ORNL/TM-2001/83

OAK RIDGE
NATIONAL LABORATORY

MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

A Stochastic Method for Estimating the Effect of Isotopic Uncertainties in Spent Nuclear Fuel

M. D. DeHart

UT-BATTELLE

ORNL-27 (4-00)

ORNL/TM-2001/83

Computational Physics and Engineering Division (10)

A Stochastic Method for Estimating the Effect of Isotopic Uncertainties in Spent Nuclear Fuel

M. D. DeHart

Oak Ridge National Laboratory,
P.O. Box 2008,
Oak Ridge, TN 37831-6370

Date Published: September 2001

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed and operated by
UT-Battelle, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The author acknowledges the following individuals for their various contributions which made this work possible: C. K. Bayne for his assistance in developing the statistical theory described in this report, J. J. Sapyta and J. Pegram of Framatome ANP for their comments and suggestions in the genesis of this study, S. W. Willoughby for installation and support of the MPI package on the local workstation cluster, and W. C. Carter for her high standards, attention to detail, and rapid preparation of this report. Finally, the author acknowledges the review and comments provided by C. V. Parks, C. K. Bayne, I. C. Gauld and J. C. Wagner.

ABSTRACT

This report describes a novel approach developed at the Oak Ridge National Laboratory (ORNL) for the estimation of the uncertainty in the prediction of the neutron multiplication factor for spent nuclear fuel. This technique focuses on burnup credit, where credit is taken in criticality safety analysis for the reduced reactivity of fuel irradiated in and discharged from a reactor. Validation methods for burnup credit have attempted to separate the uncertainty associated with isotopic prediction methods from that of criticality eigenvalue calculations. Biases and uncertainties obtained in each step are combined additively. This approach, while conservative, can be excessive because of aphysical assumptions employed. This report describes a statistical approach based on Monte Carlo sampling to directly estimate the total uncertainty in eigenvalue calculations resulting from uncertainties in isotopic predictions. The results can also be used to demonstrate the relative conservatism and statistical confidence associated with the method of additively combining uncertainties.

This report does not make definitive conclusions on the magnitude of biases and uncertainties associated with isotopic predictions in a burnup credit analysis. These terms will vary depending on system design and the set of isotopic measurements used as a basis for estimating isotopic variances. Instead, the report describes a method that can be applied with a given design and set of isotopic data for estimating design-specific biases and uncertainties.

1. INTRODUCTION

During the last decade, significant effort has been directed to improve estimates of the reactivity worth of spent nuclear fuel for storage and transportation. Currently, spent fuel storage in dry casks is licensed under the requirement that the cask would remain subcritical if loaded with fresh fuel. In other words, no credit is taken for the reduction in the fuel reactivity as a result of in-reactor burnup and post-irradiation decay. This approach can be improved by applying burnup credit (i.e., taking credit for some or all of the reactivity decrement associated with fuel burnup) allowing increased cask loading or loading with higher initial enrichments than would be possible if all fuel were assumed to be fresh. Ongoing efforts in the U.S. seek to obtain licensing approval of burnup credit methods for cask design, for dry storage, transportation, and disposal applications.

Although the isotopic contents of fresh fuel are well quantified from the manufacturing process, the contents of spent fuel cannot be directly determined without destructive assay. Thus burnup credit approaches rely on a calculated estimate of spent fuel isotopic compositions that are used in subsequent criticality analyses. The two step process of calculating spent fuel contents followed by a criticality calculation must be validated in some manner to demonstrate that the calculations are accurate, and to quantify any biases and uncertainties between calculations and reality. Various validation approaches have been proposed, including both independent validation of each phase of the process and integral validation of depletion and criticality calculations together.

This report discusses an approach for assessing the net effect of biases and uncertainties associated with depletion calculations together with those associated with the predicted neutron multiplication factor (k). Such validation requires that any biases and uncertainties in the ability to predict isotopic concentrations be determined by comparison between calculations and measured data. However, the approach used in applying nuclide biases and uncertainties to obtain a conservative estimate of the neutron multiplication factor for a spent fuel configuration is not defined in any regulatory guidance or standard. The approach proposed by the United States Department of Energy (U.S. DOE) in support of transportation and storage burnup credit[1,2] takes a very conservative approach by assuming all nuclides are at statistical extremes simultaneously. In other words, given biases and uncertainties determined from the comparison of calculated and measured data for a set of nuclides, the calculated concentrations for each nuclide are corrected by applying the bias, the uncertainty, and a multiplier on the uncertainty, so as to maximize predictions of fissile nuclides and minimize those of absorbers. This results in a conservative bound for the reactivity worth of spent fuel.

There is no reason to expect that actual nuclide inventories will vary from calculated predictions is such a manner. The bounding approach described above will yield concentrations that, when used in a criticality calculation, will provide an upper estimate on the value of k for the configuration analyzed. Similarly, setting concentrations to the opposite extreme by minimizing fissile concentrations and maximizing absorber concentrations will result in a lower bound on k. The true value of k is expected to lie between these two extremes.

This report describes a method developed to assess the uncertainty in the computationally-predicted value of *k* in terms of quantified uncertainties in isotopic concentrations. Estimates of isotopic biases and uncertainties in depletion calculations are obtained based on comparison between calculated and measured nuclide concentrations performed for a limited set of spent fuel samples.[3] The goal is to obtain, with a statistical confidence, a best estimate and associated uncertainty for *k* for a subcritical system. A conservative upper limit on the value of *k* for that system can then be established without the excessive conservatism associated with other approaches.

Analyses described herein were performed to assess the uncertainty in the neutron multiplication factor in both a finite cask configuration (k_{eff}) and in an infinite lattice of pin cells (k_{inf}). For simplicity, the neutron multiplication factor will be referred to as simply *k* in the following sections of this report.

2. STATISTICAL BACKGROUND

In practice, the key parameter of interest for criticality safety in a spent nuclear fuel system is the neutron multiplication factor, *k*, to ensure an adequate subcritical margin. Proposed approaches[1,2] apply nuclide uncertainties in a bounding manner to conservatively estimate nuclide concentrations to be used in a subsequent criticality calculation. However, an alternate approach would be to estimate the uncertainty in *k* directly with respect to individual nuclide concentrations. In setting calculated isotopic concentrations to their conservative limits, one is confident that one can conservatively estimate the reactivity of a spent fuel system. However, if one were to randomly vary spent fuel isotopics independently within the range of their estimated uncertainties, calculate the neutron multiplication factor for a given fuel configuration, and repeat this process multiple times, one would obtain a normal distribution of *k* values corresponding to random variations in expected concentrations. The distribution itself will have a standard deviation, which can be used to set a confidence level on the prediction of *k*. To be meaningful; however, the selection of multiple random isotopic concentrations must be based on and representative of the expected bias and uncertainty associated with the calculated prediction of isotopic concentrations.

In the calculation of *k* for a spent fuel system, nuclide concentrations are first estimated using a depletion method. The depletion method itself can be validated by comparison of measured spent fuel isotopic concentrations to corresponding concentrations calculated in a computational depletion model of the fuel sample. This process is repeated for as many spent fuel samples as possible. Given the measured (M_i) and corresponding computed (C_i) isotopic concentrations for each nuclide *i* in each of *n* spent fuel samples, with a measured-to-computed ratio $X_i = M_i/C_i$, one can calculate an average measured-to-computed ratio for each nuclide *i* as:

$$\overline{X}_i = \sum_{j=1}^{n} (M_{i,j} / C_{i,j}) / n \qquad (1)$$

An estimate of the standard deviation, s_i, associated with $\overline{X}_i$ is readily calculated as:

$$s_i = \sqrt{\frac{\sum_{j=1}^{n} \left(X_j^i - \overline{X}_i\right)^2}{n-1}} \qquad (2)$$

The estimated standard deviation represents the uncertainty in the prediction of $\overline{X}_i$. This uncertainty is due to random deviations resulting from modeling uncertainties, operational variations, design uncertainties, random measurement errors and other factors. For each $\overline{X}_i$, a corresponding s_i can be easily computed using Eq. (2). This statistical procedure is discussed in more detail in Ref. 4.

