.0789   0   0
       12000     0.0332     0.0788   0   0
       14000     0.0332     0.0783   0   0
       16000     0.0332     0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.400000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0     0.0175     0.0006   0   0
        2000     0.0071     0.0053   0   0
        4000     0.0164     0.0148   0   0
        6000     0.0289     0.0750   0   0
        8000     0.0312     0.0775   0   0
       10000     0.0322     0.0789   0   0
       12000     0.0332     0.0788   0   0
       14000     0.0332     0.0783   0   0
       16000     0.0332     0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.500000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0     0.0175     0.0006   0   0
        2000     0.0071     0.0064   0   0
        4000     0.0164     0.0161   0   0
        6000     0.0289     0.0750   0   0
        8000     0.0312     0.0775   0   0
       10000     0.0322     0.0789   0   0
       12000     0.0332     0.0788   0   0
       14000     0.0332     0.0783   0   0
       16000     0.0332     0.0770   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0     0.0175     0.0114   0   0
        2000     0.0453     0.0081   0   0
        4000     0.0243     0.0651   0   0
        6000     0.0289     0.0750   0   0
        8000     0.0312     0.0775   0   0
       10000     0.0322     0.0789   0   0
       12000     0.0332     0.0788   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.200000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0     0.0175     0.0114   0   0
        2000     0.0453     0.0273   0   0
        4000     0.0243     0.0651   0   0
        6000     0.0289     0.0750   0   0
        8000     0.0312     0.0775   0   0
       10000     0.0322     0.0789   0   0
       12000     0.0332     0.0788   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.300000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
```

```
Criticality fraction for indicated times
           0       0.0175       0.0114   0    0
        2000       0.0453       0.0401   0    0
        4000       0.0243       0.0651   0    0
        6000       0.0289       0.0750   0    0
        8000       0.0312       0.0775   0    0
       10000       0.0322       0.0789   0    0
       12000       0.0332       0.0788   1    1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.400000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0114   0    0
        2000       0.0453       0.0509   0    0
        4000       0.0243       0.0651   0    0
        6000       0.0289       0.0750   0    0
        8000       0.0312       0.0775   0    0
       10000       0.0322       0.0789   0    0
       12000       0.0332       0.0788   1    1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.500000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0114   0    0
        2000       0.0453       0.0509   0    0
        4000       0.0243       0.0651   0    0
        6000       0.0289       0.0750   0    0
        8000       0.0312       0.0775   0    0
       10000       0.0322       0.0789   0    0
       12000       0.0332       0.0788   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0114   0    0
        2000       0.0453       0.0321   0    0
        4000       0.0243       0.0651   0    0
        6000       0.0289       0.0750   0    0
        8000       0.0312       0.0775   0    0
       10000       0.0322       0.0789   0    0
       12000       0.0332       0.0788   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.200000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0114   0    0
        2000       0.0453       0.0509   0    0
        4000       0.0243       0.0651   0    0
        6000       0.0289       0.0750   0    0
        8000       0.0312       0.0775   0    0
       10000       0.0322       0.0789   0    0
       12000       0.0332       0.0788   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.300000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0114   0    0
        2000       0.0453       0.0509   0    0
        4000       0.0243       0.0651   0    0
        6000       0.0289       0.0750   0    0
        8000       0.0312       0.0775   0    0
       10000       0.0322       0.0789   0    0
       12000       0.0332       0.0788   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.400000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0114   0    0
```

```
       2000      0.0453      0.0509   0   0
       4000      0.0243      0.0651   0   0
       6000      0.0289      0.0750   0   0
       8000      0.0312      0.0775   0   0
      10000      0.0322      0.0789   0   0
      12000      0.0332      0.0788   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.500000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0114   0   0
       2000      0.0453      0.0509   0   0
       4000      0.0243      0.0651   0   0
       6000      0.0289      0.0750   0   0
       8000      0.0312      0.0775   0   0
      10000      0.0322      0.0789   0   0
      12000      0.0332      0.0788   1   1
```

ex.sum

```
  Time Unfrm  Frac Unfrm  Time Stld  Frac Stld       Prob
      46000     0.02717      48000    0.06145    1.00000
      46000     0.02717      48000    0.06145    1.00000
      46000     0.02717      48000    0.06145    1.00000
      46000     0.02717      48000    0.06145    1.00000
      46000     0.02717      48000    0.06145    1.00000
      20000     0.03254      20000    0.07499    1.00000
      20000     0.03254      20000    0.07499    1.00000
      20000     0.03254      20000    0.07499    1.00000
      20000     0.03254      20000    0.07499    1.00000
      20000     0.03254      20000    0.07499    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
      14000     0.03322      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
       2000     0.04530      10000    0.07891    1.00000
```

time.in

```
   sscrsn    dr    pentime    ssthick0    ex    keff0    prob  pswitch
    0.08     5     3000          7        .1     .93       1       0
    0.40     5     3000          7        .1     .93       1       0
    0.40     50    3000          7        .1     .93       1       0
```

time.log

```
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
```

```
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
         0      0.0175      0.0204   0   0
      2000      0.0065      0.0050   0   0
      4000      0.0011      0.0015   0   0
      6000      0.0011      0.0020   0   0
      8000      0.0011      0.0020   0   0
     10000      0.0015      0.0020   0   0
     12000      0.0020      0.0020   0   0
     14000      0.0020      0.0020   0   0
     16000      0.0020      0.0024   0   0
     18000      0.0025      0.0025   0   0
     20000      0.0028      0.0028   0   0
     22000      0.0032      0.0029   0   0
     24000      0.0044      0.0043   0   0
     26000      0.0046      0.0044   0   0
     28000      0.0049      0.0047   0   0
     30000      0.0053      0.0051   0   0
     32000      0.0070      0.0065   0   0
     34000      0.0081      0.0071   0   0
     36000      0.0086      0.0081   0   0
     38000      0.0120      0.0100   0   0
     40000      0.0168      0.0161   0   0
     42000      0.0222      0.0232   0   0
     44000      0.0267      0.0395   0   0
     46000      0.0272      0.0592   0   0
     48000      0.0260      0.0614   0   0
     50000      0.0255      0.0610   0   0
     52000      0.0254      0.0606   0   0
     54000      0.0253      0.0599   1   1
     56000      0.0250      0.0592   1   1
     58000      0.0245      0.0589   1   1
     60000      0.0239      0.0583   1   1
     62000      0.0239      0.0581   1   1
     64000      0.0236      0.0573   1   1
     66000      0.0236      0.0572   1   1
     68000      0.0227      0.0571   1   1
     70000      0.0226      0.0568   1   1
     72000      0.0226      0.0566   1   1
     74000      0.0226      0.0565   1   1
     76000      0.0223      0.0558   1   1
     78000      0.0223      0.0551   1   1
     80000      0.0221      0.0549   1   1
     82000      0.0218      0.0548   1   1
     84000      0.0217      0.0543   1   1
     86000      0.0215      0.0541   1   1
     88000      0.0214      0.0534   1   1
     90000      0.0214      0.0514   1   1
     92000      0.0214      0.0492   1   1
     94000      0.0214      0.0492   1   1
     96000      0.0214      0.0488   1   1
     98000      0.0214      0.0486   1   1
    100000      0.0214      0.0486   1   1
    102000      0.0214      0.0486   1   1
    104000      0.0214      0.0481   1   1
    106000      0.0214      0.0477   1   1
    108000      0.0211      0.0476   1   1
    110000      0.0211      0.0476   1   1
    112000      0.0211      0.0476   1   1
    114000      0.0210      0.0470   1   1
    116000      0.0210      0.0470   1   1
    118000      0.0210      0.0469   1   1
```

```
      120000      0.0210      0.0469  1   1
      122000      0.0210      0.0469  1   1
      124000      0.0210      0.0468  1   1
      126000      0.0210      0.0468  1   1
      128000      0.0209      0.0468  1   1
      130000      0.0209      0.0468  1   1
      132000      0.0209      0.0468  1   1
      134000      0.0209      0.0468  1   1
      136000      0.0209      0.0468  1   1
      138000      0.0209      0.0468  1   1
      140000      0.0209      0.0468  1   1
      142000      0.0206      0.0468  1   1
      144000      0.0206      0.0468  1   1
      146000      0.0206      0.0467  1   1
      148000      0.0206      0.0461  1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006  0   0
        2000      0.0065      0.0032  0   0
        4000      0.0025      0.0010  0   0
        6000      0.0053      0.0044  0   0
        8000      0.0181      0.0121  0   0
       10000      0.0322      0.0789  0   0
       12000      0.0332      0.0788  0   0
       14000      0.0332      0.0783  0   0
       16000      0.0332      0.0770  0   0
       18000      0.0332      0.0762  0   0
       20000      0.0325      0.0750  1   1
       22000      0.0322      0.0740  1   1
       24000      0.0320      0.0731  1   1
       26000      0.0318      0.0726  1   1
       28000      0.0312      0.0722  1   1
       30000      0.0306      0.0712  1   1
       32000      0.0301      0.0706  1   1
       34000      0.0298      0.0701  1   1
       36000      0.0297      0.0691  1   1
       38000      0.0294      0.0690  1   1
       40000      0.0286      0.0677  1   1
       42000      0.0282      0.0662  1   1
       44000      0.0278      0.0628  1   1
       46000      0.0278      0.0617  1   1
       48000      0.0260      0.0614  1   1
       50000      0.0255      0.0610  1   1
       52000      0.0254      0.0606  1   1
       54000      0.0253      0.0599  1   1
       56000      0.0250      0.0592  1   1
       58000      0.0245      0.0589  1   1
       60000      0.0239      0.0583  1   1
       62000      0.0239      0.0581  1   1
       64000      0.0236      0.0573  1   1
       66000      0.0236      0.0572  1   1
       68000      0.0227      0.0571  1   1
       70000      0.0226      0.0568  1   1
       72000      0.0226      0.0566  1   1
       74000      0.0226      0.0565  1   1
       76000      0.0223      0.0558  1   1
       78000      0.0223      0.0551  1   1
       80000      0.0221      0.0549  1   1
       82000      0.0218      0.0548  1   1
       84000      0.0217      0.0543  1   1
       86000      0.0215      0.0541  1   1
```

```
       88000      0.0214      0.0534   1   1
       90000      0.0214      0.0514   1   1
       92000      0.0214      0.0492   1   1
       94000      0.0214      0.0492   1   1
       96000      0.0214      0.0488   1   1
       98000      0.0214      0.0486   1   1
      100000      0.0214      0.0486   1   1
      102000      0.0214      0.0486   1   1
      104000      0.0214      0.0481   1   1
      106000      0.0214      0.0477   1   1
      108000      0.0211      0.0476   1   1
      110000      0.0211      0.0476   1   1
      112000      0.0211      0.0476   1   1
      114000      0.0211      0.0470   1   1
      116000      0.0210      0.0470   1   1
      118000      0.0210      0.0469   1   1
      120000      0.0210      0.0469   1   1
      122000      0.0210      0.0469   1   1
      124000      0.0210      0.0468   1   1
      126000      0.0210      0.0468   1   1
      128000      0.0209      0.0468   1   1
      130000      0.0209      0.0468   1   1
      132000      0.0209      0.0468   1   1
      134000      0.0209      0.0468   1   1
      136000      0.0209      0.0468   1   1
      138000      0.0209      0.0468   1   1
      140000      0.0209      0.0468   1   1
      142000      0.0206      0.0468   1   1
      144000      0.0206      0.0468   1   1
      146000      0.0206      0.0467   1   1
      148000      0.0206      0.0461   1   1
nus=0.134987  nuc=1.650000  dr=50.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0007   0   0
        4000      0.0025      0.0015   0   0
        6000      0.0053      0.0051   0   0
        8000      0.0181      0.0185   0   0
       10000      0.0322      0.0789   0   0
       12000      0.0332      0.0788   0   0
       14000      0.0332      0.0783   0   0
       16000      0.0332      0.0770   0   0
       18000      0.0332      0.0762   0   0
       20000      0.0325      0.0750   1   1
       22000      0.0322      0.0740   1   1
       24000      0.0320      0.0731   1   1
       26000      0.0318      0.0726   1   1
       28000      0.0312      0.0722   1   1
       30000      0.0306      0.0712   1   1
       32000      0.0301      0.0706   1   1
       34000      0.0298      0.0701   1   1
       36000      0.0297      0.0691   1   1
       38000      0.0294      0.0690   1   1
       40000      0.0286      0.0677   1   1
       42000      0.0282      0.0662   1   1
       44000      0.0278      0.0628   1   1
       46000      0.0278      0.0617   1   1
       48000      0.0260      0.0614   1   1
       50000      0.0255      0.0610   1   1
       52000      0.0254      0.0606   1   1
       54000      0.0253      0.0599   1   1
```

```
      56000        0.0250       0.0592   1   1
      58000        0.0245       0.0589   1   1
      60000        0.0239       0.0583   1   1
      62000        0.0239       0.0581   1   1
      64000        0.0236       0.0573   1   1
      66000        0.0236       0.0572   1   1
      68000        0.0227       0.0571   1   1
      70000        0.0226       0.0568   1   1
      72000        0.0226       0.0566   1   1
      74000        0.0226       0.0565   1   1
      76000        0.0223       0.0558   1   1
      78000        0.0223       0.0551   1   1
      80000        0.0221       0.0549   1   1
      82000        0.0218       0.0548   1   1
      84000        0.0217       0.0543   1   1
      86000        0.0215       0.0541   1   1
      88000        0.0214       0.0534   1   1
      90000        0.0214       0.0514   1   1
      92000        0.0214       0.0492   1   1
      94000        0.0214       0.0492   1   1
      96000        0.0214       0.0488   1   1
      98000        0.0214       0.0486   1   1
     100000        0.0214       0.0486   1   1
     102000        0.0214       0.0486   1   1
     104000        0.0214       0.0481   1   1
     106000        0.0214       0.0477   1   1
     108000        0.0211       0.0476   1   1
     110000        0.0211       0.0476   1   1
     112000        0.0211       0.0476   1   1
     114000        0.0211       0.0470   1   1
     116000        0.0210       0.0470   1   1
     118000        0.0210       0.0469   1   1
     120000        0.0210       0.0469   1   1
     122000        0.0210       0.0469   1   1
     124000        0.0210       0.0468   1   1
     126000        0.0210       0.0468   1   1
     128000        0.0209       0.0468   1   1
     130000        0.0209       0.0468   1   1
     132000        0.0209       0.0468   1   1
     134000        0.0209       0.0468   1   1
     136000        0.0209       0.0468   1   1
     138000        0.0209       0.0468   1   1
     140000        0.0209       0.0468   1   1
     142000        0.0206       0.0468   1   1
     144000        0.0206       0.0468   1   1
     146000        0.0206       0.0467   1   1
     148000        0.0206       0.0461   1   1
```

keff.in

```
   sscrsn    dr   pentime    ssthick0    ex    keff0    prob  pswitch
    0.08      5     3000        7        .1     .91       1       1
    0.08      5     3000        7        .1     .92       1       1
    0.08      5     3000        7        .1     .93       1       1
    0.08      5     3000        7        .1     .95       1       1
    0.08      5     3000        7        .1    1.0        1       1
    0.20      5     3000        7        .1     .91       1       1
    0.20      5     3000        7        .1     .92       1       1
    0.20      5     3000        7        .1     .93       1       1
    0.20      5     3000        7        .1     .95       1       1
    0.20      5     3000        7        .1    1.0        1       1
    0.40      5     3000        7        .1     .91       1       1
```

```
    0.40      5     3000       7        .1    .92       1       1
    0.40      5     3000       7        .1    .93       1       1
    0.40      5     3000       7        .1    .95       1       1
    0.40      5     3000       7        .1    1.0       1       1
    0.80      5     3000       7        .1    .91       1       1
    0.80      5     3000       7        .1    .92       1       1
    0.80      5     3000       7        .1    .93       1       1
    0.80      5     3000       7        .1    .95       1       1
    0.80      5     3000       7        .1    1.0       1       1
    2.00      5     3000       7        .1    .91       1       1
    2.00      5     3000       7        .1    .92       1       1
    2.00      5     3000       7        .1    .93       1       1
    2.00      5     3000       7        .1    .95       1       1
    2.00      5     3000       7        .1    1.0       1       1
    4.00      5     3000       7        .1    .91       1       1
    4.00      5     3000       7        .1    .92       1       1
    4.00      5     3000       7        .1    .93       1       1
    4.00      5     3000       7        .1    .95       1       1
    4.00      5     3000       7        .1    1.0       1       1
```

keff.log

```
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.910
Criticality fraction for indicated times
          0      0.0256      0.0296   0   0
       2000      0.0081      0.0070   0   0
       4000      0.0032      0.0043   0   0
       6000      0.0037      0.0044   0   0
       8000      0.0038      0.0044   0   0
      10000      0.0043      0.0044   0   0
      12000      0.0044      0.0044   0   0
      14000      0.0044      0.0044   0   0
      16000      0.0044      0.0044   0   0
      18000      0.0046      0.0046   0   0
      20000      0.0047      0.0047   0   0
      22000      0.0049      0.0049   0   0
      24000      0.0051      0.0051   0   0
      26000      0.0065      0.0053   0   0
      28000      0.0070      0.0065   0   0
      30000      0.0079      0.0071   0   0
      32000      0.0083      0.0081   0   0
      34000      0.0100      0.0086   0   0
      36000      0.0133      0.0102   0   0
      38000      0.0159      0.0141   0   0
      40000      0.0227      0.0210   0   0
      42000      0.0330      0.0351   0   0
      44000      0.0357      0.0714   0   0
      46000      0.0353      0.1032   0   0
      48000      0.0353      0.1091   0   0
      50000      0.0346      0.1077   0   0
      52000      0.0344      0.1062   0   0
      54000      0.0342      0.1049   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.920
Criticality fraction for indicated times
          0      0.0209      0.0007   0   0
       2000      0.0070      0.0065   0   0
       4000      0.0020      0.0026   0   0
       6000      0.0025      0.0028   0   0
       8000      0.0025      0.0028   0   0
```

```
       10000      0.0026      0.0028   0   0
       12000      0.0028      0.0029   0   0
       14000      0.0028      0.0029   0   0
       16000      0.0029      0.0032   0   0
       18000      0.0037      0.0038   0   0
       20000      0.0044      0.0044   0   0
       22000      0.0044      0.0044   0   0
       24000      0.0047      0.0047   0   0
       26000      0.0050      0.0049   0   0
       28000      0.0063      0.0053   0   0
       30000      0.0070      0.0065   0   0
       32000      0.0080      0.0070   0   0
       34000      0.0085      0.0081   0   0
       36000      0.0102      0.0086   0   0
       38000      0.0141      0.0114   0   0
       40000      0.0198      0.0180   0   0
       42000      0.0275      0.0300   0   0
       44000      0.0316      0.0548   0   0
       46000      0.0320      0.0746   0   0
       48000      0.0316      0.0834   0   0
       50000      0.0313      0.0820   0   0
       52000      0.0308      0.0794   0   0
       54000      0.0303      0.0774   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0050   0   0
        4000      0.0011      0.0015   0   0
        6000      0.0011      0.0020   0   0
        8000      0.0011      0.0020   0   0
       10000      0.0015      0.0020   0   0
       12000      0.0020      0.0020   0   0
       14000      0.0020      0.0020   0   0
       16000      0.0020      0.0024   0   0
       18000      0.0025      0.0025   0   0
       20000      0.0028      0.0028   0   0
       22000      0.0032      0.0029   0   0
       24000      0.0044      0.0043   0   0
       26000      0.0046      0.0044   0   0
       28000      0.0049      0.0047   0   0
       30000      0.0053      0.0051   0   0
       32000      0.0070      0.0065   0   0
       34000      0.0081      0.0071   0   0
       36000      0.0086      0.0081   0   0
       38000      0.0120      0.0100   0   0
       40000      0.0168      0.0161   0   0
       42000      0.0222      0.0232   0   0
       44000      0.0267      0.0395   0   0
       46000      0.0272      0.0592   0   0
       48000      0.0260      0.0614   0   0
       50000      0.0255      0.0610   0   0
       52000      0.0254      0.0606   0   0
       54000      0.0253      0.0599   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.950
Criticality fraction for indicated times
           0      0.0142      0.0003   0   0
        2000      0.0046      0.0037   0   0
        4000      0.0007      0.0007   0   0
        6000      0.0007      0.0007   0   0
        8000      0.0007      0.0007   0   0
```

```
       10000      0.0007      0.0007   0    0
       12000      0.0007      0.0007   0    0
       14000      0.0007      0.0007   0    0
       16000      0.0007      0.0010   0    0
       18000      0.0010      0.0010   0    0
       20000      0.0011      0.0010   0    0
       22000      0.0011      0.0011   0    0
       24000      0.0020      0.0011   0    0
       26000      0.0025      0.0020   0    0
       28000      0.0032      0.0028   0    0
       30000      0.0044      0.0043   0    0
       32000      0.0049      0.0046   0    0
       34000      0.0065      0.0051   0    0
       36000      0.0073      0.0065   0    0
       38000      0.0085      0.0081   0    0
       40000      0.0142      0.0128   0    0
       42000      0.0169      0.0177   0    0
       44000      0.0189      0.0290   0    0
       46000      0.0191      0.0349   0    0
       48000      0.0190      0.0358   0    0
       50000      0.0190      0.0358   0    0
       52000      0.0188      0.0355   0    0
       54000      0.0188      0.0354   1    1
nus=0.026997  nuc=1.650000  dr=5.000000  ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=1.000
Criticality fraction for indicated times
           0      0.0072      0.0000   0    0
        2000      0.0007      0.0006   0    0
        4000      0.0001      0.0002   0    0
        6000      0.0001      0.0002   0    0
        8000      0.0001      0.0002   0    0
       10000      0.0002      0.0003   0    0
       12000      0.0002      0.0003   0    0
       14000      0.0003      0.0003   0    0
       16000      0.0003      0.0003   0    0
       18000      0.0003      0.0003   0    0
       20000      0.0003      0.0003   0    0
       22000      0.0003      0.0003   0    0
       24000      0.0003      0.0003   0    0
       26000      0.0004      0.0004   0    0
       28000      0.0006      0.0006   0    0
       30000      0.0006      0.0006   0    0
       32000      0.0007      0.0007   0    0
       34000      0.0011      0.0010   0    0
       36000      0.0028      0.0020   0    0
       38000      0.0046      0.0032   0    0
       40000      0.0073      0.0066   0    0
       42000      0.0103      0.0096   0    0
       44000      0.0119      0.0137   0    0
       46000      0.0119      0.0152   0    0
       48000      0.0119      0.0158   0    0
       50000      0.0119      0.0153   0    0
       52000      0.0119      0.0152   0    0
       54000      0.0119      0.0152   1    1
nus=0.067493  nuc=1.650000  dr=5.000000  ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.910
Criticality fraction for indicated times
           0      0.0256      0.0011   0    0
        2000      0.0081      0.0070   0    0
        4000      0.0032      0.0032   0    0
        6000      0.0044      0.0043   0    0
        8000      0.0046      0.0044   0    0
```

```
       10000      0.0053       0.0051   0   0
       12000      0.0081       0.0070   0   0
       14000      0.0118       0.0100   0   0
       16000      0.0262       0.0205   0   0
       18000      0.0451       0.1087   0   0
       20000      0.0452       0.1507   0   0
       22000      0.0447       0.1440   0   0
       24000      0.0444       0.1408   0   0
       26000      0.0434       0.1392   0   0
       28000      0.0424       0.1381   1   1
nus=0.067493  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.920
Criticality fraction for indicated times
           0      0.0209       0.0007   0   0
        2000      0.0070       0.0053   0   0
        4000      0.0020       0.0020   0   0
        6000      0.0028       0.0026   0   0
        8000      0.0043       0.0032   0   0
       10000      0.0048       0.0047   0   0
       12000      0.0070       0.0065   0   0
       14000      0.0100       0.0083   0   0
       16000      0.0217       0.0173   0   0
       18000      0.0363       0.0795   0   0
       20000      0.0367       0.1049   0   0
       22000      0.0358       0.0993   0   0
       24000      0.0353       0.0975   0   0
       26000      0.0350       0.0955   0   0
       28000      0.0346       0.0934   1   1
nus=0.067493  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175       0.0006   0   0
        2000      0.0065       0.0047   0   0
        4000      0.0011       0.0011   0   0
        6000      0.0020       0.0011   0   0
        8000      0.0026       0.0025   0   0
       10000      0.0044       0.0043   0   0
       12000      0.0064       0.0050   0   0
       14000      0.0085       0.0081   0   0
       16000      0.0189       0.0160   0   0
       18000      0.0324       0.0606   0   0
       20000      0.0325       0.0750   0   0
       22000      0.0322       0.0740   0   0
       24000      0.0320       0.0731   0   0
       26000      0.0318       0.0726   0   0
       28000      0.0312       0.0722   1   1
nus=0.067493  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.950
Criticality fraction for indicated times
           0      0.0142       0.0004   0   0
        2000      0.0046       0.0028   0   0
        4000      0.0007       0.0006   0   0
        6000      0.0007       0.0007   0   0
        8000      0.0010       0.0010   0   0
       10000      0.0020       0.0011   0   0
       12000      0.0044       0.0038   0   0
       14000      0.0070       0.0056   0   0
       16000      0.0145       0.0117   0   0
       18000      0.0219       0.0351   0   0
       20000      0.0232       0.0405   0   0
       22000      0.0219       0.0404   0   0
       24000      0.0219       0.0401   0   0
```

```
      26000      0.0217      0.0396   0   0
      28000      0.0217      0.0395   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=1.000
Criticality fraction for indicated times
          0      0.0072      0.0000   0   0
       2000      0.0007      0.0006   0   0
       4000      0.0001      0.0000   0   0
       6000      0.0002      0.0001   0   0
       8000      0.0003      0.0003   0   0
      10000      0.0004      0.0003   0   0
      12000      0.0007      0.0006   0   0
      14000      0.0025      0.0011   0   0
      16000      0.0081      0.0065   0   0
      18000      0.0121      0.0152   0   0
      20000      0.0126      0.0178   0   0
      22000      0.0126      0.0175   0   0
      24000      0.0125      0.0174   0   0
      26000      0.0122      0.0174   0   0
      28000      0.0121      0.0173   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.910
Criticality fraction for indicated times
          0      0.0256      0.0011   0   0
       2000      0.0081      0.0050   0   0
       4000      0.0046      0.0026   0   0
       6000      0.0079      0.0053   0   0
       8000      0.0254      0.0161   0   0
      10000      0.0451      0.1595   0   0
      12000      0.0457      0.1587   0   0
      14000      0.0457      0.1581   0   0
      16000      0.0457      0.1573   0   0
      18000      0.0455      0.1549   0   0
      20000      0.0452      0.1507   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.920
Criticality fraction for indicated times
          0      0.0209      0.0007   0   0
       2000      0.0070      0.0046   0   0
       4000      0.0037      0.0015   0   0
       6000      0.0070      0.0047   0   0
       8000      0.0209      0.0143   0   0
      10000      0.0361      0.1115   0   0
      12000      0.0372      0.1118   0   0
      14000      0.0374      0.1115   0   0
      16000      0.0372      0.1078   0   0
      18000      0.0370      0.1073   0   0
      20000      0.0367      0.1049   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0   0
       2000      0.0065      0.0032   0   0
       4000      0.0025      0.0010   0   0
       6000      0.0053      0.0044   0   0
       8000      0.0181      0.0121   0   0
      10000      0.0322      0.0789   0   0
      12000      0.0332      0.0788   0   0
      14000      0.0332      0.0783   0   0
      16000      0.0332      0.0770   0   0
      18000      0.0332      0.0762   0   0
      20000      0.0325      0.0750   1   1
```

```
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.950
Criticality fraction for indicated times
          0      0.0142      0.0004   0   0
       2000      0.0046      0.0011   0   0
       4000      0.0010      0.0006   0   0
       6000      0.0044      0.0020   0   0
       8000      0.0143      0.0095   0   0
      10000      0.0226      0.0415   0   0
      12000      0.0233      0.0418   0   0
      14000      0.0233      0.0417   0   0
      16000      0.0236      0.0413   0   0
      18000      0.0233      0.0409   0   0
      20000      0.0232      0.0405   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=1.000
Criticality fraction for indicated times
          0      0.0072      0.0000   0   0
       2000      0.0007      0.0003   0   0
       4000      0.0003      0.0000   0   0
       6000      0.0006      0.0003   0   0
       8000      0.0074      0.0046   0   0
      10000      0.0122      0.0178   0   0
      12000      0.0126      0.0178   0   0
      14000      0.0126      0.0178   0   0
      16000      0.0126      0.0178   0   0
      18000      0.0126      0.0178   0   0
      20000      0.0126      0.0178   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.910
Criticality fraction for indicated times
          0      0.0256      0.0011   0   0
       2000      0.0085      0.0032   0   0
       4000      0.0222      0.0097   0   0
       6000      0.0383      0.1469   0   0
       8000      0.0419      0.1553   0   0
      10000      0.0451      0.1595   0   0
      12000      0.0457      0.1587   0   0
      14000      0.0457      0.1581   0   0
      16000      0.0457      0.1573   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.920
Criticality fraction for indicated times
          0      0.0209      0.0007   0   0
       2000      0.0081      0.0020   0   0
       4000      0.0198      0.0082   0   0
       6000      0.0336      0.1009   0   0
       8000      0.0349      0.1076   0   0
      10000      0.0361      0.1115   0   0
      12000      0.0372      0.1118   0   0
      14000      0.0374      0.1115   0   0
      16000      0.0372      0.1078   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0   0
       2000      0.0071      0.0011   0   0
       4000      0.0164      0.0073   0   0
       6000      0.0289      0.0750   0   0
       8000      0.0312      0.0775   0   0
      10000      0.0322      0.0789   0   0
      12000      0.0332      0.0788   0   0
```

```
       14000      0.0332      0.0783   0   0
       16000      0.0332      0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.950
Criticality fraction for indicated times
           0      0.0142      0.0004   0   0
        2000      0.0050      0.0006   0   0
        4000      0.0139      0.0050   0   0
        6000      0.0200      0.0396   0   0
        8000      0.0214      0.0410   0   0
       10000      0.0226      0.0415   0   0
       12000      0.0233      0.0418   0   0
       14000      0.0233      0.0417   0   0
       16000      0.0236      0.0413   0   1
       18000      0.0233      0.0409   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=1.000
Criticality fraction for indicated times
           0      0.0072      0.0000   0   0
        2000      0.0010      0.0000   0   0
        4000      0.0073      0.0007   0   0
        6000      0.0119      0.0163   0   0
        8000      0.0120      0.0165   0   0
       10000      0.0122      0.0178   0   0
       12000      0.0126      0.0178   0   0
       14000      0.0126      0.0178   0   0
       16000      0.0126      0.0178   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.910
Criticality fraction for indicated times
           0      0.0256      0.0156   0   0
        2000      0.0846      0.0106   0   0
        4000      0.0337      0.1305   0   0
        6000      0.0383      0.1469   0   0
        8000      0.0419      0.1553   0   0
       10000      0.0451      0.1595   0   0
       12000      0.0457      0.1587   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.920
Criticality fraction for indicated times
           0      0.0209      0.0141   0   0
        2000      0.0629      0.0099   0   0
        4000      0.0296      0.0918   0   0
        6000      0.0336      0.1009   0   0
        8000      0.0349      0.1076   0   0
       10000      0.0361      0.1115   0   0
       12000      0.0372      0.1118   1   0
       14000      0.0374      0.1115   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0114   0   0
        2000      0.0453      0.0081   0   0
        4000      0.0243      0.0651   0   0
        6000      0.0289      0.0750   0   0
        8000      0.0312      0.0775   0   0
       10000      0.0322      0.0789   0   0
       12000      0.0332      0.0788   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.950
Criticality fraction for indicated times
           0      0.0142      0.0083   0   0
```

```
        2000      0.0331      0.0054   0    0
        4000      0.0180      0.0382   0    0
        6000      0.0200      0.0396   0    0
        8000      0.0214      0.0410   0    0
       10000      0.0226      0.0415   0    0
       12000      0.0233      0.0418   1    0
       14000      0.0233      0.0417   1    1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=1.000
Criticality fraction for indicated times
           0      0.0072      0.0044   0    0
        2000      0.0148      0.0007   0    0
        4000      0.0109      0.0158   0    0
        6000      0.0119      0.0163   0    0
        8000      0.0120      0.0165   0    0
       10000      0.0122      0.0178   0    0
       12000      0.0126      0.0178   1    0
       14000      0.0126      0.0178   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.910
Criticality fraction for indicated times
           0      0.0256      0.0159   0    0
        2000      0.0846      0.0469   0    0
        4000      0.0337      0.1305   0    0
        6000      0.0383      0.1469   0    0
        8000      0.0419      0.1553   0    0
       10000      0.0451      0.1595   0    0
       12000      0.0457      0.1587   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.920
Criticality fraction for indicated times
           0      0.0209      0.0141   0    0
        2000      0.0629      0.0380   0    0
        4000      0.0296      0.0918   0    0
        6000      0.0336      0.1009   0    0
        8000      0.0349      0.1076   0    0
       10000      0.0361      0.1115   0    0
       12000      0.0372      0.1118   1    0
       14000      0.0374      0.1115   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0114   0    0
        2000      0.0453      0.0321   0    0
        4000      0.0243      0.0651   0    0
        6000      0.0289      0.0750   0    0
        8000      0.0312      0.0775   0    0
       10000      0.0322      0.0789   0    0
       12000      0.0332      0.0788   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.950
Criticality fraction for indicated times
           0      0.0142      0.0083   0    0
        2000      0.0331      0.0219   0    0
        4000      0.0180      0.0382   0    0
        6000      0.0200      0.0396   0    0
        8000      0.0214      0.0410   0    0
       10000      0.0226      0.0415   0    0
       12000      0.0233      0.0418   1    0
       14000      0.0233      0.0417   1    1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=1.000
```