Given the average M/C ratio, $\overline{X}_i$, for a given isotope, one can improve the calculated estimate for a subsequent fuel depletion calculation by correcting the calculated concentration C using the relationship:

$$M_i^* = C_i^* \times \overline{X}_i. \tag{3}$$

M_i* is the isotopic concentration that would be expected for a measurement of a concentration that was calculated as C_i. However, the value of $\overline{X}_i$ is an estimate based on the limited *n* measurements, and has an associated uncertainty. In an approach to conservatively estimate an upper (MC_+*) or lower (MC_-*) bound for MC*, one may use $M_{i\pm}^* = C_i \cdot (\overline{X}_i \pm T_n \cdot s_i)$, where T is a tolerance factor assigned to bound the limits of $\overline{X}_i$ at a given confidence level; the value of T also depends on the number of measurements, *n*, used to calculate $\overline{X}_i$. Note that $\overline{X}_i$ and s_i are unique for each nuclide used.

The bounding approach described earlier sets fissile nuclide concentrations to the maximum of the range, and non-fissile absorber nuclide concentrations to the minimum of the range, where the range itself is determined on a nuclide by nuclide basis. In reality, we expect that for a calculated isotopic concentration of C for a given nuclide at a specific burnup state, the actual value M* of the isotopic concentration (if measured) would lie between MC_+* and MC_-* (to a specified level of confidence). Furthermore, there is reason to expect (because the distribution is largely if not wholly due to random errors) that for multiple measurements, values of M would be normally distributed within MC_+* and MC_-* with a mean value close to X. In fact, Ref. 5 suggests that M/C ratios are normally distributed when sufficient data points are available to test the distribution.

It is possible to generate a distribution of the expected measured concentration of a given nuclide if we modify Eq. (3) to allow us to randomly select from the expected range of $\overline{X}_i$, according to the following:

$$M_i^{*k} = C_i(\overline{X}_i + R_\sigma^k s_i) \tag{4}$$

Again, M_i^* represents the expected concentration for a calculated concentration C_i for nuclide *i* in spent fuel (i.e, the bias-corrected isotopic concentration). However, since we actually expect M_i^* to fall within a normal distribution characterized by s_i, Eq. (4) gives us a means to randomly sample from the expected range of M_i by calculating multiple instances (*k* = 1 to *N*). Note that R_σ is a random number selected from a normal distribution, i.e., the distribution of R_σ is not uniform in the range of –1 to 1, but instead has a mean of 0 and a standard distribution of 1. Given adequate sampling, the mean value of M_i^* over all M_i^{*k} would converge toward $C_i \times \overline{X}_i$, and 67% of the M_i^{*k} values would fall in the range of $\pm s_i$ of the mean.

A limitation in this approach is the assumption of a good estimate of the standard deviation for chemical assay measurements. Unfortunately, existing chemical assay data are limited for many isotopes. With sufficient measurements, we can have some confidence that s_i for the set of samples is a reasonable approximation of σ_i for the population of all spent fuel. However, if a limited number of measurements are available, we must account for uncertainty in s_i, the estimate of σ_i. In the bounding approach described in Ref. 4, a tolerance factor was applied as a multiplier to set an upper estimate on the standard deviation; the tolerance factor is selected based on the number of measurments available and the desired confidence level. Simply put, an upper estimate on s, s_{max}, is defined as:

$$s_{i,\max} = s_i \times T_{95/95}(n_i), \tag{5}$$

where n_i is the number of measurements for nuclide *i* used as a basis for the calculation of s_i, and $T_{95/95}$ represents a tolerance factor statistically derived to bound 95% of the population at a 95% confidence level. However, to apply this formulation in Eq. (4), one other change is necessary. The random number function R_σ of Eq. (4) is designed to normally distribute calculated M_i^{*k} values about the expected mean. However, when insufficient data are available to accurately determine the mean and standard deviation, it is more conservative to assume that the M_i^{*k} values vary randomly and uniformly within the bounds set by $M_i^* \pm s_{i,max}$. Hence, for nuclides with limited available data, Eq. (4) is rewritten as:

$$M_i^{*k} = C_i \left[\overline{X}_i + R_u^k s_i T_{95/95}(n_i) \right], \tag{6}$$

where R_u is a random number selected uniformly within the range –1 to 1.

Although both Eqs. (4) and (6) provide a randomized concentration, the concentration is quite clearly constrained. The term "random concentration" used in this report refers to nuclide concentrations that are random within well quantified criteria that represent the random variations around an expected mean. Equation (6) limits concentrations to bounds defined by $C_i \left[\overline{X}_i \pm s_i T_{95/95}(n_i) \right]$. And although R_σ of Eq. (4) can vary within the range of $-\infty$ to $+\infty$, the mean is constrained to zero, and the distribution is normalized with a standard deviation of 1, so that 99.5% of all modified concentrations would be found in the range of $C_i \left(\overline{X}_i \pm 3s_i \right)$. Additionally, since negative nuclide concentrations are not physically possible, any modified concentration calculated to be less than zero is set to zero.

For this study, it is assumed that predicted nuclide concentrations are themselves interdependent, and dependencies of one nuclide on others are manifest as a predictive bias. However, *variations* in these concentrations are independent of variations in concentrations for other nuclides, i.e., variations around the bias are random and independent of the variations observed for other nuclides. Under this assumption, one can then estimate the maximum potential variation in k due to variations in nuclide concentrations by simultaneously varying nuclide concentrations within expected bounds for each nuclide using Eqs. (4) and (6). The following section describes the approach used to vary isotopic concentrations in a single criticality calculation, together with the procedure used to automate the preparation and processing of a large number of such criticality calculations. This set of calculations will provide a statistical estimate of the expected value of k for a given configuration, together with an estimate of the uncertainty in k due to isotopic uncertainties.

3. APPROACH

In order to apply the formulations developed earlier, values of $\overline{X}_i$ and s_i must be determined for each nuclide that is to be included in a criticality model. If isotopic assay data are not available for a given nuclide, it is not appropriate to include it in this type of analysis. For this work, results of validation analyses with the SAS2H[6] sequence of SCALE and the ENDF/B-V-based 44-group cross-section library[7] were used, as provided in Table 22 of Ref. 4. Values of $\overline{X}$, s, n, and $T_{95/95}$ (for $n \leq 10$) from this reference are listed in Table 1.

In order to converge on the value of *k* for a given configuration, a large number of independent calculations is necessary. Although it departs from the nature of Monte Carlo calculations typically applied in criticality safety analysis, the approach described here is a Monte Carlo analysis where the neutron multiplication factor *k* is generated by a sequence of batches, each batch being a set of randomly varied isotopic concentrations. A sufficient number of batches (or histories) is necessary to obtain a convergence.

To serve this need, the computer code KRONOS was developed to automate the process of setting up, executing, and parsing the output of a large number of independent calculations with either the CSAS1X (1-D XSDRNPM) or the CSAS25 (3-D KENO V.a) sequences of SCALE.[8] KRONOS was developed and compiled using parallelization routines of MPI (Message Passing Interface)[9] to allow simultaneous execution of a number of calculations on a distributed network to improve execution time. A listing of the source for KRONOS is included in Appendix A.

KRONOS was developed to perform calculations based on a single input specification. Given a SCALE input listing (either CSAS1X or CSAS25 format), KRONOS identifies actinides and fission products in the fuel material specifications. Fuel isotopic concentrations, represented as C_i in Eqs. (4) and (6), are stored and represent the baseline input case. For each of a sequence of criticality calculations, KRONOS applies Eq. (4) for nuclides with $n > 10$, and Eq. (6) for nuclides with $n \leq 10$. (The choice of 10 measurements as a cutoff is somewhat arbitrary, although it is based on experience that demonstrates a chi-squared-tested normal distribution with 6–9 measurements.) All fuel nuclide concentrations are modified simultaneously and independently, using a random number generated from a normal distribution when applying Eq. (4), and from a uniform distribution when applying Eq. (6). For models with an axial burnup distribution, nuclide concentrations were modified independently in each axial zone. In each individual criticality calculation, the appropriate input [either a one-dimensional (1-D) CSAS1X or a 3-D CSAS25 model] is prepared based on the configuration specified in the initial input model, but with modified isotopic concentrations. The criticality calculation is executed as a normal SCALE calculation. Once a calculation is completed the resulting output file is parsed to read the calculated eigenvalue, and a new case is generated and submitted for execution. This process is repeated until a specified number of calculations have been completed.