```
Criticality fraction for indicated times
          0       0.0071      0.0044   0   0
       2000       0.0148      0.0115   0   0
       4000       0.0109      0.0158   0   0
       6000       0.0119      0.0163   0   0
       8000       0.0120      0.0165   0   0
      10000       0.0122      0.0178   0   0
      12000       0.0126      0.0178   1   0
      14000       0.0126      0.0178   1   1
```

keff.sum

```
  Time Unfrm   Frac Unfrm   Time Stld   Frac Stld        Prob
       44000      0.03567       48000     0.10914     1.00000
       46000      0.03196       48000     0.08337     1.00000
       46000      0.02717       48000     0.06145     1.00000
       46000      0.01906       48000     0.03576     1.00000
       48000      0.01195       48000     0.01578     1.00000
       20000      0.04520       20000     0.15074     1.00000
       20000      0.03669       20000     0.10488     1.00000
       20000      0.03254       20000     0.07499     1.00000
       20000      0.02325       20000     0.04052     1.00000
       20000      0.01263       20000     0.01782     1.00000
       12000      0.04569       10000     0.15949     1.00000
       14000      0.03744       12000     0.11182     1.00000
       14000      0.03322       10000     0.07891     1.00000
       16000      0.02355       12000     0.04176     1.00000
       14000      0.01263       12000     0.01785     1.00000
       12000      0.04569       10000     0.15949     1.00000
       14000      0.03744       12000     0.11182     1.00000
       14000      0.03322       10000     0.07891     1.00000
       16000      0.02355       12000     0.04176     1.00000
       14000      0.01263       12000     0.01785     1.00000
        2000      0.08461       10000     0.15949     1.00000
        2000      0.06294       12000     0.11182     1.00000
        2000      0.04530       10000     0.07891     1.00000
        2000      0.03311       12000     0.04176     1.00000
        2000      0.01480       12000     0.01785     1.00000
        2000      0.08461       10000     0.15949     1.00000
        2000      0.06294       12000     0.11182     1.00000
        2000      0.04530       10000     0.07891     1.00000
        2000      0.03311       12000     0.04176     1.00000
        2000      0.01480       12000     0.01785     1.00000
```

inf.in

```
 sscrsn   dr   pentime    ssthick0   ex   keff0   prob  pswitch
  0.08    .1    3000         7       .1    .93      1      1
  0.08    .5    3000         7       .1    .93      1      1
  0.08     5    3000         7       .1    .93      1      1
  0.08    50    3000         7       .1    .93      1      1
  0.08    500   3000         7       .1    .93      1      1
  0.20    .1    3000         7       .1    .93      1      1
  0.20    .5    3000         7       .1    .93      1      1
  0.20     5    3000         7       .1    .93      1      1
  0.20    50    3000         7       .1    .93      1      1
  0.20    500   3000         7       .1    .93      1      1
  0.40    .1    3000         7       .1    .93      1      1
  0.40    .5    3000         7       .1    .93      1      1
  0.40     5    3000         7       .1    .93      1      1
  0.40    50    3000         7       .1    .93      1      1
```

```
    0.40     500   3000       7        .1     .93       1       1
    0.80    .1     3000       7        .1     .93       1       1
    0.80    .5     3000       7        .1     .93       1       1
    0.80     5     3000       7        .1     .93       1       1
    0.80     50    3000       7        .1     .93       1       1
    0.80     500   3000       7        .1     .93       1       1
    2.00    .1     3000       7        .1     .93       1       1
    2.00    .5     3000       7        .1     .93       1       1
    2.00     5     3000       7        .1     .93       1       1
    2.00     50    3000       7        .1     .93       1       1
    2.00     500   3000       7        .1     .93       1       1
    4.00    .1     3000       7        .1     .93       1       1
    4.00    .5     3000       7        .1     .93       1       1
    4.00     5     3000       7        .1     .93       1       1
    4.00     50    3000       7        .1     .93       1       1
    4.00     500   3000       7        .1     .93       1       1
```

inf.log

```
nus=0.026997  nuc=1.650000  dr=0.100000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0204   0   0
        2000      0.0065      0.0029   0   0
        4000      0.0011      0.0003   0   0
        6000      0.0011      0.0000   0   0
        8000      0.0011      0.0000   0   0
       10000      0.0015      0.0000   0   0
       12000      0.0020      0.0000   0   0
       14000      0.0020      0.0000   0   0
       16000      0.0020      0.0000   0   0
       18000      0.0025      0.0000   0   0
       20000      0.0028      0.0000   0   0
       22000      0.0032      0.0000   0   0
       24000      0.0044      0.0000   0   0
       26000      0.0046      0.0000   0   0
       28000      0.0049      0.0000   0   0
       30000      0.0053      0.0000   0   0
       32000      0.0070      0.0000   0   0
       34000      0.0081      0.0000   0   0
       36000      0.0086      0.0000   0   0
       38000      0.0120      0.0000   0   0
       40000      0.0168      0.0000   0   0
       42000      0.0222      0.0000   0   0
       44000      0.0267      0.0000   0   0
       46000      0.0272      0.0000   0   0
       48000      0.0260      0.0000   0   0
       50000      0.0255      0.0003   0   0
       52000      0.0254      0.0004   0   0
       54000      0.0253      0.0006   1   0
       56000      0.0250      0.0008   1   0
       58000      0.0245      0.0022   1   0
       60000      0.0239      0.0034   1   0
       62000      0.0239      0.0048   1   0
       64000      0.0236      0.0064   1   0
       66000      0.0236      0.0069   1   0
       68000      0.0227      0.0079   1   0
       70000      0.0226      0.0100   1   0
       72000      0.0226      0.0105   1   0
       74000      0.0226      0.0119   1   0
       76000      0.0223      0.0121   1   0
```

```
     78000      0.0223      0.0141   1   0
     80000      0.0221      0.0149   1   0
     82000      0.0218      0.0152   1   0
     84000      0.0217      0.0172   1   0
     86000      0.0215      0.0185   1   0
     88000      0.0214      0.0200   1   0
     90000      0.0214      0.0213   1   0
     92000      0.0214      0.0228   1   0
     94000      0.0214      0.0247   1   0
     96000      0.0214      0.0272   1   0
     98000      0.0214      0.0296   1   0
    100000      0.0214      0.0308   1   0
    102000      0.0214      0.0320   1   0
    104000      0.0214      0.0332   1   0
    106000      0.0214      0.0337   1   0
    108000      0.0211      0.0342   1   0
    110000      0.0211      0.0346   1   0
    112000      0.0211      0.0356   1   0
    114000      0.0210      0.0360   1   0
    116000      0.0210      0.0366   1   0
    118000      0.0210      0.0370   1   0
    120000      0.0210      0.0377   1   0
    122000      0.0210      0.0377   1   0
    124000      0.0210      0.0468   1   0
    126000      0.0210      0.0468   1   1
nus=0.026997  nuc=1.650000  dr=0.500000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
         0      0.0175      0.0006   0   0
      2000      0.0065      0.0044   0   0
      4000      0.0011      0.0006   0   0
      6000      0.0011      0.0004   0   0
      8000      0.0011      0.0004   0   0
     10000      0.0015      0.0003   0   0
     12000      0.0020      0.0003   0   0
     14000      0.0020      0.0003   0   0
     16000      0.0020      0.0004   0   0
     18000      0.0025      0.0004   0   0
     20000      0.0028      0.0004   0   0
     22000      0.0032      0.0006   0   0
     24000      0.0044      0.0006   0   0
     26000      0.0046      0.0006   0   0
     28000      0.0049      0.0007   0   0
     30000      0.0053      0.0010   0   0
     32000      0.0070      0.0011   0   0
     34000      0.0081      0.0024   0   0
     36000      0.0086      0.0038   0   0
     38000      0.0120      0.0048   0   0
     40000      0.0168      0.0071   0   0
     42000      0.0222      0.0087   0   0
     44000      0.0267      0.0120   0   0
     46000      0.0272      0.0188   0   0
     48000      0.0260      0.0309   0   0
     50000      0.0255      0.0371   0   0
     52000      0.0254      0.0439   0   0
     54000      0.0253      0.0599   1   0
     56000      0.0250      0.0592   1   1
nus=0.026997  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
         0      0.0175      0.0006   0   0
      2000      0.0065      0.0050   0   0
```

```
       4000      0.0011      0.0015   0    0
       6000      0.0011      0.0020   0    0
       8000      0.0011      0.0020   0    0
      10000      0.0015      0.0020   0    0
      12000      0.0020      0.0020   0    0
      14000      0.0020      0.0020   0    0
      16000      0.0020      0.0024   0    0
      18000      0.0025      0.0025   0    0
      20000      0.0028      0.0028   0    0
      22000      0.0032      0.0029   0    0
      24000      0.0044      0.0043   0    0
      26000      0.0046      0.0044   0    0
      28000      0.0049      0.0047   0    0
      30000      0.0053      0.0051   0    0
      32000      0.0070      0.0065   0    0
      34000      0.0081      0.0071   0    0
      36000      0.0086      0.0081   0    0
      38000      0.0120      0.0100   0    0
      40000      0.0168      0.0161   0    0
      42000      0.0222      0.0232   0    0
      44000      0.0267      0.0395   0    0
      46000      0.0272      0.0592   0    0
      48000      0.0260      0.0614   0    0
      50000      0.0255      0.0610   0    0
      52000      0.0254      0.0606   0    0
      54000      0.0253      0.0599   1    1
nus=0.026997  nuc=1.650000  dr=50.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0    0
       2000      0.0065      0.0006   0    0
       4000      0.0011      0.0007   0    0
       6000      0.0011      0.0007   0    0
       8000      0.0011      0.0007   0    0
      10000      0.0015      0.0007   0    0
      12000      0.0020      0.0010   0    0
      14000      0.0020      0.0010   0    0
      16000      0.0020      0.0011   0    0
      18000      0.0025      0.0011   0    0
      20000      0.0028      0.0015   0    0
      22000      0.0032      0.0020   0    0
      24000      0.0044      0.0026   0    0
      26000      0.0046      0.0037   0    0
      28000      0.0049      0.0044   0    0
      30000      0.0053      0.0048   0    0
      32000      0.0070      0.0053   0    0
      34000      0.0081      0.0070   0    0
      36000      0.0086      0.0081   0    0
      38000      0.0120      0.0100   0    0
      40000      0.0168      0.0162   0    0
      42000      0.0222      0.0285   0    0
      44000      0.0267      0.0395   0    0
      46000      0.0272      0.0592   0    0
      48000      0.0260      0.0614   0    0
      50000      0.0255      0.0610   0    0
      52000      0.0254      0.0606   0    0
      54000      0.0253      0.0599   1    1
nus=0.026997  nuc=1.650000  dr=500.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0    0
       2000      0.0065      0.0006   0    0
```

```
         4000      0.0011      0.0007  0   0
         6000      0.0011      0.0007  0   0
         8000      0.0011      0.0007  0   0
        10000      0.0015      0.0007  0   0
        12000      0.0020      0.0010  0   0
        14000      0.0020      0.0010  0   0
        16000      0.0020      0.0011  0   0
        18000      0.0025      0.0011  0   0
        20000      0.0028      0.0015  0   0
        22000      0.0032      0.0020  0   0
        24000      0.0044      0.0026  0   0
        26000      0.0046      0.0037  0   0
        28000      0.0049      0.0044  0   0
        30000      0.0053      0.0048  0   0
        32000      0.0070      0.0053  0   0
        34000      0.0081      0.0070  0   0
        36000      0.0086      0.0081  0   0
        38000      0.0120      0.0100  0   0
        40000      0.0168      0.0162  0   0
        42000      0.0222      0.0285  0   0
        44000      0.0270      0.0395  0   0
        46000      0.0272      0.0592  0   0
        48000      0.0260      0.0614  0   0
        50000      0.0255      0.0610  0   0
        52000      0.0254      0.0606  0   0
        54000      0.0253      0.0599  1   1
nus=0.067493  nuc=1.650000  dr=0.100000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
            0      0.0175      0.0006  0   0
         2000      0.0065      0.0006  0   0
         4000      0.0011      0.0000  0   0
         6000      0.0020      0.0000  0   0
         8000      0.0026      0.0000  0   0
        10000      0.0044      0.0000  0   0
        12000      0.0064      0.0000  0   0
        14000      0.0085      0.0000  0   0
        16000      0.0189      0.0000  0   0
        18000      0.0324      0.0000  0   0
        20000      0.0325      0.0000  0   0
        22000      0.0322      0.0000  0   0
        24000      0.0320      0.0000  0   0
        26000      0.0318      0.0000  0   0
        28000      0.0312      0.0000  1   0
        30000      0.0306      0.0000  1   0
        32000      0.0301      0.0000  1   0
        34000      0.0298      0.0003  1   0
        36000      0.0297      0.0004  1   0
        38000      0.0294      0.0006  1   0
        40000      0.0286      0.0008  1   0
        42000      0.0282      0.0022  1   0
        44000      0.0278      0.0039  1   0
        46000      0.0278      0.0052  1   0
        48000      0.0260      0.0067  1   0
        50000      0.0255      0.0069  1   0
        52000      0.0254      0.0094  1   0
        54000      0.0253      0.0102  1   0
        56000      0.0250      0.0113  1   0
        58000      0.0245      0.0119  1   0
        60000      0.0239      0.0132  1   0
        62000      0.0239      0.0146  1   0
        64000      0.0236      0.0151  1   0
```

```
         66000      0.0236      0.0170   1   0
         68000      0.0227      0.0182   1   0
         70000      0.0226      0.0194   1   0
         72000      0.0226      0.0208   1   0
         74000      0.0226      0.0219   1   0
         76000      0.0223      0.0240   1   0
         78000      0.0223      0.0258   1   0
         80000      0.0221      0.0291   1   0
         82000      0.0218      0.0306   1   0
         84000      0.0217      0.0320   1   0
         86000      0.0215      0.0332   1   0
         88000      0.0214      0.0337   1   0
         90000      0.0214      0.0343   1   0
         92000      0.0214      0.0347   1   0
         94000      0.0214      0.0356   1   0
         96000      0.0214      0.0366   1   0
         98000      0.0214      0.0371   1   0
        100000      0.0214      0.0371   1   0
        102000      0.0214      0.0382   1   0
        104000      0.0214      0.0385   1   0
        106000      0.0214      0.0477   1   0
        108000      0.0211      0.0476   1   1
nus=0.067493  nuc=1.650000  dr=0.500000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
             0      0.0175      0.0006   0   0
          2000      0.0065      0.0007   0   0
          4000      0.0011      0.0000   0   0
          6000      0.0020      0.0000   0   0
          8000      0.0026      0.0000   0   0
         10000      0.0044      0.0000   0   0
         12000      0.0064      0.0000   0   0
         14000      0.0085      0.0003   0   0
         16000      0.0189      0.0006   0   0
         18000      0.0324      0.0022   0   0
         20000      0.0325      0.0099   0   0
         22000      0.0322      0.0151   0   0
         24000      0.0320      0.0242   0   0
         26000      0.0318      0.0350   0   0
         28000      0.0312      0.0448   1   0
         30000      0.0306      0.0563   1   0
         32000      0.0301      0.0706   1   0
         34000      0.0298      0.0701   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
             0      0.0175      0.0006   0   0
          2000      0.0065      0.0047   0   0
          4000      0.0011      0.0011   0   0
          6000      0.0020      0.0011   0   0
          8000      0.0026      0.0025   0   0
         10000      0.0044      0.0043   0   0
         12000      0.0064      0.0050   0   0
         14000      0.0085      0.0081   0   0
         16000      0.0189      0.0160   0   0
         18000      0.0324      0.0606   0   0
         20000      0.0325      0.0750   0   0
         22000      0.0322      0.0740   0   0
         24000      0.0320      0.0731   0   0
         26000      0.0318      0.0726   0   0
         28000      0.0312      0.0722   1   1
nus=0.067493  nuc=1.650000  dr=50.000000 ex=0.100000 pentime=3000
```

```
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
        0       0.0175       0.0006   0   0
     2000       0.0065       0.0007   0   0
     4000       0.0011       0.0007   0   0
     6000       0.0020       0.0010   0   0
     8000       0.0026       0.0020   0   0
    10000       0.0044       0.0037   0   0
    12000       0.0064       0.0051   0   0
    14000       0.0085       0.0081   0   0
    16000       0.0189       0.0184   0   0
    18000       0.0324       0.0606   0   0
    20000       0.0325       0.0750   0   0
    22000       0.0322       0.0740   0   0
    24000       0.0320       0.0731   0   0
    26000       0.0318       0.0726   0   0
    28000       0.0312       0.0722   1   1
nus=0.067493  nuc=1.650000  dr=500.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
        0       0.0175       0.0006   0   0
     2000       0.0065       0.0007   0   0
     4000       0.0011       0.0007   0   0
     6000       0.0020       0.0010   0   0
     8000       0.0026       0.0020   0   0
    10000       0.0044       0.0037   0   0
    12000       0.0064       0.0051   0   0
    14000       0.0085       0.0081   0   0
    16000       0.0189       0.0184   0   0
    18000       0.0324       0.0606   0   0
    20000       0.0325       0.0750   0   0
    22000       0.0322       0.0740   0   0
    24000       0.0320       0.0731   0   0
    26000       0.0318       0.0726   0   0
    28000       0.0312       0.0722   1   1
nus=0.134987  nuc=1.650000  dr=0.100000  ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
        0       0.0175       0.0006   0   0
     2000       0.0065       0.0000   0   0
     4000       0.0025       0.0000   0   0
     6000       0.0053       0.0000   0   0
     8000       0.0181       0.0000   0   0
    10000       0.0322       0.0000   0   0
    12000       0.0332       0.0000   0   0
    14000       0.0332       0.0000   0   0
    16000       0.0332       0.0000   0   0
    18000       0.0332       0.0000   0   0
    20000       0.0325       0.0000   1   0
    22000       0.0322       0.0000   1   0
    24000       0.0320       0.0000   1   0
    26000       0.0318       0.0000   1   0
    28000       0.0312       0.0001   1   0
    30000       0.0306       0.0003   1   0
    32000       0.0301       0.0004   1   0
    34000       0.0298       0.0007   1   0
    36000       0.0297       0.0020   1   0
    38000       0.0294       0.0028   1   0
    40000       0.0286       0.0047   1   0
    42000       0.0282       0.0062   1   0
    44000       0.0278       0.0068   1   0
    46000       0.0278       0.0079   1   0
```

```
       48000      0.0260      0.0100   1   0
       50000      0.0255      0.0105   1   0
       52000      0.0254      0.0119   1   0
       54000      0.0253      0.0121   1   0
       56000      0.0250      0.0137   1   0
       58000      0.0245      0.0150   1   0
       60000      0.0239      0.0153   1   0
       62000      0.0239      0.0172   1   0
       64000      0.0236      0.0188   1   0
       66000      0.0236      0.0202   1   0
       68000      0.0227      0.0215   1   0
       70000      0.0226      0.0234   1   0
       72000      0.0226      0.0254   1   0
       74000      0.0226      0.0286   1   0
       76000      0.0223      0.0300   1   0
       78000      0.0223      0.0316   1   0
       80000      0.0221      0.0329   1   0
       82000      0.0218      0.0337   1   0
       84000      0.0217      0.0339   1   0
       86000      0.0215      0.0346   1   0
       88000      0.0214      0.0356   1   0
       90000      0.0214      0.0366   1   0
       92000      0.0214      0.0371   1   0
       94000      0.0214      0.0372   1   0
       96000      0.0214      0.0383   1   0
       98000      0.0214      0.0386   1   0
      100000      0.0214      0.0392   1   0
      102000      0.0214      0.0486   1   0
      104000      0.0214      0.0481   1   1
nus=0.134987  nuc=1.650000  dr=0.500000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0000   0   0
        4000      0.0025      0.0000   0   0
        6000      0.0053      0.0000   0   0
        8000      0.0181      0.0000   0   0
       10000      0.0322      0.0003   0   0
       12000      0.0332      0.0040   0   0
       14000      0.0332      0.0106   0   0
       16000      0.0332      0.0174   0   0
       18000      0.0332      0.0290   0   0
       20000      0.0325      0.0381   1   0
       22000      0.0322      0.0481   1   0
       24000      0.0320      0.0586   1   0
       26000      0.0318      0.0726   1   0
       28000      0.0312      0.0722   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0032   0   0
        4000      0.0025      0.0010   0   0
        6000      0.0053      0.0044   0   0
        8000      0.0181      0.0121   0   0
       10000      0.0322      0.0789   0   0
       12000      0.0332      0.0788   0   0
       14000      0.0332      0.0783   0   0
       16000      0.0332      0.0770   0   0
       18000      0.0332      0.0762   0   0
       20000      0.0325      0.0750   1   1
nus=0.134987  nuc=1.650000  dr=50.000000 ex=0.100000 pentime=3000
```

```
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0   0
       2000      0.0065      0.0007   0   0
       4000      0.0025      0.0015   0   0
       6000      0.0053      0.0051   0   0
       8000      0.0181      0.0185   0   0
      10000      0.0322      0.0789   0   0
      12000      0.0332      0.0788   0   0
      14000      0.0332      0.0783   0   0
      16000      0.0332      0.0770   0   0
      18000      0.0332      0.0762   0   0
      20000      0.0325      0.0750   1   1
nus=0.134987  nuc=1.650000  dr=500.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0   0
       2000      0.0065      0.0007   0   0
       4000      0.0025      0.0015   0   0
       6000      0.0053      0.0051   0   0
       8000      0.0181      0.0185   0   0
      10000      0.0322      0.0789   0   0
      12000      0.0332      0.0788   0   0
      14000      0.0332      0.0783   0   0
      16000      0.0332      0.0770   0   0
      18000      0.0332      0.0762   0   0
      20000      0.0325      0.0750   1   1
nus=0.269973  nuc=1.650000  dr=0.100000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0   0
       2000      0.0071      0.0000   0   0
       4000      0.0164      0.0000   0   0
       6000      0.0289      0.0000   0   0
       8000      0.0312      0.0000   0   0
      10000      0.0322      0.0000   0   0
      12000      0.0332      0.0000   0   0
      14000      0.0332      0.0000   0   0
      16000      0.0332      0.0000   1   0
      18000      0.0332      0.0000   1   0
      20000      0.0325      0.0000   1   0
      22000      0.0322      0.0000   1   0
      24000      0.0320      0.0000   1   0
      26000      0.0318      0.0001   1   0
      28000      0.0312      0.0004   1   0
      30000      0.0306      0.0006   1   0
      32000      0.0301      0.0007   1   0
      34000      0.0298      0.0022   1   0
      36000      0.0297      0.0033   1   0
      38000      0.0294      0.0047   1   0
      40000      0.0286      0.0064   1   0
      42000      0.0282      0.0069   1   0
      44000      0.0278      0.0086   1   0
      46000      0.0278      0.0100   1   0
      48000      0.0260      0.0106   1   0
      50000      0.0255      0.0119   1   0
      52000      0.0254      0.0125   1   0
      54000      0.0253      0.0141   1   0
      56000      0.0250      0.0150   1   0
      58000      0.0245      0.0158   1   0
      60000      0.0239      0.0182   1   0
      62000      0.0239      0.0188   1   0
```

```
      64000      0.0236     0.0207  1   0
      66000      0.0236     0.0217  1   0
      68000      0.0227     0.0240  1   0
      70000      0.0226     0.0257  1   0
      72000      0.0226     0.0290  1   0
      74000      0.0226     0.0303  1   0
      76000      0.0223     0.0318  1   0
      78000      0.0223     0.0332  1   0
      80000      0.0221     0.0337  1   0
      82000      0.0218     0.0343  1   0
      84000      0.0217     0.0349  1   0
      86000      0.0215     0.0358  1   0
      88000      0.0214     0.0367  1   0
      90000      0.0214     0.0371  1   0
      92000      0.0214     0.0374  1   0
      94000      0.0214     0.0386  1   0
      96000      0.0214     0.0387  1   0
      98000      0.0214     0.0393  1   0
     100000      0.0214     0.0486  1   0
     102000      0.0214     0.0486  1   1
nus=0.269973  nuc=1.650000  dr=0.500000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175     0.0006  0   0
       2000      0.0071     0.0000  0   0
       4000      0.0164     0.0000  0   0
       6000      0.0289     0.0000  0   0
       8000      0.0312     0.0004  0   0
      10000      0.0322     0.0066  0   0
      12000      0.0332     0.0122  0   0
      14000      0.0332     0.0206  0   0
      16000      0.0332     0.0334  1   0
      18000      0.0332     0.0420  1   0
      20000      0.0325     0.0564  1   0
      22000      0.0322     0.0740  1   0
      24000      0.0320     0.0731  1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175     0.0006  0   0
       2000      0.0071     0.0011  0   0
       4000      0.0164     0.0073  0   0
       6000      0.0289     0.0750  0   0
       8000      0.0312     0.0775  0   0
      10000      0.0322     0.0789  0   0
      12000      0.0332     0.0788  0   0
      14000      0.0332     0.0783  0   0
      16000      0.0332     0.0770  1   1
nus=0.269973  nuc=1.650000  dr=50.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175     0.0006  0   0
       2000      0.0071     0.0065  0   0
       4000      0.0164     0.0164  0   0
       6000      0.0289     0.0750  0   0
       8000      0.0312     0.0775  0   0
      10000      0.0322     0.0789  0   0
      12000      0.0332     0.0788  0   0
      14000      0.0332     0.0783  0   0
      16000      0.0332     0.0770  1   1
nus=0.269973  nuc=1.650000  dr=500.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
```

```
Criticality fraction for indicated times
         0       0.0175       0.0006   0    0
      2000       0.0071       0.0011   0    0
      4000       0.0164       0.0181   0    0
      6000       0.0289       0.0750   0    0
      8000       0.0312       0.0775   0    0
     10000       0.0322       0.0789   0    0
     12000       0.0332       0.0788   0    0
     14000       0.0333       0.0783   0    0
     16000       0.0332       0.0770   1    1
nus=0.674933  nuc=1.650000  dr=0.100000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
         0       0.0175       0.0114   0    0
      2000       0.0453       0.0000   0    0
      4000       0.0243       0.0000   0    0
      6000       0.0289       0.0000   0    0
      8000       0.0312       0.0000   0    0
     10000       0.0322       0.0000   0    0
     12000       0.0332       0.0000   1    0
     14000       0.0332       0.0000   1    0
     16000       0.0332       0.0000   1    0
     18000       0.0332       0.0000   1    0
     20000       0.0325       0.0000   1    0
     22000       0.0322       0.0000   1    0
     24000       0.0320       0.0000   1    0
     26000       0.0318       0.0003   1    0
     28000       0.0312       0.0004   1    0
     30000       0.0306       0.0006   1    0
     32000       0.0301       0.0019   1    0
     34000       0.0298       0.0024   1    0
     36000       0.0297       0.0041   1    0
     38000       0.0294       0.0054   1    0
     40000       0.0286       0.0068   1    0
     42000       0.0282       0.0076   1    0
     44000       0.0278       0.0100   1    0
     46000       0.0278       0.0105   1    0
     48000       0.0260       0.0118   1    0
     50000       0.0255       0.0121   1    0
     52000       0.0254       0.0137   1    0
     54000       0.0253       0.0150   1    0
     56000       0.0250       0.0152   1    0
     58000       0.0245       0.0172   1    0
     60000       0.0239       0.0186   1    0
     62000       0.0239       0.0202   1    0
     64000       0.0236       0.0215   1    0
     66000       0.0236       0.0234   1    0
     68000       0.0227       0.0254   1    0
     70000       0.0226       0.0286   1    0
     72000       0.0226       0.0300   1    0
     74000       0.0226       0.0317   1    0
     76000       0.0223       0.0329   1    0
     78000       0.0223       0.0337   1    0
     80000       0.0221       0.0339   1    0
     82000       0.0218       0.0346   1    0
     84000       0.0217       0.0358   1    0
     86000       0.0215       0.0366   1    0
     88000       0.0214       0.0371   1    0
     90000       0.0214       0.0373   1    0
     92000       0.0214       0.0386   1    0
     94000       0.0214       0.0387   1    0
     96000       0.0214       0.0394   1    0
```

```
       98000      0.0214     0.0486   1   0
      100000      0.0214     0.0486   1   1
nus=0.674933  nuc=1.650000  dr=0.500000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175     0.0114   0   0
        2000      0.0453     0.0000   0   0
        4000      0.0243     0.0000   0   0
        6000      0.0289     0.0003   0   0
        8000      0.0312     0.0042   0   0
       10000      0.0322     0.0115   0   0
       12000      0.0332     0.0185   1   0
       14000      0.0332     0.0310   1   0
       16000      0.0332     0.0398   1   0
       18000      0.0332     0.0532   1   0
       20000      0.0325     0.0607   1   0
       22000      0.0322     0.0740   1   0
       24000      0.0320     0.0731   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175     0.0114   0   0
        2000      0.0453     0.0081   0   0
        4000      0.0243     0.0651   0   0
        6000      0.0289     0.0750   0   0
        8000      0.0312     0.0775   0   0
       10000      0.0322     0.0789   0   0
       12000      0.0332     0.0788   1   1
nus=0.674933  nuc=1.650000  dr=50.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175     0.0114   0   0
        2000      0.0453     0.0509   0   0
        4000      0.0243     0.0651   0   0
        6000      0.0289     0.0750   0   0
        8000      0.0312     0.0775   0   0
       10000      0.0322     0.0789   0   0
       12000      0.0332     0.0788   1   1
nus=0.674933  nuc=1.650000  dr=500.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175     0.0203   0   0
        2000      0.0453     0.0509   0   0
        4000      0.0243     0.0651   0   0
        6000      0.0289     0.0750   0   0
        8000      0.0312     0.0775   0   0
       10000      0.0322     0.0789   0   0
       12000      0.0332     0.0788   1   1
nus=1.349866  nuc=1.650000  dr=0.100000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175     0.0114   0   0
        2000      0.0453     0.0000   0   0
        4000      0.0243     0.0000   0   0
        6000      0.0289     0.0000   0   0
        8000      0.0312     0.0000   0   0
       10000      0.0322     0.0000   0   0
       12000      0.0332     0.0000   1   0
       14000      0.0332     0.0000   1   0
       16000      0.0332     0.0000   1   0
       18000      0.0332     0.0000   1   0
       20000      0.0325     0.0000   1   0
```

```
      22000      0.0322      0.0000   1   0
      24000      0.0320      0.0000   1   0
      26000      0.0318      0.0003   1   0
      28000      0.0312      0.0004   1   0
      30000      0.0306      0.0007   1   0
      32000      0.0301      0.0020   1   0
      34000      0.0298      0.0028   1   0
      36000      0.0297      0.0047   1   0
      38000      0.0294      0.0064   1   0
      40000      0.0286      0.0068   1   0
      42000      0.0282      0.0079   1   0
      44000      0.0278      0.0100   1   0
      46000      0.0278      0.0106   1   0
      48000      0.0260      0.0119   1   0
      50000      0.0255      0.0121   1   0
      52000      0.0254      0.0141   1   0
      54000      0.0253      0.0150   1   0
      56000      0.0250      0.0158   1   0
      58000      0.0245      0.0177   1   0
      60000      0.0239      0.0188   1   0
      62000      0.0239      0.0202   1   0
      64000      0.0236      0.0215   1   0
      66000      0.0236      0.0235   1   0
      68000      0.0227      0.0256   1   0
      70000      0.0226      0.0290   1   0
      72000      0.0226      0.0303   1   0
      74000      0.0226      0.0318   1   0
      76000      0.0223      0.0332   1   0
      78000      0.0223      0.0337   1   0
      80000      0.0221      0.0343   1   0
      82000      0.0218      0.0349   1   0
      84000      0.0217      0.0358   1   0
      86000      0.0215      0.0367   1   0
      88000      0.0214      0.0372   1   0
      90000      0.0214      0.0374   1   0
      92000      0.0214      0.0386   1   0
      94000      0.0214      0.0388   1   0
      96000      0.0214      0.0395   1   0
      98000      0.0214      0.0486   1   0
     100000      0.0214      0.0486   1   1
nus=1.349866  nuc=1.650000  dr=0.500000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0114   0   0
       2000      0.0453      0.0000   0   0
       4000      0.0243      0.0000   0   0
       6000      0.0289      0.0004   0   0
       8000      0.0312      0.0065   0   0
      10000      0.0322      0.0121   0   0
      12000      0.0332      0.0201   1   0
      14000      0.0332      0.0331   1   0
      16000      0.0332      0.0413   1   0
      18000      0.0332      0.0566   1   0
      20000      0.0325      0.0750   1   0
      22000      0.0322      0.0740   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0114   0   0
       2000      0.0453      0.0321   0   0
       4000      0.0243      0.0651   0   0
       6000      0.0289      0.0750   0   0
```