Table 1. Validation results used in uncertainty analyses

Nuclide	$\overline{X}$	s	n	$T_{95/95}$	Nuclide	$\overline{X}$	s	n	$T_{95/95}$
Am-241[a]	1.1420	0.176	9	3.031	Am-243[a]	1.0491	0.066	6	3.708
Cm-242[a]	1.3916	0.087	15		Cm-243[a]	1.0266	0.063	9	3.031
Cm-244[a]	1.1090	0.053	15		Cs-133	0.9759	0.009	3	7.656
Cs-135	0.9471	0.029	9	3.031	Eu-151	0.7584	0.033	3	7.656
Eu-153	0.9395	0.039	3	7.656	Eu-154	1.2735	0.070	9	3.031
Eu-155	1.3586	0.109	3	7.656	Gd-154	1.0144	0.035	3	7.656
Gd-155	1.3586	0.109	3	7.656	Nd-143	1.0000	0.005	3	7.656
Nd-145	1.0032	0.004	3	7.656	Nd-148	0.9992	0.018	16	
Np-237[a]	0.9484	0.094	13		Pm-147	1.0170	0.042	3	7.656
Pu-238[a]	1.0338	0.077	24		Pu-239[a]	1.0142	0.029	38	
Pu-240[a]	1.0030	0.027	38		Pu-241[a]	1.0119	0.035	38	
Pu-242[a]	0.9875	0.064	34		Sm-147	1.0170	0.042	3	7.656
Sm-149	1.5095	0.406	3	7.656	Sm-150	1.0018	0.050	3	7.656
Sm-151	0.7584	0.033	3	7.656	U-234[a]	0.9829	0.133	14	
U-235[a]	1.0104	0.035	38		U-236[a]	1.0132	0.048	38	
U-238[a]	1.0026	0.005	32						

[a] Nuclides used in actinide-only analysis.

In addition to the sequence of shuffled-concentration criticality calculations, four additional reference calculations are performed. The first uses *nominal* isotopics, i.e., the set originally specified in the user-supplied case. The second uses *biased* isotopics, with the original nominal concentrations corrected to expected values by multiplication by $\overline{X}_i$. The third calculates a *maximum* value of *k* using the upper estimate of fissile nuclide concentrations and the lower estimate of non-fissile nuclide concentrations, using the bounding approach described earlier. Finally, a fourth case calculates the minimum value of *k* in a similar fashion, by minimizing fissile and maximizing non-fissile concentrations.

Note that nuclide concentrations correspond to a specific burnup history, and must be prepared using the same codes and data used to determine the bias ($\overline{X}$) and uncertainty (s) used in subsequent analysis. In this case, depletion calculations were performed using SAS2H and the SCALE 44-group library, consistent with the results of Table 1.

4. PARALLEL PROCESSING

This section provides an overview of the implementation of parallel processing within KRONOS. It does not provide a detailed description of the logic required for parallel implementation, nor does it describe the MPI-specific calls that are embedded in the KRONOS source code. Reference 9 provides all the detail needed to understand the parallel functionality of KRONOS. This section is merely intended to give an overview of the features of this parallel code to provide a better understanding of the advantages of this type of implementation.

Through the use of calls to MPI in KRONOS, it is possible to run a large number of SCALE calculations in parallel on a distributed network of computational platforms. All of the calculations described in this report were performed using 1000 independent calculations with randomly-varied concentrations, plus the four reference calculations described earlier. Assuming 30 CPU-minutes to perform cross-section processing and KENO analysis for a cask model, 1004 cases would require almost 3 weeks to process on a dedicated CPU. Running in parallel on 20 machines would reduce the execution time to something on the order of 1–2 days, even with competing calculations running on the same machines.

KRONOS is designed to function in a master/slave mode of operation. The single master process is responsible for reading in the initial input, generating a sequence of random numbers, creating each of the 1004 standard SCALE inputs, assigning cases to CPUs as they become available, parsing output from each completed case, and printing results. The only function of a slave processor is to set up a batch file to execute each case, then execute that batch file. The only communication needed between master and slave is the number of the next case to be processed, provided to each slave by the master, and a signal from each slave to the master indicating it has completed a calculation and that it is ready for a new case.

At the beginning of a KRONOS calculation, the "mpirun" command is used to specify the number of processors to use, the names of those machines, and the name of the executable on each machine. Given N+1 processors, the first is designated as the master, and the remaining N processors function as slaves. After initial setup, the master process provides a starting case to each of the N slave CPUs. It then sits idle and waits for any of the processes to complete. The processes can complete their assigned calculations in any order – once one calculation is complete on a given processor and it signals to the master processor that it is done, this slave processor is assigned the number of the next case to be processed. In this manner, each machine is able to process calculations as fast as it can, without being limited by slower or busier machines. It is possible for one CPU to complete several calculations while a different CPU processes a single case. This process continues until all cases have been provided to the various machines. After this point, when a slave machine completes a calculation, the master process passes a 0 back to the slave, telling it that there are no more cases to process. When all slave processes have returned their final results and terminated, the master process also terminates, completing the KRONOS calculation.

MPI itself is processor independent, so that different versions of KRONOS can be compiled on different computer architectures, and still operate and communicate with the master process. All that is necessary for KRONOS to operate on a given machine is the installation of MPI on that machine, as well as the availability of SCALE in its standard location. Because of the extremely small amount of data transmitted between processors (typically just two integers), the network speed between machines is not an issue. For the calculations described here, KRONOS was run on 14 different CPUs, consisting of 9 Compaq Alpha workstations (running OSF 4.0 and 5.0, and a wide range of processor speeds) and 5 IBM RS/6000 workstations. The older IBM machines ran at a much slower speed than most of the Alphas, but were rarely running other calculations and were therefore essentially dedicated. Additionally, because MPI allows more than one process on a single CPU, one CPU served to host both the master process and one of the slave processes, letting the slave process take advantage of the majority of the processing power available on that machine while the master process was idle.

Finally, it is worth mentioning that KRONOS was designed to "play well with others." Because of the number of simultaneous calculations occuring at a given time, and over an extended period of time, KRONOS has the ability to hamper the calculational efforts of other individuals using the same hardware. Therefore, SCALE calculations launched as child processes of each slave process were assigned an execution priority using the unix "nice" command. This allowed other users to utilitize most of the CPU processing power when running at the same time as a slave process on a given machine, but allowed KRONOS to use all available CPU cycles when not in use by others.

The power of parallel processing allowed the study of a number of different burnup states and modeling approximations in a reasonable amount of time. The following section describes the cases studied and the results of those analyses.

5. RESULTS

KRONOS calculations were performed for 30 different burnup/composition/modeling combinations. Table 2 provides a summary of the different analysis types and the uncertainty results associated with each set of calculations. Calculations were performed for two geometric configurations. The first was a generic burnup credit cask design for ongoing burnup credit studies.[10] This model consists of a 32 PWR assembly cask design fully loaded with Westinghouse 17×17 OFA fuel assemblies. The second model type was a simple pin-cell model, representing an infinite lattice of fuel pins of the Westinghouse 17×17 OFA design. Calculations with the cask model were performed using KENO V.a, while pin-cell calculations were performed using both KENO V.a and XSDRNPM. KENO V.a is a 3-D criticality code using a Monte Carlo simulation of neutron transport; XSDRNPM is a 1-D deterministic code for criticality calculations. For the KENO V.a pin-cell calculations, a full-length rod was assumed, with reflective boundary conditions on the cell boundaries and vacuum boundary conditions on the ends of the rods. Sample inputs for all three model/code calculations are included in Appendix B.

Calculations were also performed for isotopic concentrations predicted at burnups of 20, 40, and 60 GWd/MTU, both with and without fission products present. In each of the 3-D KENO V.a models, calculations were performed (1) assuming an axial burnup profile with a mean corresponding to nominal burnups listed earlier, using 18 uniform-height axial zones,[2] and (2) for a single uniform burnup. Because of the 1-D nature of XSDRNPM calculations, axially-varying concentrations cannot be easily modeled, and were not analyzed.