```
       8000       0.0312       0.0775    0    0
      10000       0.0322       0.0789    0    0
      12000       0.0332       0.0788    1    1
nus=1.349866  nuc=1.650000  dr=50.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0       0.0175       0.0114    0    0
       2000       0.0453       0.0509    0    0
       4000       0.0243       0.0651    0    0
       6000       0.0289       0.0750    0    0
       8000       0.0312       0.0775    0    0
      10000       0.0322       0.0789    0    0
      12000       0.0332       0.0788    1    1
nus=1.349866  nuc=1.650000  dr=500.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0       0.0175       0.0203    0    0
       2000       0.0453       0.0509    0    0
       4000       0.0243       0.0651    0    0
       6000       0.0289       0.0750    0    0
       8000       0.0312       0.0775    0    0
      10000       0.0322       0.0789    0    0
      12000       0.0332       0.0788    1    1
```

inf.sum

```
  Time Unfrm  Frac Unfrm   Time Stld   Frac Stld        Prob
       46000     0.02717      124000     0.04681     1.00000
       46000     0.02717       54000     0.05995     1.00000
       46000     0.02717       48000     0.06145     1.00000
       46000     0.02717       48000     0.06145     1.00000
       46000     0.02721       48000     0.06145     1.00000
       20000     0.03254      106000     0.04773     1.00000
       20000     0.03254       32000     0.07064     1.00000
       20000     0.03254       20000     0.07499     1.00000
       20000     0.03254       20000     0.07499     1.00000
       20000     0.03254       20000     0.07499     1.00000
       14000     0.03322      102000     0.04858     1.00000
       14000     0.03322       26000     0.07264     1.00000
       14000     0.03322       10000     0.07891     1.00000
       14000     0.03322       10000     0.07891     1.00000
       14000     0.03322       10000     0.07891     1.00000
       14000     0.03322      100000     0.04858     1.00000
       14000     0.03322       22000     0.07402     1.00000
       14000     0.03322       10000     0.07891     1.00000
       14000     0.03322       10000     0.07891     1.00000
       14000     0.03330       10000     0.07891     1.00000
        2000     0.04530       98000     0.04865     1.00000
        2000     0.04530       22000     0.07402     1.00000
        2000     0.04530       10000     0.07891     1.00000
        2000     0.04530       10000     0.07891     1.00000
        2000     0.04530       10000     0.07891     1.00000
        2000     0.04530       98000     0.04865     1.00000
        2000     0.04530       20000     0.07499     1.00000
        2000     0.04530       10000     0.07891     1.00000
        2000     0.04530       10000     0.07891     1.00000
        2000     0.04530       10000     0.07891     1.00000
```

thick.in

```
   sscrsn   dr   pentime   ssthick0   ex   keff0   prob  pswitch
    0.08     5     3000       7        .1    .93      1       1
```

```
0.08     5     3000      8       .1    .93      1       1
0.08     5     3000      9       .1    .93      1       1
0.08     5     3000      10      .1    .93      1       1
0.20     5     3000      7       .1    .93      1       1
0.20     5     3000      8       .1    .93      1       1
0.20     5     3000      9       .1    .93      1       1
0.20     5     3000      10      .1    .93      1       1
0.40     5     3000      7       .1    .93      1       1
0.40     5     3000      8       .1    .93      1       1
0.40     5     3000      9       .1    .93      1       1
0.40     5     3000      10      .1    .93      1       1
0.80     5     3000      7       .1    .93      1       1
0.80     5     3000      8       .1    .93      1       1
0.80     5     3000      9       .1    .93      1       1
0.80     5     3000      10      .1    .93      1       1
2.00     5     3000      7       .1    .93      1       1
2.00     5     3000      8       .1    .93      1       1
2.00     5     3000      9       .1    .93      1       1
2.00     5     3000      10      .1    .93      1       1
4.00     5     3000      7       .1    .93      1       1
4.00     5     3000      8       .1    .93      1       1
4.00     5     3000      9       .1    .93      1       1
4.00     5     3000      10      .1    .93      1       1
```

thick.log

```
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0204   0   0
       2000      0.0065      0.0050   0   0
       4000      0.0011      0.0015   0   0
       6000      0.0011      0.0020   0   0
       8000      0.0011      0.0020   0   0
      10000      0.0015      0.0020   0   0
      12000      0.0020      0.0020   0   0
      14000      0.0020      0.0020   0   0
      16000      0.0020      0.0024   0   0
      18000      0.0025      0.0025   0   0
      20000      0.0028      0.0028   0   0
      22000      0.0032      0.0029   0   0
      24000      0.0044      0.0043   0   0
      26000      0.0046      0.0044   0   0
      28000      0.0049      0.0047   0   0
      30000      0.0053      0.0051   0   0
      32000      0.0070      0.0065   0   0
      34000      0.0081      0.0071   0   0
      36000      0.0086      0.0081   0   0
      38000      0.0120      0.0100   0   0
      40000      0.0168      0.0161   0   0
      42000      0.0222      0.0232   0   0
      44000      0.0267      0.0395   0   0
      46000      0.0272      0.0592   0   0
      48000      0.0260      0.0614   0   0
      50000      0.0255      0.0610   0   0
      52000      0.0254      0.0606   0   0
      54000      0.0253      0.0599   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=48131  ssthick0=8  keff0=0.930
Criticality fraction for indicated times
          0      0.0167      0.0006   0   0
```

```
         2000       0.0055       0.0048   0   0
         4000       0.0011       0.0011   0   0
         6000       0.0011       0.0011   0   0
         8000       0.0011       0.0011   0   0
        10000       0.0011       0.0011   0   0
        12000       0.0011       0.0011   0   0
        14000       0.0011       0.0015   0   0
        16000       0.0011       0.0015   0   0
        18000       0.0011       0.0015   0   0
        20000       0.0011       0.0020   0   0
        22000       0.0015       0.0020   0   0
        24000       0.0020       0.0020   0   0
        26000       0.0020       0.0025   0   0
        28000       0.0026       0.0026   0   0
        30000       0.0029       0.0032   0   0
        32000       0.0044       0.0044   0   0
        34000       0.0046       0.0046   0   0
        36000       0.0050       0.0049   0   0
        38000       0.0065       0.0053   0   0
        40000       0.0071       0.0070   0   0
        42000       0.0083       0.0081   0   0
        44000       0.0114       0.0101   0   0
        46000       0.0162       0.0161   0   0
        48000       0.0203       0.0223   0   0
        50000       0.0226       0.0370   0   0
        52000       0.0228       0.0532   0   0
        54000       0.0234       0.0599   0   0
        56000       0.0226       0.0592   0   0
        58000       0.0226       0.0589   0   0
        60000       0.0223       0.0583   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=54148  ssthick0=9  keff0=0.930
Criticality fraction for indicated times
            0       0.0159       0.0004   0   0
         2000       0.0050       0.0046   0   0
         4000       0.0010       0.0011   0   0
         6000       0.0011       0.0011   0   0
         8000       0.0011       0.0011   0   0
        10000       0.0011       0.0011   0   0
        12000       0.0011       0.0011   0   0
        14000       0.0011       0.0011   0   0
        16000       0.0011       0.0011   0   0
        18000       0.0011       0.0011   0   0
        20000       0.0011       0.0011   0   0
        22000       0.0011       0.0011   0   0
        24000       0.0011       0.0011   0   0
        26000       0.0011       0.0011   0   0
        28000       0.0011       0.0011   0   0
        30000       0.0011       0.0020   0   0
        32000       0.0015       0.0020   0   0
        34000       0.0020       0.0025   0   0
        36000       0.0025       0.0028   0   0
        38000       0.0029       0.0037   0   0
        40000       0.0044       0.0044   0   0
        42000       0.0047       0.0047   0   0
        44000       0.0051       0.0052   0   0
        46000       0.0065       0.0065   0   0
        48000       0.0081       0.0074   0   0
        50000       0.0108       0.0101   0   0
        52000       0.0148       0.0160   0   0
        54000       0.0183       0.0217   0   0
        56000       0.0211       0.0350   0   0
```

```
       58000      0.0213      0.0446   0   0
       60000      0.0214      0.0583   0   0
       62000      0.0214      0.0581   0   0
       64000      0.0211      0.0573   0   0
       66000      0.0211      0.0572   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=60164  ssthick0=10  keff0=0.930
Criticality fraction for indicated times
           0      0.0136      0.0003   0   0
        2000      0.0046      0.0032   0   0
        4000      0.0007      0.0007   0   0
        6000      0.0007      0.0010   0   0
        8000      0.0010      0.0010   0   0
       10000      0.0010      0.0011   0   0
       12000      0.0010      0.0011   0   0
       14000      0.0010      0.0011   0   0
       16000      0.0010      0.0011   0   0
       18000      0.0010      0.0011   0   0
       20000      0.0010      0.0011   0   0
       22000      0.0010      0.0011   0   0
       24000      0.0010      0.0011   0   0
       26000      0.0010      0.0011   0   0
       28000      0.0010      0.0011   0   0
       30000      0.0010      0.0011   0   0
       32000      0.0010      0.0011   0   0
       34000      0.0010      0.0011   0   0
       36000      0.0010      0.0011   0   0
       38000      0.0011      0.0015   0   0
       40000      0.0011      0.0020   0   0
       42000      0.0020      0.0025   0   0
       44000      0.0025      0.0029   0   0
       46000      0.0029      0.0043   0   0
       48000      0.0044      0.0046   0   0
       50000      0.0048      0.0050   0   0
       52000      0.0055      0.0065   0   0
       54000      0.0070      0.0072   0   0
       56000      0.0101      0.0102   0   0
       58000      0.0143      0.0149   0   0
       60000      0.0165      0.0211   0   0
       62000      0.0189      0.0343   0   0
       64000      0.0189      0.0415   0   0
       66000      0.0201      0.0566   0   0
       68000      0.0191      0.0571   0   0
       70000      0.0190      0.0568   0   0
       72000      0.0189      0.0566   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0065      0.0047   0   0
        4000      0.0011      0.0011   0   0
        6000      0.0020      0.0011   0   0
        8000      0.0026      0.0025   0   0
       10000      0.0044      0.0043   0   0
       12000      0.0064      0.0050   0   0
       14000      0.0085      0.0081   0   0
       16000      0.0189      0.0160   0   0
       18000      0.0324      0.0606   0   0
       20000      0.0325      0.0750   0   0
       22000      0.0322      0.0740   0   0
       24000      0.0320      0.0731   0   0
       26000      0.0318      0.0726   0   0
```

```
       28000       0.0312      0.0722   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=19252  ssthick0=8  keff0=0.930
Criticality fraction for indicated times
           0       0.0167      0.0006   0   0
        2000       0.0053      0.0047   0   0
        4000       0.0011      0.0011   0   0
        6000       0.0011      0.0011   0   0
        8000       0.0011      0.0011   0   0
       10000       0.0020      0.0020   0   0
       12000       0.0037      0.0029   0   0
       14000       0.0050      0.0047   0   0
       16000       0.0080      0.0070   0   0
       18000       0.0148      0.0139   0   0
       20000       0.0298      0.0351   0   0
       22000       0.0303      0.0740   0   0
       24000       0.0298      0.0731   0   0
       26000       0.0298      0.0726   0   0
       28000       0.0297      0.0722   0   0
       30000       0.0290      0.0712   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=21659  ssthick0=9  keff0=0.930
Criticality fraction for indicated times
           0       0.0159      0.0004   0   0
        2000       0.0051      0.0044   0   0
        4000       0.0010      0.0010   0   0
        6000       0.0010      0.0010   0   0
        8000       0.0010      0.0011   0   0
       10000       0.0011      0.0011   0   0
       12000       0.0011      0.0015   0   0
       14000       0.0025      0.0026   0   0
       16000       0.0046      0.0044   0   0
       18000       0.0070      0.0065   0   0
       20000       0.0122      0.0113   0   0
       22000       0.0236      0.0243   0   0
       24000       0.0280      0.0731   0   0
       26000       0.0276      0.0726   0   0
       28000       0.0263      0.0722   0   0
       30000       0.0262      0.0712   0   0
       32000       0.0253      0.0706   1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=24065  ssthick0=10  keff0=0.930
Criticality fraction for indicated times
           0       0.0136      0.0003   0   0
        2000       0.0047      0.0032   0   0
        4000       0.0007      0.0007   0   0
        6000       0.0010      0.0010   0   0
        8000       0.0010      0.0010   0   0
       10000       0.0010      0.0010   0   0
       12000       0.0010      0.0011   0   0
       14000       0.0011      0.0011   0   0
       16000       0.0020      0.0020   0   0
       18000       0.0038      0.0043   0   0
       20000       0.0053      0.0053   0   0
       22000       0.0096      0.0086   0   0
       24000       0.0200      0.0205   0   0
       26000       0.0243      0.0618   0   0
       28000       0.0243      0.0722   0   0
       30000       0.0239      0.0712   0   0
       32000       0.0237      0.0706   0   0
       34000       0.0236      0.0701   0   0
       36000       0.0225      0.0691   1   1
```

```
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0006   0   0
       2000      0.0065      0.0032   0   0
       4000      0.0025      0.0010   0   0
       6000      0.0053      0.0044   0   0
       8000      0.0181      0.0121   0   0
      10000      0.0322      0.0789   0   0
      12000      0.0332      0.0788   0   0
      14000      0.0332      0.0783   0   0
      16000      0.0332      0.0770   0   0
      18000      0.0332      0.0762   0   0
      20000      0.0325      0.0750   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=9626  ssthick0=8  keff0=0.930
Criticality fraction for indicated times
          0      0.0167      0.0006   0   0
       2000      0.0053      0.0029   0   0
       4000      0.0011      0.0007   0   0
       6000      0.0029      0.0011   0   0
       8000      0.0079      0.0053   0   0
      10000      0.0297      0.0227   0   0
      12000      0.0312      0.0788   0   0
      14000      0.0313      0.0783   0   0
      16000      0.0313      0.0770   0   0
      18000      0.0311      0.0762   0   0
      20000      0.0310      0.0750   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=10829  ssthick0=9  keff0=0.930
Criticality fraction for indicated times
          0      0.0159      0.0004   0   0
       2000      0.0051      0.0026   0   0
       4000      0.0010      0.0006   0   0
       6000      0.0011      0.0007   0   0
       8000      0.0044      0.0026   0   0
      10000      0.0121      0.0084   0   0
      12000      0.0292      0.0788   0   0
      14000      0.0293      0.0783   0   0
      16000      0.0293      0.0770   0   0
      18000      0.0291      0.0762   0   0
      20000      0.0291      0.0750   0   0
      22000      0.0286      0.0740   1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=12032  ssthick0=10  keff0=0.930
Criticality fraction for indicated times
          0      0.0137      0.0003   0   0
       2000      0.0049      0.0024   0   0
       4000      0.0007      0.0006   0   0
       6000      0.0010      0.0007   0   0
       8000      0.0020      0.0010   0   0
      10000      0.0053      0.0046   0   0
      12000      0.0200      0.0149   0   0
      14000      0.0263      0.0783   0   0
      16000      0.0263      0.0770   0   0
      18000      0.0263      0.0762   0   0
      20000      0.0261      0.0750   0   0
      22000      0.0260      0.0740   0   0
      24000      0.0253      0.0731   1   1
nus=0.269973  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
```

```
         0      0.0175      0.0006   0   0
      2000      0.0071      0.0011   0   0
      4000      0.0164      0.0073   0   0
      6000      0.0289      0.0750   0   0
      8000      0.0312      0.0775   0   0
     10000      0.0322      0.0789   0   0
     12000      0.0332      0.0788   0   0
     14000      0.0332      0.0783   0   0
     16000      0.0332      0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4813  ssthick0=8  keff0=0.930
Criticality fraction for indicated times
         0      0.0167      0.0006   0   0
      2000      0.0063      0.0007   0   0
      4000      0.0073      0.0025   0   0
      6000      0.0261      0.0750   0   0
      8000      0.0294      0.0775   0   0
     10000      0.0309      0.0789   0   0
     12000      0.0312      0.0788   0   0
     14000      0.0313      0.0783   0   0
     16000      0.0313      0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=5414  ssthick0=9  keff0=0.930
Criticality fraction for indicated times
         0      0.0159      0.0006   0   0
      2000      0.0050      0.0007   0   0
      4000      0.0044      0.0007   0   0
      6000      0.0246      0.0311   0   0
      8000      0.0262      0.0775   0   0
     10000      0.0284      0.0789   0   0
     12000      0.0292      0.0788   0   0
     14000      0.0293      0.0783   0   0
     16000      0.0293      0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=6016  ssthick0=10  keff0=0.930
Criticality fraction for indicated times
         0      0.0137      0.0003   0   0
      2000      0.0049      0.0007   0   0
      4000      0.0011      0.0004   0   0
      6000      0.0188      0.0094   0   0
      8000      0.0246      0.0775   0   0
     10000      0.0255      0.0789   0   0
     12000      0.0262      0.0788   0   0
     14000      0.0263      0.0783   0   0
     16000      0.0263      0.0770   0   0
     18000      0.0263      0.0762   1   1
nus=0.674933  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
         0      0.0175      0.0114   0   0
      2000      0.0453      0.0081   0   0
      4000      0.0243      0.0651   0   0
      6000      0.0289      0.0750   0   0
      8000      0.0312      0.0775   0   0
     10000      0.0322      0.0789   0   0
     12000      0.0332      0.0788   1   1
nus=0.674933  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1925  ssthick0=8  keff0=0.930
Criticality fraction for indicated times
         0      0.0167      0.0102   0   0
      2000      0.0526      0.0008   0   0
      4000      0.0225      0.0651   0   0
```

```
        6000       0.0261       0.0750   0   0
        8000       0.0294       0.0775   0   0
       10000       0.0309       0.0789   0   0
       12000       0.0312       0.0788   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=2165  ssthick0=9  keff0=0.930
Criticality fraction for indicated times
           0       0.0160       0.0090   0   0
        2000       0.0221       0.0007   0   0
        4000       0.0206       0.0651   0   0
        6000       0.0246       0.0750   0   0
        8000       0.0262       0.0775   0   0
       10000       0.0284       0.0789   0   0
       12000       0.0292       0.0788   0   0
       14000       0.0293       0.0783   0   1
       16000       0.0293       0.0770   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=2406  ssthick0=10  keff0=0.930
Criticality fraction for indicated times
           0       0.0137       0.0081   0   0
        2000       0.0102       0.0003   0   0
        4000       0.0198       0.0651   0   0
        6000       0.0225       0.0750   0   0
        8000       0.0246       0.0775   0   0
       10000       0.0255       0.0789   0   0
       12000       0.0262       0.0788   0   0
       14000       0.0263       0.0783   0   1
       16000       0.0263       0.0770   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0175       0.0114   0   0
        2000       0.0453       0.0321   0   0
        4000       0.0243       0.0651   0   0
        6000       0.0289       0.0750   0   0
        8000       0.0312       0.0775   0   0
       10000       0.0322       0.0789   0   0
       12000       0.0332       0.0788   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=962  ssthick0=8  keff0=0.930
Criticality fraction for indicated times
           0       0.0167       0.0102   0   0
        2000       0.0408       0.0256   0   0
        4000       0.0225       0.0651   0   0
        6000       0.0261       0.0750   0   0
        8000       0.0294       0.0775   0   0
       10000       0.0309       0.0789   0   0
       12000       0.0312       0.0788   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1082  ssthick0=9  keff0=0.930
Criticality fraction for indicated times
           0       0.0161       0.0096   0   0
        2000       0.0383       0.0197   0   0
        4000       0.0206       0.0651   0   0
        6000       0.0246       0.0750   0   0
        8000       0.0262       0.0775   0   0
       10000       0.0284       0.0789   0   0
       12000       0.0292       0.0788   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1203  ssthick0=10  keff0=0.930
Criticality fraction for indicated times
           0       0.0138       0.0081   0   0
```

```
     2000       0.0355       0.0145   0    0
     4000       0.0198       0.0651   0    0
     6000       0.0225       0.0750   0    0
     8000       0.0246       0.0775   0    0
    10000       0.0255       0.0789   0    0
    12000       0.0262       0.0788   1    1
```

thick.sum

```
  Time Unfrm  Frac Unfrm   Time Stld   Frac Stld        Prob
     46000     0.02717       48000      0.06145      1.00000
     54000     0.02335       54000      0.05995      1.00000
     60000     0.02136       60000      0.05835      1.00000
     66000     0.02005       68000      0.05707      1.00000
     20000     0.03254       20000      0.07499      1.00000
     22000     0.03034       22000      0.07402      1.00000
     24000     0.02803       24000      0.07313      1.00000
     26000     0.02433       28000      0.07224      1.00000
     14000     0.03322       10000      0.07891      1.00000
     14000     0.03132       12000      0.07883      1.00000
     14000     0.02932       12000      0.07883      1.00000
     14000     0.02635       14000      0.07828      1.00000
     14000     0.03322       10000      0.07891      1.00000
     14000     0.03132       10000      0.07891      1.00000
     14000     0.02932       10000      0.07891      1.00000
     14000     0.02635       10000      0.07891      1.00000
      2000     0.04530       10000      0.07891      1.00000
      2000     0.05258       10000      0.07891      1.00000
     14000     0.02932       10000      0.07891      1.00000
     14000     0.02635       10000      0.07891      1.00000
      2000     0.04530       10000      0.07891      1.00000
      2000     0.04083       10000      0.07891      1.00000
      2000     0.03834       10000      0.07891      1.00000
      2000     0.03546       10000      0.07891      1.00000
```

pentime.in

```
  sscrsn    dr   pentime    ssthick0    ex    keff0    prob   pswitch
   0.08      5     3000        7        .1     .93       1        1
   0.08      5     5000        7        .1     .93       1        1
   0.08      5     7000        7        .1     .93       1        1
   0.08      5     9000        7        .1     .93       1        1
   0.20      5     3000        7        .1     .93       1        1
   0.20      5     5000        7        .1     .93       1        1
   0.20      5     7000        7        .1     .93       1        1
   0.20      5     9000        7        .1     .93       1        1
   0.40      5     3000        7        .1     .93       1        1
   0.40      5     5000        7        .1     .93       1        1
   0.40      5     7000        7        .1     .93       1        1
   0.40      5     9000        7        .1     .93       1        1
   0.80      5     3000        7        .1     .93       1        1
   0.80      5     5000        7        .1     .93       1        1
   0.80      5     7000        7        .1     .93       1        1
   0.80      5     9000        7        .1     .93       1        1
   2.00      5     3000        7        .1     .93       1        1
   2.00      5     5000        7        .1     .93       1        1
   2.00      5     7000        7        .1     .93       1        1
   2.00      5     9000        7        .1     .93       1        1
   4.00      5     3000        7        .1     .93       1        1
   4.00      5     5000        7        .1     .93       1        1
   4.00      5     7000        7        .1     .93       1        1
   4.00      5     9000        7        .1     .93       1        1
```

pentime.log

```
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0175      0.0204   0   0
       2000      0.0065      0.0050   0   0
       4000      0.0011      0.0015   0   0
       6000      0.0011      0.0020   0   0
       8000      0.0011      0.0020   0   0
      10000      0.0015      0.0020   0   0
      12000      0.0020      0.0020   0   0
      14000      0.0020      0.0020   0   0
      16000      0.0020      0.0024   0   0
      18000      0.0025      0.0025   0   0
      20000      0.0028      0.0028   0   0
      22000      0.0032      0.0029   0   0
      24000      0.0044      0.0043   0   0
      26000      0.0046      0.0044   0   0
      28000      0.0049      0.0047   0   0
      30000      0.0053      0.0051   0   0
      32000      0.0070      0.0065   0   0
      34000      0.0081      0.0071   0   0
      36000      0.0086      0.0081   0   0
      38000      0.0120      0.0100   0   0
      40000      0.0168      0.0161   0   0
      42000      0.0222      0.0232   0   0
      44000      0.0267      0.0395   0   0
      46000      0.0272      0.0592   0   0
      48000      0.0260      0.0614   0   0
      50000      0.0255      0.0610   0   0
      52000      0.0254      0.0606   0   0
      54000      0.0253      0.0599   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=5000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
          0      0.0189      0.0006   0   0
       2000      0.0065      0.0051   0   0
       4000      0.0011      0.0020   0   0
       6000      0.0011      0.0020   0   0
       8000      0.0015      0.0020   0   0
      10000      0.0020      0.0020   0   0
      12000      0.0020      0.0020   0   0
      14000      0.0020      0.0020   0   0
      16000      0.0020      0.0020   0   0
      18000      0.0025      0.0025   0   0
      20000      0.0028      0.0026   0   0
      22000      0.0032      0.0029   0   0
      24000      0.0044      0.0038   0   0
      26000      0.0046      0.0044   0   0
      28000      0.0049      0.0047   0   0
      30000      0.0053      0.0050   0   0
      32000      0.0070      0.0065   0   0
      34000      0.0081      0.0070   0   0
      36000      0.0086      0.0081   0   0
      38000      0.0118      0.0100   0   0
      40000      0.0168      0.0161   0   0
      42000      0.0222      0.0230   0   0
      44000      0.0267      0.0386   0   0
      46000      0.0259      0.0583   0   0
      48000      0.0255      0.0610   0   0
```

```
       50000      0.0254      0.0606   0   0
       52000      0.0253      0.0599   0   0
       54000      0.0250      0.0592   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=7000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0194      0.0007   0   0
        2000      0.0065      0.0051   0   0
        4000      0.0015      0.0020   0   0
        6000      0.0015      0.0020   0   0
        8000      0.0015      0.0020   0   0
       10000      0.0020      0.0020   0   0
       12000      0.0020      0.0020   0   0
       14000      0.0020      0.0020   0   0
       16000      0.0020      0.0020   0   0
       18000      0.0025      0.0025   0   0
       20000      0.0026      0.0026   0   0
       22000      0.0029      0.0029   0   0
       24000      0.0043      0.0037   0   0
       26000      0.0044      0.0044   0   0
       28000      0.0048      0.0047   0   0
       30000      0.0053      0.0050   0   0
       32000      0.0070      0.0064   0   0
       34000      0.0081      0.0070   0   0
       36000      0.0086      0.0081   0   0
       38000      0.0114      0.0096   0   0
       40000      0.0163      0.0161   0   0
       42000      0.0217      0.0230   0   0
       44000      0.0255      0.0380   0   0
       46000      0.0255      0.0577   0   0
       48000      0.0254      0.0606   0   0
       50000      0.0253      0.0599   0   0
       52000      0.0250      0.0592   0   0
       54000      0.0245      0.0589   1   1
nus=0.026997  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=9000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=42115  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0199      0.0007   0   0
        2000      0.0065      0.0052   0   0
        4000      0.0015      0.0020   0   0
        6000      0.0015      0.0020   0   0
        8000      0.0016      0.0020   0   0
       10000      0.0020      0.0020   0   0
       12000      0.0020      0.0020   0   0
       14000      0.0020      0.0020   0   0
       16000      0.0020      0.0020   0   0
       18000      0.0025      0.0025   0   0
       20000      0.0026      0.0026   0   0
       22000      0.0029      0.0028   0   0
       24000      0.0043      0.0037   0   0
       26000      0.0044      0.0044   0   0
       28000      0.0048      0.0047   0   0
       30000      0.0053      0.0050   0   0
       32000      0.0065      0.0064   0   0
       34000      0.0080      0.0070   0   0
       36000      0.0085      0.0081   0   0
       38000      0.0114      0.0090   0   0
       40000      0.0163      0.0160   0   0
       42000      0.0217      0.0223   0   0
       44000      0.0248      0.0380   0   0
       46000      0.0253      0.0573   0   0
       48000      0.0253      0.0599   0   0
```

```
       50000      0.0250      0.0592  0   0
       52000      0.0245      0.0589  0   0
       54000      0.0239      0.0583  1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006  0   0
        2000      0.0065      0.0047  0   0
        4000      0.0011      0.0011  0   0
        6000      0.0020      0.0011  0   0
        8000      0.0026      0.0025  0   0
       10000      0.0044      0.0043  0   0
       12000      0.0064      0.0050  0   0
       14000      0.0085      0.0081  0   0
       16000      0.0189      0.0160  0   0
       18000      0.0324      0.0606  0   0
       20000      0.0325      0.0750  0   0
       22000      0.0322      0.0740  0   0
       24000      0.0320      0.0731  0   0
       26000      0.0318      0.0726  0   0
       28000      0.0312      0.0722  1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=5000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0189      0.0007  0   0
        2000      0.0065      0.0048  0   0
        4000      0.0011      0.0011  0   0
        6000      0.0020      0.0015  0   0
        8000      0.0028      0.0025  0   0
       10000      0.0044      0.0043  0   0
       12000      0.0065      0.0050  0   0
       14000      0.0085      0.0080  0   0
       16000      0.0189      0.0160  0   0
       18000      0.0320      0.0601  0   0
       20000      0.0322      0.0740  0   0
       22000      0.0320      0.0731  0   0
       24000      0.0318      0.0726  0   0
       26000      0.0312      0.0722  0   0
       28000      0.0306      0.0712  1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=7000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0194      0.0007  0   0
        2000      0.0065      0.0049  0   0
        4000      0.0015      0.0011  0   0
        6000      0.0020      0.0015  0   0
        8000      0.0028      0.0025  0   0
       10000      0.0044      0.0043  0   0
       12000      0.0065      0.0050  0   0
       14000      0.0085      0.0080  0   0
       16000      0.0183      0.0159  0   0
       18000      0.0320      0.0590  0   0
       20000      0.0320      0.0731  0   0
       22000      0.0318      0.0726  0   0
       24000      0.0312      0.0722  0   0
       26000      0.0306      0.0712  0   0
       28000      0.0301      0.0706  1   1
nus=0.067493  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=9000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=16846  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0199      0.0007  0   0
        2000      0.0065      0.0049  0   0
```

```
        4000      0.0015      0.0011  0   0
        6000      0.0020      0.0015  0   0
        8000      0.0028      0.0025  0   0
       10000      0.0044      0.0043  0   0
       12000      0.0065      0.0050  0   0
       14000      0.0085      0.0080  0   0
       16000      0.0183      0.0159  0   0
       18000      0.0314      0.0583  0   0
       20000      0.0318      0.0726  0   0
       22000      0.0312      0.0722  0   0
       24000      0.0306      0.0712  0   0
       26000      0.0301      0.0706  0   0
       28000      0.0298      0.0701  1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006  0   0
        2000      0.0065      0.0032  0   0
        4000      0.0025      0.0010  0   0
        6000      0.0053      0.0044  0   0
        8000      0.0181      0.0121  0   0
       10000      0.0322      0.0789  0   0
       12000      0.0332      0.0788  0   0
       14000      0.0332      0.0783  0   0
       16000      0.0332      0.0770  0   0
       18000      0.0332      0.0762  0   0
       20000      0.0325      0.0750  1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=5000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0189      0.0007  0   0
        2000      0.0065      0.0038  0   0
        4000      0.0025      0.0010  0   0
        6000      0.0063      0.0044  0   0
        8000      0.0183      0.0122  0   0
       10000      0.0332      0.0788  0   0
       12000      0.0332      0.0783  0   0
       14000      0.0332      0.0770  0   0
       16000      0.0332      0.0762  0   0
       18000      0.0325      0.0750  0   0
       20000      0.0322      0.0740  1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=7000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0194      0.0007  0   0
        2000      0.0065      0.0043  0   0
        4000      0.0026      0.0010  0   0
        6000      0.0064      0.0044  0   0
        8000      0.0185      0.0122  0   0
       10000      0.0332      0.0783  0   0
       12000      0.0332      0.0770  0   0
       14000      0.0332      0.0762  0   0
       16000      0.0325      0.0750  0   0
       18000      0.0322      0.0740  0   0
       20000      0.0320      0.0731  1   1
nus=0.134987  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=9000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=8423  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0199      0.0007  0   0
        2000      0.0065      0.0043  0   0
        4000      0.0028      0.0011  0   0
        6000      0.0064      0.0044  0   0
```

```
        8000      0.0189      0.0122   0   0
       10000      0.0332      0.0770   0   0
       12000      0.0332      0.0762   0   0
       14000      0.0325      0.0750   0   0
       16000      0.0322      0.0740   0   0
       18000      0.0320      0.0731   0   0
       20000      0.0318      0.0726   1   1
nus=0.269973  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0006   0   0
        2000      0.0071      0.0011   0   0
        4000      0.0164      0.0073   0   0
        6000      0.0289      0.0750   0   0
        8000      0.0312      0.0775   0   0
       10000      0.0322      0.0789   0   0
       12000      0.0332      0.0788   0   0
       14000      0.0332      0.0783   0   0
       16000      0.0332      0.0770   1   1
nus=0.269973  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=5000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0189      0.0007   0   0
        2000      0.0072      0.0011   0   0
        4000      0.0173      0.0073   0   0
        6000      0.0312      0.0775   0   0
        8000      0.0322      0.0789   0   0
       10000      0.0332      0.0788   0   0
       12000      0.0332      0.0783   0   0
       14000      0.0332      0.0770   0   0
       16000      0.0332      0.0762   1   1
nus=0.269973  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=7000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0194      0.0007   0   0
        2000      0.0073      0.0011   0   0
        4000      0.0182      0.0073   0   0
        6000      0.0322      0.0789   0   0
        8000      0.0332      0.0788   0   0
       10000      0.0332      0.0783   0   0
       12000      0.0332      0.0770   0   0
       14000      0.0332      0.0762   0   0
       16000      0.0325      0.0750   1   1
nus=0.269973  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=9000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=4211  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0199      0.0007   0   0
        2000      0.0079      0.0011   0   0
        4000      0.0183      0.0074   0   0
        6000      0.0332      0.0788   0   0
        8000      0.0332      0.0783   0   0
       10000      0.0332      0.0770   0   0
       12000      0.0332      0.0762   0   0
       14000      0.0325      0.0750   0   0
       16000      0.0322      0.0740   1   1
nus=0.674933  nuc=1.650000  dr=5.000000  ex=0.100000  pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0114   0   0
        2000      0.0453      0.0081   0   0
        4000      0.0243      0.0651   0   0
        6000      0.0289      0.0750   0   0
```