As described earlier, KRONOS first performs four calculations with specific isotopic sets, to obtain nominal, best-estimate, minimum and maximum values of *k* for the given case; 1000 cases were then calculated with randomly varying isotopic concentrations derived using the methods described earlier. The last two columns of Table 2 provide the mean value of *k* and the corresponding uncertainty associated with this value. The KRONOS standard deviation given in the last column characterizes the distribution of the set of calculated *k* values around the mean, and represents the uncertainty in the mean value of *k* **as a result of isotopic uncertainties**. This is different from the uncertainty associated with the calculation of each individual value of *k*. The uncertainty in the prediction of each eigenvalue for the individual Monte Carlo calculations is not listed in Table 2. This individual case uncertainty is a factor related to the number of histories run. Each KENO calculation was based on 1100 generations of neutrons, with 1000 neutrons per generation, and the first 100 generations skipped, or 1,000,000 total neutron histories. This uncertainty value varied case to case, but was on the order of 0.0007, and in no case was it larger than 0.0010. To avoid confusion, it is noted that the remainder of this report focuses on the uncertainty in *k* arising from uncertainty in isotopic concentrations, where the standard deviation is a measure of the variability in *k* as a function of isotopic variations. Individual uncertainties associated with each calculation are small with respect to isotopic uncertainty effects, and are not considered further.

Table 2. Results of KRONOS calculations for various configurations and burnups.

Case No.	Model Type	Criticality Code	Burnup (GWd/MTU)	Fission Products Included	Axial Burnup Profile Included	Neutron Multiplcation Factor (k)					KRONOS Standard Deviation
						Nominal	Best Estimate	Minimum	Maximum	KRONOS (mean)	
1	Cask	KENO V.a	20	Yes	Yes	0.9777	0.9754	0.9109	1.0139	0.9749	0.0099
2	Cask	KENO V.a	40	Yes	Yes	0.8742	0.8699	0.8057	0.9110	0.8673	0.0147
3	Cask	KENO V.a	60	Yes	Yes	0.7900	0.7856	0.7229	0.8288	0.7835	0.0160
4	Cask	KENO V.a	20	No	Yes	1.0375	1.0394	1.0168	1.0643	1.0406	0.0025
5	Cask	KENO V.a	40	No	Yes	0.9517	0.9544	0.9249	0.9800	0.9536	0.0035
6	Cask	KENO V.a	60	No	Yes	0.8829	0.8850	0.8553	0.9124	0.8851	0.0042
7	Cask	KENO V.a	20	Yes	No	0.9739	0.9698	0.9032	1.0121	0.9658	0.0258
8	Cask	KENO V.a	40	Yes	No	0.8304	0.8232	0.7557	0.8697	0.8196	0.0269
9	Cask	KENO V.a	60	Yes	No	0.7157	0.7118	0.6468	0.7591	0.7076	0.0257
10	Cask	KENO V.a	20	No	No	1.0334	1.0373	1.0117	1.0595	1.0363	0.0067
11	Cask	KENO V.a	40	No	No	0.9184	0.9200	0.8863	0.9524	0.9209	0.0067
12	Cask	KENO V.a	60	No	No	0.8242	0.8254	0.7870	0.8616	0.8257	0.0074

Table 2 (continued)

Case No.	Model Type	Criticality Code	Burnup (GWd/MTU)	Fission Products Included	Axial Burnup Profile Included	Neutron Multiplcation Factor (*k*)					KRONOS Standard Deviation
						Nominal	Best Estimate	Minimum	Maximum	KRONOS (mean)	
13	Pin-cell	KENO V.a	20	Yes	Yes	1.2251	1.2176	1.1360	1.2636	1.2207	0.0116
14	Pin-cell	KENO V.a	40	Yes	Yes	1.0852	1.0756	0.9959	1.1260	1.0741	0.0192
15	Pin-cell	KENO V.a	60	Yes	Yes	0.9768	0.9672	0.8880	1.0196	0.9645	0.0208
16	Pin-cell	KENO V.a	20	No	Yes	1.3174	1.3196	1.2921	1.3435	1.3189	0.0015
17	Pin-cell	KENO V.a	40	No	Yes	1.2076	1.2071	1.1750	1.2384	1.2072	0.0034
18	Pin-cell	KENO V.a	60	No	Yes	1.1220	1.1221	1.0856	1.1587	1.1224	0.0042
19	Pin-cell	KENO V.a	20	Yes	No	1.2277	1.2193	1.1365	1.269	1.2144	0.0351
20	Pin-cell	KENO V.a	40	Yes	No	1.0498	1.0393	0.9533	1.0971	1.035	0.0375
21	Pin-cell	KENO V.a	60	Yes	No	0.9124	0.9021	0.8195	0.9622	0.8981	0.0361
22	Pin-cell	KENO V.a	20	No	No	1.3412	1.3159	1.3048	1.2864	1.3145	0.0063
23	Pin-cell	KENO V.a	40	No	No	1.1805	1.1813	1.1407	1.2199	1.1811	0.0079
24	Pin-cell	KENO V.a	60	No	No	1.0699	1.0723	1.0244	1.1185	1.0714	0.0093
25	Pin-cell	XSDRNPM	20	Yes	N/A	1.2301	1.2217	1.1379	1.2711	1.2168	0.0351

Table 2 (continued)

Case No.	Model Type	Criticality Code	Burnup (GWd/MTU)	Fission Products Included	Axial Burnup Profile Included	Neutron Multiplcation Factor (k)					KRONOS Standard Deviation
						Nominal	Best Estimate	Minimum	Maximum	KRONOS (mean)	
26	Pin-cell	XSDRNPM	40	Yes	N/A	1.0514	1.0416	0.9548	1.0981	1.0367	0.0375
27	Pin-cell	XSDRNPM	60	Yes	N/A	0.9142	0.9040	0.8206	0.9638	0.8995	0.0362
28	Pin-cell	XSDRNPM	20	No	N/A	1.3162	1.3173	1.2889	1.3436	1.3171	0.0065
29	Pin-cell	XSDRNPM	40	No	N/A	1.1827	1.1834	1.1430	1.2219	1.1834	0.0078
30	Pin-cell	XSDRNPM	60	No	N/A	1.0726	1.0733	1.0254	1.1201	1.0735	0.0091

Many conclusions and interpretations are possible when the results of Table 2 are compared and contrasted. Further insights are possible by looking at the set of 1000 eigenvalues as a whole for each of the burnup cases. The following subsections attempt to describe some of the most significant observations made in the study of these results.

5.1. Convergence

Both the KRONOS neutron multiplication factor and uncertainty are converged values, indicating that a sufficient number of cases have been run that the distribution of *k* values is a close approximation to the form of the distribution that would be seen for an infinite number of cases. All cases of Table 2 were run using 1000 individual criticality calculations. This number was picked based on early studies with KRONOS that indicated that the mean value of *k* and its standard deviation appeared to converge within the first 500 cases. Figure 1 illustrates the mean value of *k* as a function of the number of isotopically varied criticality calculations run, for cases 3, 6, 9 and 12. These cases are cask models with a burnup of 60 GWd/MTU. Figure 2 shows the convergence of the standard deviation, s, with an increasing number of cases.

Although it is difficult to see because of the different relative y-axis scales between the two figures, it can be shown that the mean value of *k*, $\overline{k}$, converges much more rapidly than the standard deviation, but for all cases both $\overline{k}$ and s are converged within 800 calculations. The high burnup 60 GWd/MTU case was selected because it exhibits the slowest convergence. This is not surprising, since the highest burnup cases have the largest fraction of fission products and higher-order actinides relative to the uranium nuclides. From Table 1, it is clear that the uncertainty for these nuclides is larger than for the uranium isotopes. Thus the higher the burnup, the more variability there is in the constituent nuclides, and the slower the convergence.

Figure 2 also shows that the case with fission products included and with a uniform axial burnup (case 9 of Table 2) is the slowest to converge. This behavior is also seen for the lower burnup cases. Convergence is delayed in part by the larger uncertainty associated with fission products (see Table 1). This effect is compounded by the fact that the uniform burnup profile over-weights the importance of fission products by forcing a cosine-shaped fission density profile, rather than the physical reality where the fission density is highest away from the axial center of the fuel, where fission product inventories are smaller. This phenomenon is described in more detail in Ref. 5.