```
        8000      0.0312      0.0775   0   0
       10000      0.0322      0.0789   0   0
       12000      0.0332      0.0788   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=5000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0189      0.0120   0   0
        2000      0.0748      0.0093   0   0
        4000      0.0289      0.0750   0   0
        6000      0.0312      0.0775   0   0
        8000      0.0322      0.0789   0   0
       10000      0.0332      0.0788   0   0
       12000      0.0332      0.0783   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=7000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0194      0.0129   0   0
        2000      0.0953      0.0098   0   0
        4000      0.0312      0.0775   0   0
        6000      0.0322      0.0789   0   0
        8000      0.0332      0.0788   0   0
       10000      0.0332      0.0783   0   0
       12000      0.0332      0.0770   1   1
nus=0.674933  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=9000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=1684  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0199      0.0133   0   0
        2000      0.1088      0.0099   0   0
        4000      0.0322      0.0789   0   0
        6000      0.0332      0.0788   0   0
        8000      0.0332      0.0783   0   0
       10000      0.0332      0.0770   0   0
       12000      0.0332      0.0762   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=3000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0175      0.0114   0   0
        2000      0.0453      0.0321   0   0
        4000      0.0243      0.0651   0   0
        6000      0.0289      0.0750   0   0
        8000      0.0312      0.0775   0   0
       10000      0.0322      0.0789   0   0
       12000      0.0332      0.0788   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=5000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0189      0.0120   0   0
        2000      0.0748      0.0363   0   0
        4000      0.0289      0.0750   0   0
        6000      0.0312      0.0775   0   0
        8000      0.0322      0.0789   0   0
       10000      0.0332      0.0788   0   0
       12000      0.0332      0.0783   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=7000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0      0.0194      0.0129   0   0
        2000      0.0953      0.0381   0   0
        4000      0.0312      0.0775   0   0
        6000      0.0322      0.0789   0   0
        8000      0.0332      0.0788   0   0
       10000      0.0332      0.0783   0   0
```

```
       12000       0.0332       0.0770   1   1
nus=1.349866  nuc=1.650000  dr=5.000000 ex=0.100000 pentime=9000
f=0.000000  s=0.000100  Sigma=0.100000  tbskt=842  ssthick0=7  keff0=0.930
Criticality fraction for indicated times
           0       0.0199       0.0133   0   0
        2000       0.1088       0.0392   0   0
        4000       0.0322       0.0789   0   0
        6000       0.0332       0.0788   0   0
        8000       0.0332       0.0783   0   0
       10000       0.0332       0.0770   0   0
       12000       0.0332       0.0762   1   1
```

pentime.sum

```
  Time Unfrm  Frac Unfrm   Time Stld   Frac Stld        Prob
       46000     0.02717       48000     0.06145     1.00000
       44000     0.02666       48000     0.06097     1.00000
       46000     0.02553       48000     0.06056     1.00000
       46000     0.02535       48000     0.05995     1.00000
       20000     0.03254       20000     0.07499     1.00000
       20000     0.03216       20000     0.07402     1.00000
       20000     0.03200       20000     0.07313     1.00000
       20000     0.03182       20000     0.07264     1.00000
       14000     0.03322       10000     0.07891     1.00000
       12000     0.03322       10000     0.07883     1.00000
       10000     0.03322       10000     0.07828     1.00000
       10000     0.03319       10000     0.07703     1.00000
       14000     0.03322       10000     0.07891     1.00000
       12000     0.03322        8000     0.07891     1.00000
       10000     0.03322        6000     0.07891     1.00000
        8000     0.03322        6000     0.07883     1.00000
        2000     0.04530       10000     0.07891     1.00000
        2000     0.07480        8000     0.07891     1.00000
        2000     0.09530        6000     0.07891     1.00000
        2000     0.10885        4000     0.07891     1.00000
        2000     0.04530       10000     0.07891     1.00000
        2000     0.07480        8000     0.07891     1.00000
        2000     0.09530        6000     0.07891     1.00000
        2000     0.10885        4000     0.07891     1.00000
```

```
/*preproc3.c generates input to generate.c for 3 varying parameters:
 *all combinations and the joint probability as a product of the 3
 *marginal probabilities, with the number of combinations equal to the
 *product of the point numbers for each of the three parameters.  Each
 *input line consists of the value-probability pairs of one input parameters.
 *The line begins with the parameter label, followed by an integer indicating
 *the number of value-parameter pairs to follow.  This first number is read
 *as an integer; all the rest are read as floating point.  The routine to read
 *through blanks is rather simple minded, so the floating points cannot begin
 *with a decimal point. */

#include <stdio.h>
#include <stdlib.h>
#include <ctype.h>

#define NUMSPECIES 10 //max number of input parameters which will be read
#define MAXVALS 5 //max number of values for any species

int getint(),n;
float getfloat();
void readspace();
char dummy[100],buffer[200];//for reading input files

void main()
{int i=0,j,k,num,  //number of species actually read from input file
numvals[MAXVALS];  //number of values for each species
float vals[NUMSPECIES][MAXVALS]={{0}},
probs[NUMSPECIES][MAXVALS]={{0}},sum=0,prob;
FILE *fin,*fout;
char datastr[]="   7    .1    .93   ";//to be the same for all cases
fin=fopen("preproc3.in","r");
fout=fopen("preproc.out","w"); /*for input to snfpkg.c or generate.c*/
j=0;
while(fgets(buffer,199,fin)!=NULL) //loop to read input records
  {i=0;
  while(isdigit(buffer[i])==0)i++;//readthrough variable label
  n=i;
  numvals[j]=getint();
  for(i=0;i<numvals[j];i++) //read value-probability pairs
    {readspace();
    vals[j][i]=getfloat();
    readspace();
    probs[j][i]=getfloat();}
  j++;}
num=j;
if(num!=3)
  {printf("wrong number of species in preproc.in");
  exit(0);}
fprintf(fout,"%12s%12s%12s%s%12s\n","sscrsn","driprate",
         "pentime"," SSth    ex    Keff ","probability");//header for output
for(i=0;i<numvals[0];i++)
  for(j=0;j<numvals[1];j++)
    for(k=0;k<numvals[2];k++)
      {prob=probs[0][i]*probs[1][j]*probs[2][k];
      sum+=prob;
      fprintf(fout,"%12.4e%12.4e%12d%s%12.4e%5d\n",//individual cases
```

```
            vals[0][i],vals[1][j],(int)vals[2][k],datastr,prob,1);}
printf("cume probability = %f\n",sum);}  //check = 1

int getint()  //read an integer to blank or CR
{int i=0;
char temp[20];
while ((buffer[n+i]!=' ')&&(buffer[n+i]!='\n'))
  {temp[i]=buffer[n+i];
  i++;}
n+=i;
temp[i]='\0';
return atoi(temp);}

float getfloat()  //read a float to blank, CR, or tab
{int i=0;
char temp[20];
while ((buffer[n+i]!=' ')&&(buffer[n+i]!='\n')&&(buffer[n+i]!='\t'))
  {temp[i]=buffer[n+i];
  i++;}
n+=i;
temp[i]='\0';
return atof(temp);}

void readspace()  //readthrough blanks to the next number
{int i=0;
char temp[20];
while(isdigit(buffer[n+i])==0)i++;
n+=i;}
```

```
preproc3.in
sscrsn    4  0.08  0.25  0.2  0.25   0.4  0.25   0.8   0.25
driprate  3   0.5   0.3   5.0   0.4   50.0   0.3
pentime    3    3000.0    0.4    5000.0   0.4   7000.0    0.2
```

```
preproc.out
      sscrsn     driprate       pentime SSth    ex    Keff  probability
 8.0000e-002 5.0000e-001          3000   7     .1    .93   3.0000e-002    1
 8.0000e-002 5.0000e-001          5000   7     .1    .93   3.0000e-002    1
 8.0000e-002 5.0000e-001          7000   7     .1    .93   1.5000e-002    1
 8.0000e-002 5.0000e+000          3000   7     .1    .93   4.0000e-002    1
 8.0000e-002 5.0000e+000          5000   7     .1    .93   4.0000e-002    1
 8.0000e-002 5.0000e+000          7000   7     .1    .93   2.0000e-002    1
 8.0000e-002 5.0000e+001          3000   7     .1    .93   3.0000e-002    1
 8.0000e-002 5.0000e+001          5000   7     .1    .93   3.0000e-002    1
 8.0000e-002 5.0000e+001          7000   7     .1    .93   1.5000e-002    1
 2.0000e-001 5.0000e-001          3000   7     .1    .93   3.0000e-002    1
 2.0000e-001 5.0000e-001          5000   7     .1    .93   3.0000e-002    1
 2.0000e-001 5.0000e-001          7000   7     .1    .93   1.5000e-002    1
 2.0000e-001 5.0000e+000          3000   7     .1    .93   4.0000e-002    1
 2.0000e-001 5.0000e+000          5000   7     .1    .93   4.0000e-002    1
 2.0000e-001 5.0000e+000          7000   7     .1    .93   2.0000e-002    1
 2.0000e-001 5.0000e+001          3000   7     .1    .93   3.0000e-002    1
 2.0000e-001 5.0000e+001          5000   7     .1    .93   3.0000e-002    1
 2.0000e-001 5.0000e+001          7000   7     .1    .93   1.5000e-002    1
 4.0000e-001 5.0000e-001          3000   7     .1    .93   3.0000e-002    1
 4.0000e-001 5.0000e-001          5000   7     .1    .93   3.0000e-002    1
```

```
4.0000e-001 5.0000e-001      7000    7     .1     .93     1.5000e-002     1
4.0000e-001 5.0000e+000      3000    7     .1     .93     4.0000e-002     1
4.0000e-001 5.0000e+000      5000    7     .1     .93     4.0000e-002     1
4.0000e-001 5.0000e+000      7000    7     .1     .93     2.0000e-002     1
4.0000e-001 5.0000e+001      3000    7     .1     .93     3.0000e-002     1
4.0000e-001 5.0000e+001      5000    7     .1     .93     3.0000e-002     1
4.0000e-001 5.0000e+001      7000    7     .1     .93     1.5000e-002     1
8.0000e-001 5.0000e-001      3000    7     .1     .93     3.0000e-002     1
8.0000e-001 5.0000e-001      5000    7     .1     .93     3.0000e-002     1
8.0000e-001 5.0000e-001      7000    7     .1     .93     1.5000e-002     1
8.0000e-001 5.0000e+000      3000    7     .1     .93     4.0000e-002     1
8.0000e-001 5.0000e+000      5000    7     .1     .93     4.0000e-002     1
8.0000e-001 5.0000e+000      7000    7     .1     .93     2.0000e-002     1
8.0000e-001 5.0000e+001      3000    7     .1     .93     3.0000e-002     1
8.0000e-001 5.0000e+001      5000    7     .1     .93     3.0000e-002     1
8.0000e-001 5.0000e+001      7000    7     .1     .93     1.5000e-002     1
```

```
/*postprc4.c  Sorts the values of an output parameter of snfpkg.c and
 *computs a CDF from the probabilities associated with each value.
 *This version handles 4 output parameters simultaneously, plus the
 *probability.  */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#define NUMCASES 100
#define PARAMS 4 //The fscanf must be changed if this is changed.

void main()
{int i,j,k,num,sorted,swapped;
float vals[PARAMS][NUMCASES];
char dummy[100];
float probs[NUMCASES]={0},ftemp,sum=0;
FILE *fin,*fout;
fin=fopen("summary.out","r");
fout=fopen("postproc.out","w");
i=0;
fgets(dummy,99,fin); //Readthrough header
while(fscanf(fin,"%f %f %f %f %f",&vals[0][i],  //Only valid for PARAMS=4.
       &vals[1][i],&vals[2][i],&vals[3][i],&probs[i])!=EOF)i++;
num=i;          //number of records to be sorted
fprintf(fout,"%12s%12s%12s\n","Value","Prob","Cume");
for(k=0;k<PARAMS;k++)         //loop all the parameter sets
 {sorted=0;
 i=0;
 while((sorted==0)&&(i<num-1))
  {swapped=0;
  for(j=0;j<num-1-i;j++)         //basic sort loop
    if(vals[k][j]>vals[k][j+1])
      {ftemp=vals[k][j];         //swap value-probability pair
      vals[k][j]=vals[k][j+1];
      vals[k][j+1]=ftemp;
      ftemp=probs[j];
      probs[j]=probs[j+1];
      probs[j+1]=ftemp;
      swapped=1;}
  if (swapped==0) sorted=1;
  i++;}
 for(i=0;i<num;i++)
  {sum+=probs[i];
  if(k%2==0)  //different output format for integer and float parameters
    fprintf(fout,"%12.1f%12.6f%12.6f\n",vals[k][i],probs[i],sum);
  else fprintf(fout,"%12.6f%12.6f%12.6f\n",vals[k][i],probs[i],sum);}
 sum=0;                  //reset for next output parameter
 fprintf(fout,"\n");}}
```

```
summary.out
 Crrsn Rte  Kthrshld   TPPCF U    PPCF U   TPPCF S    PPCF S      Prob
      0.08     0.910     46000   0.03532     48000   0.10914   1.00000
      0.08     0.920     48000   0.03162     48000   0.08337   1.00000
      0.08     0.930     46000   0.02696     48000   0.06145   1.00000
      0.08     0.950     48000   0.01904     48000   0.03576   1.00000
      0.08     1.000     48000   0.01195     48000   0.01578   1.00000
```

```
0.20     0.910     20000    0.04520     20000    0.15074    1.00000
0.20     0.920     20000    0.03669     20000    0.10488    1.00000
0.20     0.930     20000    0.03254     20000    0.07499    1.00000
0.20     0.950     20000    0.02325     20000    0.04052    1.00000
0.20     1.000     20000    0.01263     20000    0.01782    1.00000
0.40     0.910     12000    0.04569     10000    0.15949    1.00000
0.40     0.920     14000    0.03744     12000    0.11182    1.00000
0.40     0.930     14000    0.03321     10000    0.07891    1.00000
0.40     0.950     16000    0.02355     12000    0.04176    1.00000
0.40     1.000     14000    0.01263     12000    0.01785    1.00000
0.80     0.910     12000    0.04569     10000    0.15949    1.00000
0.80     0.920     14000    0.03744     12000    0.11182    1.00000
0.80     0.930     14000    0.03322     10000    0.07891    1.00000
0.80     0.950     16000    0.02355     12000    0.04176    1.00000
0.80     1.000     14000    0.01263     12000    0.01785    1.00000
2.00     0.910      2000    0.08461     10000    0.15949    1.00000
2.00     0.920      2000    0.06294     12000    0.11182    1.00000
2.00     0.930      2000    0.04530     10000    0.07891    1.00000
2.00     0.950      2000    0.03311     12000    0.04176    1.00000
2.00     1.000      2000    0.01480     12000    0.01785    1.00000
4.00     0.910      2000    0.08461     10000    0.15949    1.00000
4.00     0.920      2000    0.06294     12000    0.11182    1.00000
4.00     0.930      2000    0.04530     10000    0.07891    1.00000
4.00     0.950      2000    0.03311     12000    0.04176    1.00000
4.00     1.000      2000    0.01480     12000    0.01785    1.00000
```

```
postproc.out
     Value         Prob         Cume
   10000.0     0.015000     0.015000
   10000.0     0.020000     0.035000
   10000.0     0.015000     0.050000
   10000.0     0.015000     0.065000
   10000.0     0.020000     0.085000
   10000.0     0.015000     0.100000
   12000.0     0.030000     0.130000
   12000.0     0.040000     0.170000
   12000.0     0.030000     0.200000
   12000.0     0.030000     0.230000
   12000.0     0.040000     0.270000
   12000.0     0.030000     0.300000
   14000.0     0.030000     0.330000
   14000.0     0.040000     0.370000
   14000.0     0.030000     0.400000
   14000.0     0.030000     0.430000
   14000.0     0.040000     0.470000
   14000.0     0.030000     0.500000
   18000.0     0.030000     0.530000
   18000.0     0.030000     0.560000
   18000.0     0.015000     0.575000
   18000.0     0.040000     0.615000
   18000.0     0.040000     0.655000
   18000.0     0.020000     0.675000
   18000.0     0.030000     0.705000
   18000.0     0.030000     0.735000
   18000.0     0.015000     0.750000
   44000.0     0.030000     0.780000
```

```
     44000.0      0.030000      0.810000
     44000.0      0.015000      0.825000
     44000.0      0.040000      0.865000
     44000.0      0.040000      0.905000
     44000.0      0.020000      0.925000
     44000.0      0.030000      0.955000
     44000.0      0.030000      0.985000
     44000.0      0.015000      1.000000

    0.026980      0.015000      0.015000
    0.026980      0.015000      0.030000
    0.026980      0.030000      0.060000
    0.027790      0.020000      0.080000
    0.027790      0.020000      0.100000
    0.027790      0.040000      0.140000
    0.028150      0.015000      0.155000
    0.028150      0.015000      0.170000
    0.028150      0.030000      0.200000
    0.032160      0.030000      0.230000
    0.032160      0.030000      0.260000
    0.032160      0.030000      0.290000
    0.032540      0.040000      0.330000
    0.032540      0.040000      0.370000
    0.032540      0.040000      0.410000
    0.033160      0.030000      0.440000
    0.033160      0.030000      0.470000
    0.033160      0.030000      0.500000
    0.033210      0.030000      0.530000
    0.033210      0.030000      0.560000
    0.033210      0.015000      0.575000
    0.033210      0.040000      0.615000
    0.033210      0.040000      0.655000
    0.033210      0.020000      0.675000
    0.033210      0.030000      0.705000
    0.033210      0.030000      0.735000
    0.033210      0.015000      0.750000
    0.033220      0.030000      0.780000
    0.033220      0.030000      0.810000
    0.033220      0.015000      0.825000
    0.033220      0.040000      0.865000
    0.033220      0.040000      0.905000
    0.033220      0.020000      0.925000
    0.033220      0.030000      0.955000
    0.033220      0.030000      0.985000
    0.033220      0.015000      1.000000

      6000.0      0.020000      0.020000
      6000.0      0.015000      0.035000
      8000.0      0.040000      0.075000
      8000.0      0.030000      0.105000
     10000.0      0.040000      0.145000
     10000.0      0.040000      0.185000
     10000.0      0.020000      0.205000
     10000.0      0.030000      0.235000
     10000.0      0.030000      0.265000
     10000.0      0.015000      0.280000
```

10000.0	0.040000	0.320000
10000.0	0.030000	0.350000
18000.0	0.030000	0.380000
18000.0	0.030000	0.410000
18000.0	0.030000	0.440000
20000.0	0.040000	0.480000
20000.0	0.040000	0.520000
20000.0	0.040000	0.560000
22000.0	0.030000	0.590000
22000.0	0.030000	0.620000
22000.0	0.015000	0.635000
26000.0	0.030000	0.665000
26000.0	0.030000	0.695000
26000.0	0.015000	0.710000
32000.0	0.030000	0.740000
32000.0	0.030000	0.770000
32000.0	0.030000	0.800000
44000.0	0.015000	0.815000
44000.0	0.015000	0.830000
44000.0	0.030000	0.860000
46000.0	0.020000	0.880000
46000.0	0.020000	0.900000
46000.0	0.040000	0.940000
56000.0	0.015000	0.955000
56000.0	0.015000	0.970000
56000.0	0.030000	1.000000

0.058350	0.040000	0.040000
0.058940	0.015000	0.055000
0.059190	0.020000	0.075000
0.060970	0.040000	0.115000
0.061450	0.040000	0.155000
0.061450	0.030000	0.185000
0.061720	0.030000	0.215000
0.061720	0.030000	0.245000
0.062770	0.020000	0.265000
0.069070	0.030000	0.295000
0.070060	0.040000	0.335000
0.070640	0.015000	0.350000
0.071230	0.015000	0.365000
0.072240	0.030000	0.395000
0.072640	0.030000	0.425000
0.072640	0.030000	0.455000
0.073130	0.030000	0.485000
0.073130	0.015000	0.500000
0.074020	0.030000	0.530000
0.074020	0.040000	0.570000
0.074020	0.015000	0.585000
0.074990	0.030000	0.615000
0.074990	0.040000	0.655000
0.076180	0.040000	0.695000
0.078280	0.015000	0.710000
0.078280	0.030000	0.740000
0.078830	0.030000	0.770000
0.078830	0.030000	0.800000
0.078910	0.030000	0.830000

```
0.078910     0.030000     0.860000
0.078910     0.020000     0.880000
0.078910     0.020000     0.900000
0.078910     0.040000     0.940000
0.078910     0.015000     0.955000
0.078910     0.015000     0.970000
0.078910     0.030000     1.000000
```

```
/*loadcurv.c program to evaluate loading curves against the EIA database of
 *expected discharges as expressed by WSM expected deliveries.  Presently
 *has kinf as calculated from the ORNL regression (which would be evaluated
 *at 10 years and the keff peak (over all times) from the "Criticality
 *Evaluation of Degraded Internal Configuraitons of the PWR AUCF WP
 *Designs."*/
#include <string.h>
#include <stdlib.h>
#include <stdio.h>
#include <math.h>
#include <malloc.h>
#include <string.h>
#include <ctype.h>

float getfloat();
int getint();
FILE *ferr;
long int numassy=0;/*Counts total assemblies processed (PWR, 1st repository)*/

void main()
{int i,j,k=0,ndyr,/*Yr of discharge from reactor; not used*/
   npyr,          /*Yr delivered to the repository; not used*/
   na,            /*number of assy in this batch          */
   nb,            /*index for burnup bin                  */
   nk,            /*index for kinf bin                    */
   nr;            /*index for enrichment bin              */
float b,          /*burnup for this batch of SNF          */
   w,             /*total MTU in this batch               */
   a,             /*Enrichment for this batch             */
   c,             /*Age since dschg, set to 10 yrs        */
   kinf,/*Neutron multiplication factor for an infinite lattice of this assy type*/
   keff,

   kinf12=0,kinf13=0,kinf14=0,keff91=0,keff92=0,keff93=0,keff95=0,keff1=0,
   co[10]={0},
   testfrac[10]={0},
   testks[]={.91,.92,.93,.95,1.0},
   wtotal=0; /*Total mass of this batch;  Not used  in this version*/
FILE *fout,       /*Output for this run*/
   *fin;          /*Input: EIA/WSM commercial SNF history and forecast;
                        processing by WSM for format only*/
char buffer[300],      /*temporary for reading input file  */
  type,                /* B or P                           */
  rname[30];           /* Name of reactor site (not used this version)*/
co[0]=.640653056;      //Keff regression (time independent, worst case)
co[1]=-.010291212;
co[2]=.300169252;
co[3]=-2.54581e-05;
co[4]=-.049092949;
co[5]=9.92025e-07;
co[6]=.003645209;
if ((fin=fopen("data.in","r"))==NULL)
  {printf("Can't open input file\n");exit(0);}
fout=fopen("loadcurv.out","w");
ferr=fopen("junk.out","w");    /*To record anomalous assemblies*/
c=10;                          /*arbitrary age for all SNF; used in kinf calc*/
```

```
while(fgets(buffer,300,fin)!=NULL)
  {w=getfloat(buffer,21,10);  /*Total MTU in this batch        */
  b=getfloat(buffer,51,10);   /*Burnup in MWd/MTU              */
  ndyr=getint(buffer,71,8);   /*Year of discharge from reactor (not used)*/
  npyr=getint(buffer,287,4);  /*Year of delivery to repository (not used)*/
  type=buffer[123];           /*BWR or PWR (1st character)     */
  na=getint(buffer,31,10);    /*number of assemblies this batch */
  a=getfloat(buffer,41,10);   /*initial enrichment             */
  strncpy(rname,buffer+1,20); /*reactor name (not used)        */
  rname[20]='\0';
  if(type=='P')               /*Process PWR only               */
    {wtotal+=w;               /*Increment total MTU processed */
    numassy+=na;              /*Increment number of assemblies processed */
    b/=1000;            /*Burnup reduced to GWd/MTU (for use in regression)*/
    kinf=1.06-.01*b-.002*c+.114*a+.00007081*b*b+.00007565*c*c
          -.007*a*a-.0002671*b*a-.0001145*b*c+.0002318*c*a+
           .000009366*b*c*a; /*Regression from ORNL study */
    keff=co[0]+co[1]*b+co[2]*a+co[3]*b*b+co[4]*a*a+co[5]*b*b*b+co[6]*a*a*a;//John's load
curve
    if(kinf<1.13)
      for(i=0;i<5;i++) if(keff>testks[i])testfrac[i]+=na;
    if(kinf>1.12)
      {kinf12+=na;
      if(kinf>1.13)
        {kinf13+=na;
        if(kinf>1.14)kinf14+=na;}}
    if(keff>.91)
      {keff91+=na;
      if(keff>.92)
       {keff92+=na;
       if(keff>.93)
        {keff93+=na;
        if(keff>.95)
          {keff95+=na;
          if(keff>1.0)keff1+=na;}}}}}}
for(i=0;i<5;i++)testfrac[i]/=numassy;
kinf12/=numassy;
kinf13/=numassy;
kinf14/=numassy;
keff91/=numassy;
keff92/=numassy;
keff93/=numassy;
keff95/=numassy;
keff1/=numassy;
fprintf(fout,"Fractions of PWR fuel having Kinf above the indicated value\n");
fprintf(fout,"kinf12 frac=%f\n",kinf12);
fprintf(fout,"kinf13 frac=%f\n",kinf13);
fprintf(fout,"kinf14 frac=%f\n",kinf14);
fprintf(fout,"\nFractions of PWR fuel having Keff above the indicated value\n");
fprintf(fout,"keff91 frac=%f\n",keff91);
fprintf(fout,"keff92 frac=%f\n",keff92);
fprintf(fout,"keff93 frac=%f\n",keff93);
fprintf(fout,"keff95 frac=%f\n",keff95);
fprintf(fout,"keff1 frac=%f\n",keff1);
fprintf(fout,"\nFractions of PWR fuel having Kinf<1.13 but Keff above the indicate
value\n");
```

```
for(i=0;i<5;i++)fprintf(fout,"testfrac%d=%f\n",i,testfrac[i]);}


float getfloat(string, start, length)  /*Extract floating point from buffer */
char string[300];
int start,length;
{char temp[20];
int i;
for(i=start;i<start+length;i++) temp[i-start]=string[i];
temp[length]='\0';
return(atof(temp));}

int getint(string, start, length)    /*Extract integer from buffer   */
char string[300];
int start,length;
{char temp[20];
int i;
for(i=start;i<start+length;i++) temp[i-start]=string[i];
temp[length]='\0';
return(atoi(temp));}
```

```
loadcurv.out
Fractions of PWR fuel having Kinf above the indicated value
kinf12 frac=0.045079
kinf13 frac=0.036822
kinf14 frac=0.033058

Fractions of PWR fuel having Keff above the indicated value
keff91 frac=0.184952
keff92 frac=0.137038
keff93 frac=0.111628
keff95 frac=0.073126
keff1 frac=0.040570

Fractions of PWR fuel having Kinf<1.13 but Keff above the indicate value
testfrac0=0.148130
testfrac1=0.100216
testfrac2=0.074807
testfrac3=0.036305
testfrac4=0.005322
```

Water Drop Penetration Depth

Density of water at 27°C $\rho s := 995.8\cdot\frac{kg}{m^3}$

Viscosity of water at 27°C $\mu := 8.6\cdot 10^{-4}\cdot\frac{kg}{m\cdot sec}$ (See Sect. 4.1.6 for Refs.)

Density of Air $\rho f := 1.1774\cdot\frac{kg}{m^3}$

Terminal velocity as a function of diameter for small sphere's using Stoke's law (Re<=1) from From Ref. 5.36, p. 461

$$Fd = m\cdot g - Fb$$

$$3\cdot\pi\cdot\mu\cdot v\cdot D = \rho s\cdot\frac{4}{3}\cdot\pi\cdot\left(\frac{D}{2}\right)^3\cdot g - \rho f\cdot g\cdot\frac{4}{3}\cdot\pi\cdot\left(\frac{D}{2}\right)^3$$

Solving for v yields

$$v(D) := \frac{1}{18}\cdot D^2\cdot g\cdot\frac{(\rho s - \rho f)}{\mu} \qquad Re(D) := \frac{v(D)\cdot D\cdot\rho f}{\mu}$$

$v(3\cdot mm) = 5.671\cdot m\cdot sec^{-1}$

$Re(3\cdot mm) = 23.291$ (note that terminal velocity for 3 mm will be a little slower than indicated because Re is just outside the limit for using Stoke's law)

$v(1\cdot mm) = 0.63\cdot m\cdot sec^{-1}$

$Re(1\cdot mm) = 0.863$

Calculation of Penetration Depth using Viscous Drag

$$m\cdot a = m\cdot g - 3\cdot\pi\cdot\mu\cdot D\cdot v$$

Neutral buoyancy so mg = 0

$$m\cdot\frac{d}{dt}v + 3\cdot\pi\cdot D\cdot v = 0 \qquad v(0) = v_0 \qquad v = v_0\cdot e^{\frac{-3\cdot\pi\cdot\mu\cdot D}{\rho\cdot\frac{4}{3}\cdot\pi\cdot\left(\frac{D}{2}\right)^3}\cdot t}$$

$$x = \int_0^{\infty} v_0\cdot e^{\frac{-3\cdot\pi\cdot\mu\cdot D}{\rho\cdot\frac{4}{3}\cdot\pi\cdot\left(\frac{D}{2}\right)^3}\cdot t}\,dt$$

$$x = \frac{v_0}{\frac{3\cdot\pi\cdot\mu\cdot D}{\rho\cdot\frac{4}{3}\cdot\pi\cdot\left(\frac{D}{2}\right)^3}} \qquad Pen(D) := \frac{v(D)}{18\cdot\frac{\mu}{\left(D^2\cdot\rho s\right)}}$$

$Pen(3\cdot mm) = 3.283\cdot m$

$Pen(1\cdot mm) = 0.041\cdot m$

Diffusion of Boron in Solution

No diffusion coefficient available in for HBO_3 in water, so coefficients for substances similar in size are used:

size are used:	For Cl_2	D=1.22×10^{-5} cm^2/sec
(assumption 4.3.5)	For O_2	D=1.80×10^{-5} cm^2/sec
	For HNO_3	D=2.64×10^{-5} cm^2/sec (see Section 4.1.6 for Refs.)

$A := \pi\cdot\left(\frac{1.41\cdot m}{2}\right)^2\cdot .8$ $A = 1.249\cdot m^2$ Cross sectional area free for diffusion parallel to WP axis (WP inner barrier ID cross section 80% full)

$dx := \frac{4.585\cdot m}{2}$ $dx = 2.293\cdot m$ Distance from inner end of WP to center

Concentration gradient with zero at point of flushing: $dC := 1\cdot\frac{kg}{m^3}$

Fick's Law of Diffusion: $Flux(D) := A\cdot D\cdot\frac{dC}{dx}$

$$Flux\left(1.2\cdot10^{-5}\cdot\frac{cm^2}{sec}\right) = 6.539\cdot10^{-10}\cdot kg\cdot sec^{-1} \qquad Flux\left(2.6\cdot10^{-5}\cdot\frac{cm^2}{sec}\right) = 1.417\cdot10^{-9}\cdot kg\cdot sec^{-1}$$

$$\frac{1\cdot kg}{Flux\left(1.2\cdot10^{-5}\cdot\frac{cm^2}{sec}\right)} = 48.464\cdot yr \qquad \frac{1\cdot kg}{Flux\left(2.6\cdot10^{-5}\cdot\frac{cm^2}{sec}\right)} = 22.368\cdot yr$$

WP Filling Time

WP void space = inner barrier internal volume - 21 PWR asssemblies - iron oxide volume

$WPvoid := 7.158\cdot m^3 - 21\cdot0.081\cdot m^3 - 1.792\cdot m^3$ $WPvoid = 3.665\cdot m^3$

(volumes from Ref. 5.5, p. III-1)

Time to fill at 5 mm/yr: $\frac{WPvoid}{0.05\cdot\frac{m^3}{yr}} = 73.3\cdot yr$

Time to fill at 50 mm/yr: $\frac{WPvoid}{0.5\cdot\frac{m^3}{yr}} = 7.33\cdot yr$

Exchange Efficiency Range

Low: $\frac{7.33 \cdot yr}{48 \cdot yr} = 0.153$

High: $\frac{73.3 \cdot yr}{22 \cdot yr} = 3.332$, but limited by 1

So range is approximately 0.1 to 1