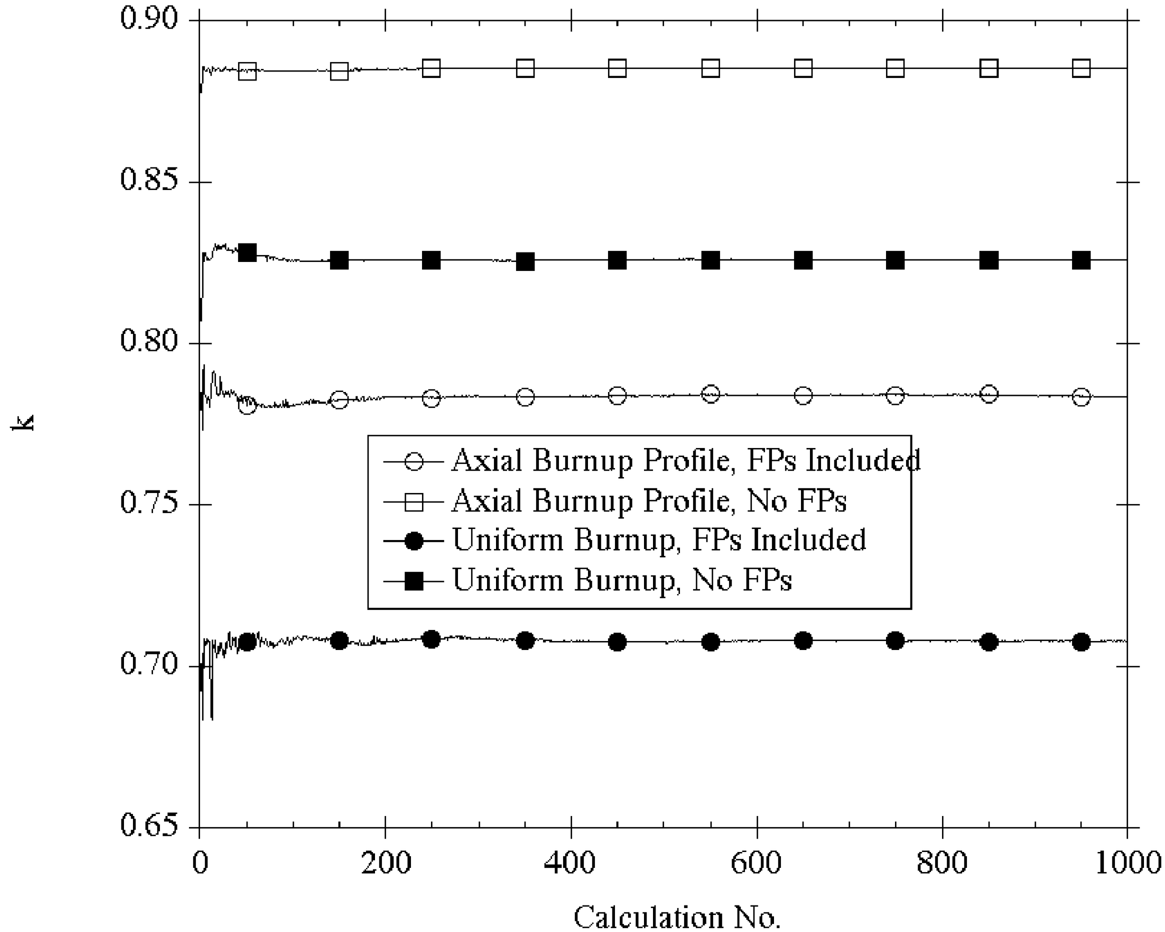

Fig. 1. Convergence of mean value of *k* for 60 GWd/MTU cask models.

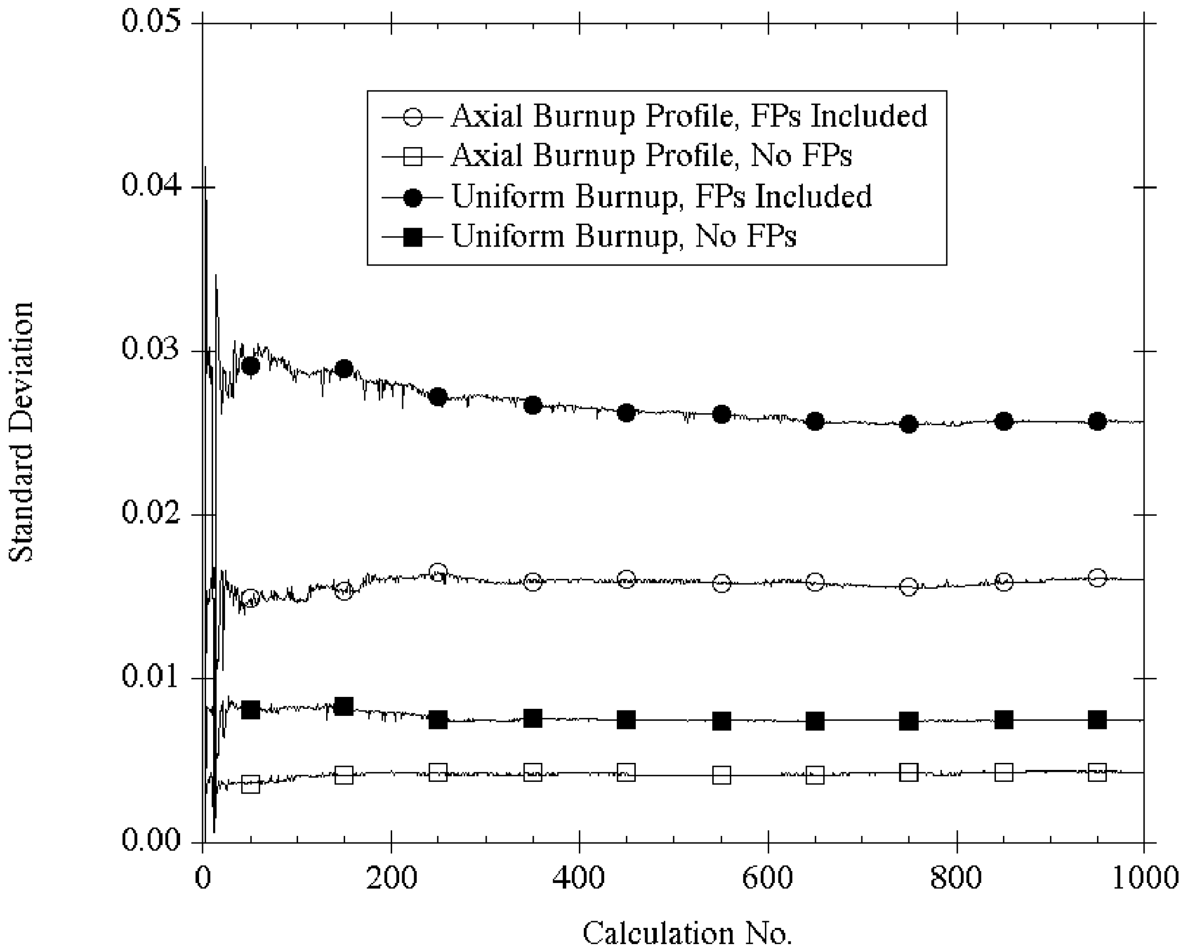

Fig. 2. Convergence of population standard deviation for 60 GWd/MTU cask models.

5.2. Distribution of Eigenvalues

As seen in Figure 3, the distribution of *k* values from Case 1 is in the form of a normal distribution, with the largest number of observances falling close to the mean and dropping off to very few cases found outside of a 3*s* band around the mean (0.9452 – 1.0046). In fact, the upper bound calculated based on "bounding" isotopic concentrations for this case is 1.0139 is 4*s* from the mean value, demonstrating the conservatism of such an approach.

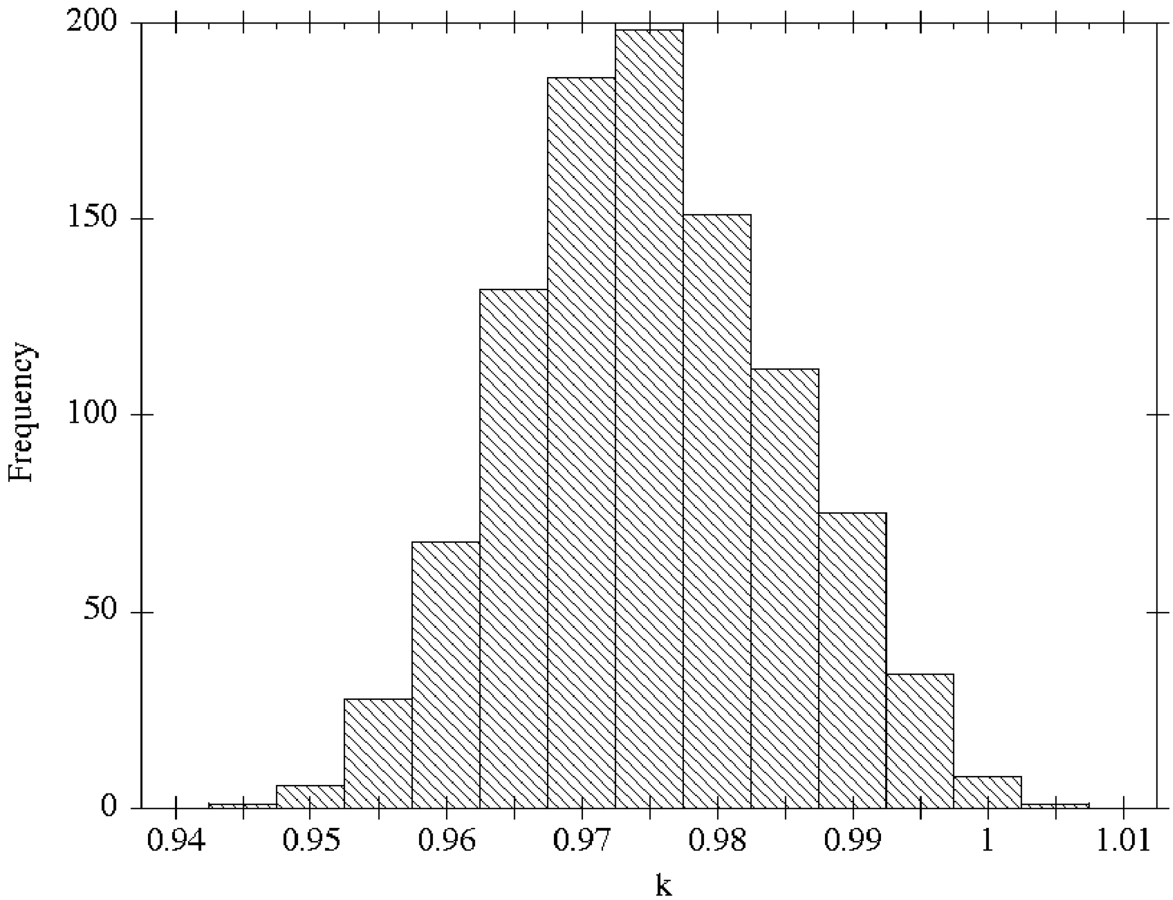

Fig. 3. Distribution of *k* values for Case 1, 20 GWd/MTU.

Figures 4 and 5 show the distribution of eigenvalues obtained for the same model at higher burnups. Note that as the burnup increases, the shape of the profile begins to depart slightly from a normal distribution, as it becomes more weighted on the lower tail region. The effect is due to the larger uncertainties associated with certain fission products. As the fission products build up, they begin to have a more pronounced effect on the system eigenvalues. However, although fission concentrations are allowed to vary randomly in a form prescribed by Eqs. (4) or (6), there is a physical lower limit of zero for a concentration. When the random variation in the nuclide concentration is less than zero, the concentration is set to zero. Thus, for extreme cases where the uncertainty range is greater than the calculated concentration, the effective worth of the absorber is more heavily weighted, resulting in a shift of the distribution toward the left tail. However, the effect is relatively small.

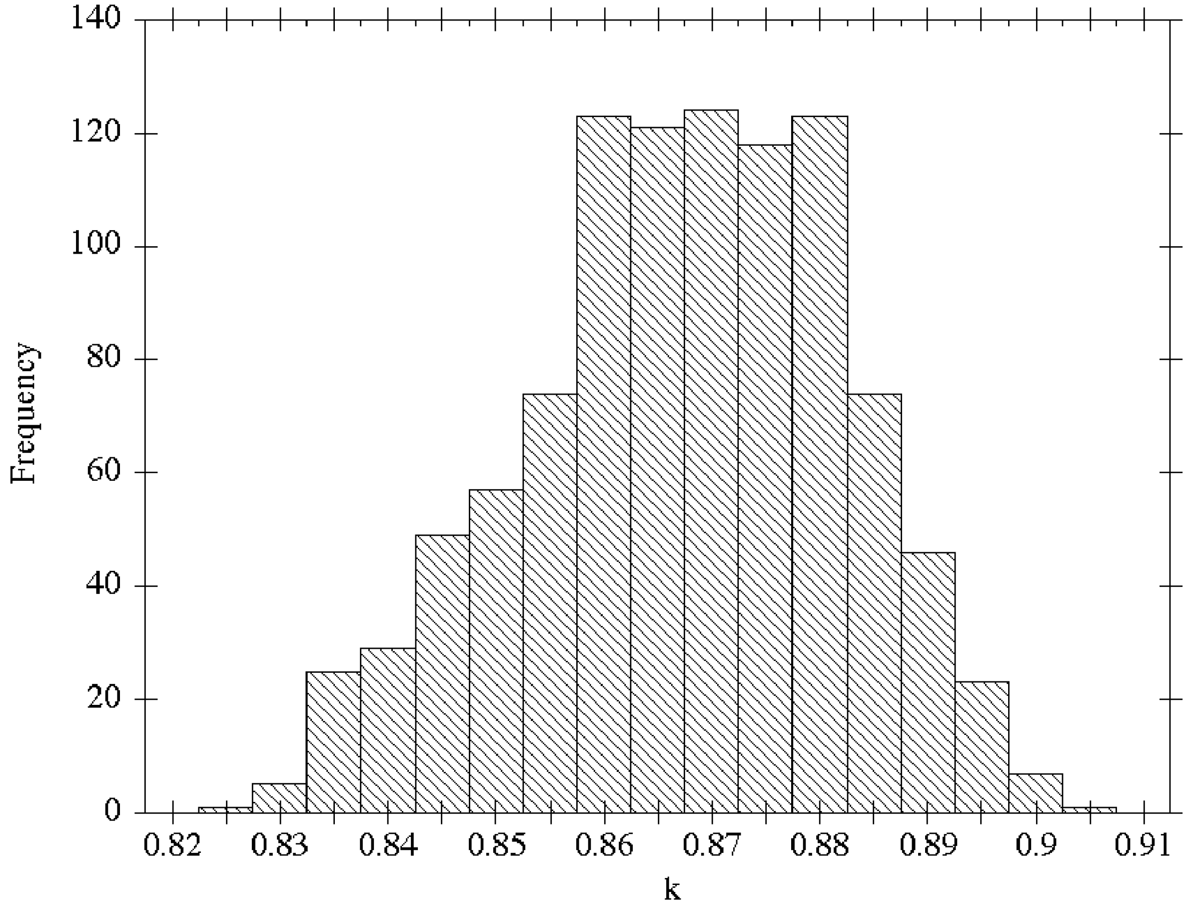

Fig. 4. Distribution of *k* values for Case 2, 40 GWd/MTU.

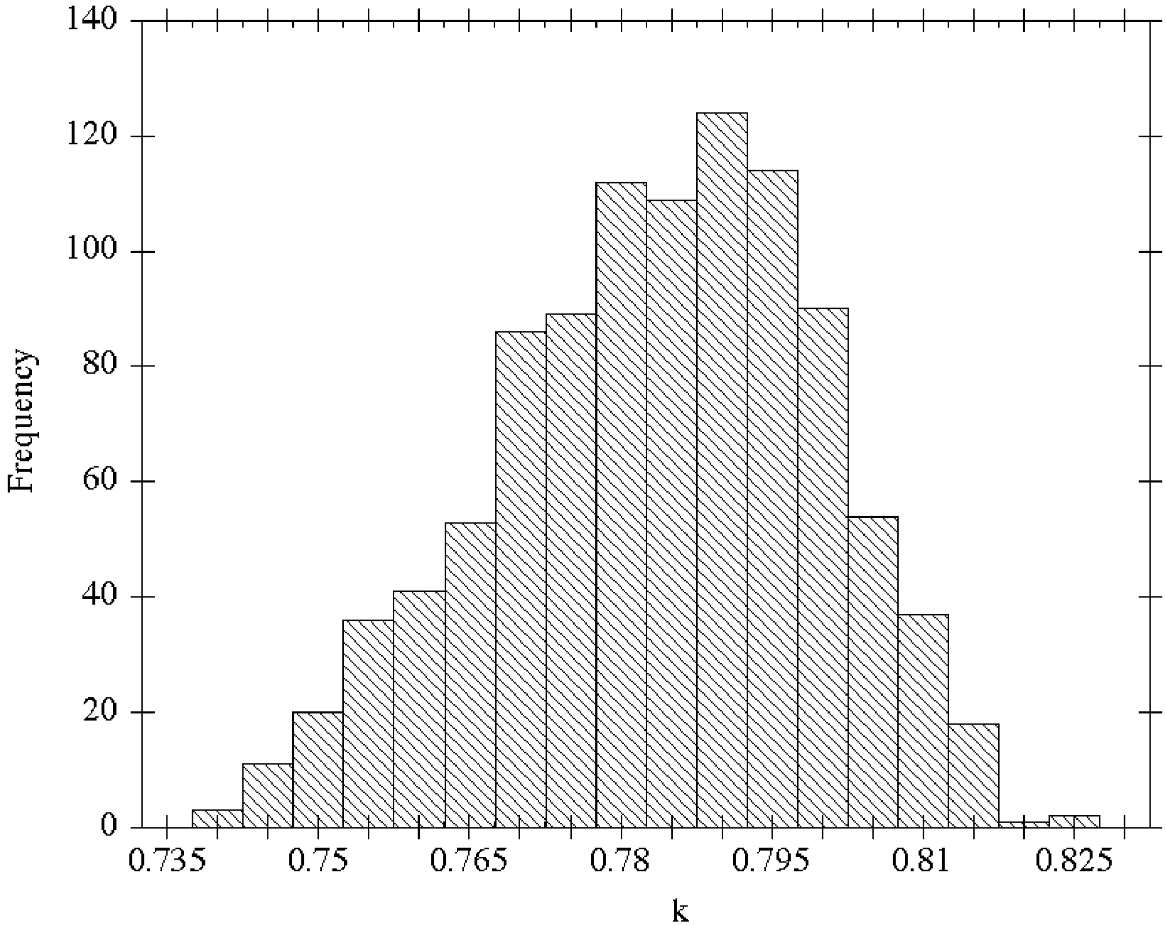

Fig. 5. Distribution of *k* values for Case 3, 60 GWd/MTU.

5.3. Actinide-Only vs. "Full" Burnup Credit

Current directions for first-generation burnup credit implementation for transportation casks are based on taking only partial credit for reactivity reduction due only to primary actinides for which radiochemical assay data are available. The term "full burnup credit" has often been applied to approaches such as that currently being considered for disposal applications where credit is taken for a set of the most important fission product absorbers. The word "full" is a misnomer in the sense that this approach takes credit for only a small subset of fission product nuclides, ignoring a large number of lesser absorbers that as a whole amount to roughly 20% of the total fission product worth in burned fuel.[5] In general, fission product biases and uncertainties are larger than those of actinides, due both to the availability of fewer fission product measurements and weaknesses in the accuracy of fission product cross-section data. This work shows the different responses of k due to the two modeling assumptions.

Different studies have applied different sets of nuclides in both actinide-only and full burnup credit modeling. The current work makes no attempt to evaluate different sets of nuclides. Instead, these calculations were performed using all nuclides for which radiochemical assay data are available, as listed in Table 1. Actinide-only calculations were performed with the full contingent of actinides listed in the table.

Table 3 provides a comparison of the differences between the mean or expected value of k (KRONOS k) for corresponding cases with and without fission products. The table also shows the difference in the uncertainty between the two nuclide sets. The Δk results are consistent with the known behavior of fission products: As would be expected, the results show that reactivity worth becomes increasingly negative with increasing burnup, as fission product inventories increase. Trends in these results are more easily seen in Fig. 6, which shows the reactivity decrease with increasing burnup for each of the model types. This plot also allows several observations (not new to this work, but certainly worth noting):

- Fission products are worth less in a model that uses an axially varying burnup profile instead of the assumption of axially uniform burnup. This is due to the shift of the neutron flux away from the most highly poisoned axial center with increasing burnup; this shift does not occur when an (aphysical) uniform burnup is assumed.

- Fission products are worth less in a cask model than in an infinite lattice. This is due to the presence of intra-assembly boron plates in the cask, which remove thermal neutrons and thereby reduce the effectiveness of fission products as absorbers.

- The worth of fission products in a simple 1-D pin-cell model is almost identical to that in a 3-D infinite lattice, even though the 3-D model has axial leakage.

- Fission product worth (known to be zero at beginning of life) increases more rapidly early in life and increases less rapidly at higher burnups. This may be due to increased competition for neutrons at higher burnups due to high concentrations of poisons.

Table 3. Reactivity worth of fission products and associated uncertainties

Case nos.	Model Type	Criticality Code	Burnup (GWd/MTU)	Axial Burnup Profile Included	Δk ($k_{full} - k_{AO}$)	Δs ($s_{full} - s_{AO}$)
1 & 4	Cask	KENO V.a	20	Yes	–0.0657	0.0074
2 & 5	Cask	KENO V.a	40	Yes	–0.0863	0.0112
3 & 6	Cask	KENO V.a	60	Yes	–0.1016	0.0118
7 & 10	Cask	KENO V.a	20	No	–0.0705	0.0191
8 & 11	Cask	KENO V.a	40	No	–0.1013	0.0202
9 & 12	Cask	KENO V.a	60	No	–0.1181	0.0183
13 & 16	Pin-cell	KENO V.a	20	Yes	–0.0982	0.0101
14 & 17	Pin-cell	KENO V.a	40	Yes	–0.1331	0.0158
15 & 18	Pin-cell	KENO V.a	60	Yes	–0.1579	0.0166
19 & 22	Pin-cell	KENO V.a	20	No	–0.1001	0.0288
20 & 23	Pin-cell	KENO V.a	40	No	–0.1461	0.0296
21 & 24	Pin-cell	KENO V.a	60	No	–0.1733	0.0268
25 & 28	Pin-cell	XSDRNPM	20	N/A	–0.1003	0.0286
26 & 29	Pin-cell	XSDRNPM	40	N/A	–0.1467	0.0297
27 & 30	Pin-cell	XSDRNPM	60	N/A	–0.1740	0.0271

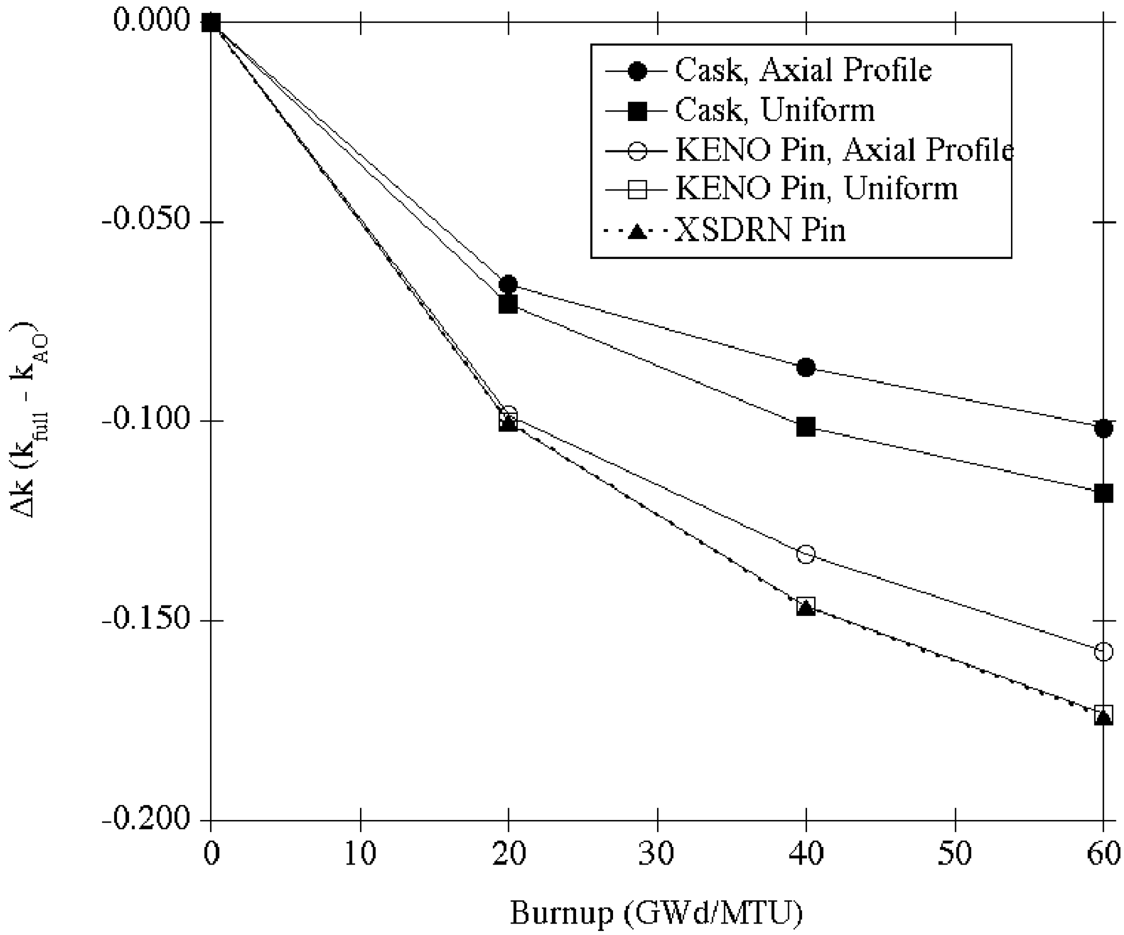

Fig. 6. Fission product reactivity worth as a function of burnup.

None of the above results are unique to the capabilities of KRONOS, and could be determined from a single set of calculations for each model type (e.g., nominal or best estimate results listed in Table 2). More interesting therefore is the behavior of the uncertainty associated with the neutron multiplication factor as a function of the nuclide set applied in a model. The last column of Table 3 shows the difference in the uncertainty in *k* as a function of the nuclide set modeled. This effectively shows the component of uncertainty due to fission products alone: Δs, the difference in the net uncertainty between cases with and without fission products, is always positive. These results are shown graphically in Fig. 7. Again, a list of observations is made:

- The uncertainty due to fission products is lower in a cask model than in a pin cell model. This is consistent with the fact that fission products themselves are worth less in a cask model, as discussed earlier.

- The component of uncertainty due to fission product contributions is greater when a uniform axial burnup is assumed. As indicated in the previous discussion, the uniform profile over-weights the worth of fission products relative to a distributed burnup profile. As a result, the fission product uncertainty is also amplified.

- In a cask model, fission product uncertainty increases with burnup. This would be expected, since fission product inventories are increasing with burnup.
- In contrast, for pin-cell models although fission product uncertainty increases with burnup initially, this trend reverses as fission product uncertainty decrease at a faster rate as burnup proceeds. This trend is consistent whether an axial burnup profile or a uniform burnup approximation is used. The reason for this behavior is unknown and will require further study.

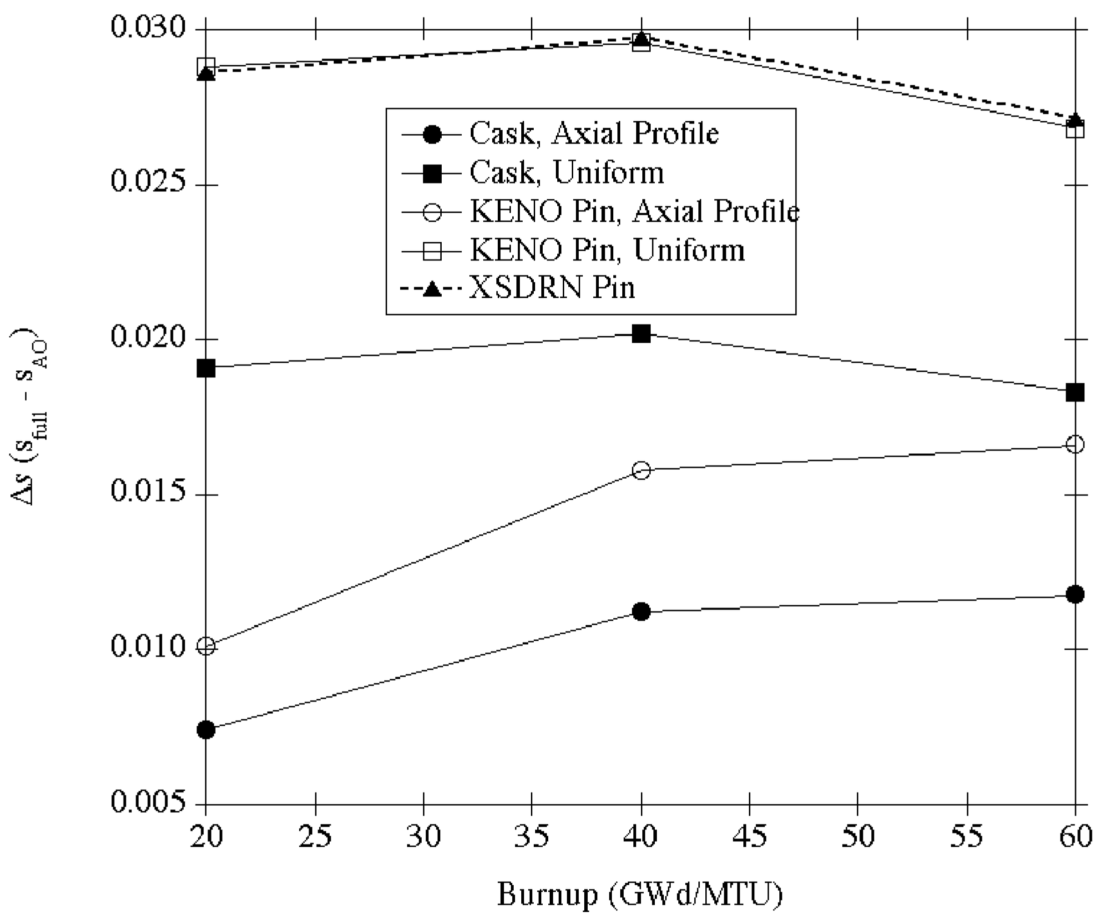

Fig. 7. Uncertainty due to fission products as a function of burnup.

5.4. Conservatism of Bounding Approach

Given the large number of criticality calculations performed for each 30 cases studied, it is possible to generate a statistical probability plot for a normal distribution. Figures 8 and 9 show probability plots generated from the results of each of the three burnups. Figure 8 shows the statistical plot for KENO V.a cask models with actinides and fission products (i.e., cases 1–3). Similarly, Fig. 9 shows the same analysis for the actinide-only cases (cases 4–6). Each plot shows the probability distribution functions for the range of results obtained for 1000 calculations at each burnup. For a given value of *k*, the plot shows the probability that this value will bound another *k* value calculated from the distribution. K_{max} is the bounding value of k given in Table 2, obtained using ultraconservative assumptions.

As an example, consider the 20 GWd/MTU line in Fig. 8. Assuming a desired limit of 0.98 for *k* in the cask, 0.98 corresponds to a point on the curve at approximately 90% on the x-ordinate. This indicates that 10% of the *possible* isotopic configurations for this burnup would result in a value of *k* larger than 0.98. A limit of 0.95 would be met with roughly a 0.5% probability, i.e., 99.5% of possible isotopic distributions would result in cask *k* values of ≥0.95. Basically, these results tell us that for 4 wt % fuel with a 20 GWd/MTU burnup, a sufficiently subcritical loading is not possible in the analyzed cask design. This is consistent with the bounding approach, which gives a maximum *k* value of 1.0139 (well over a 0.95 upper limit).

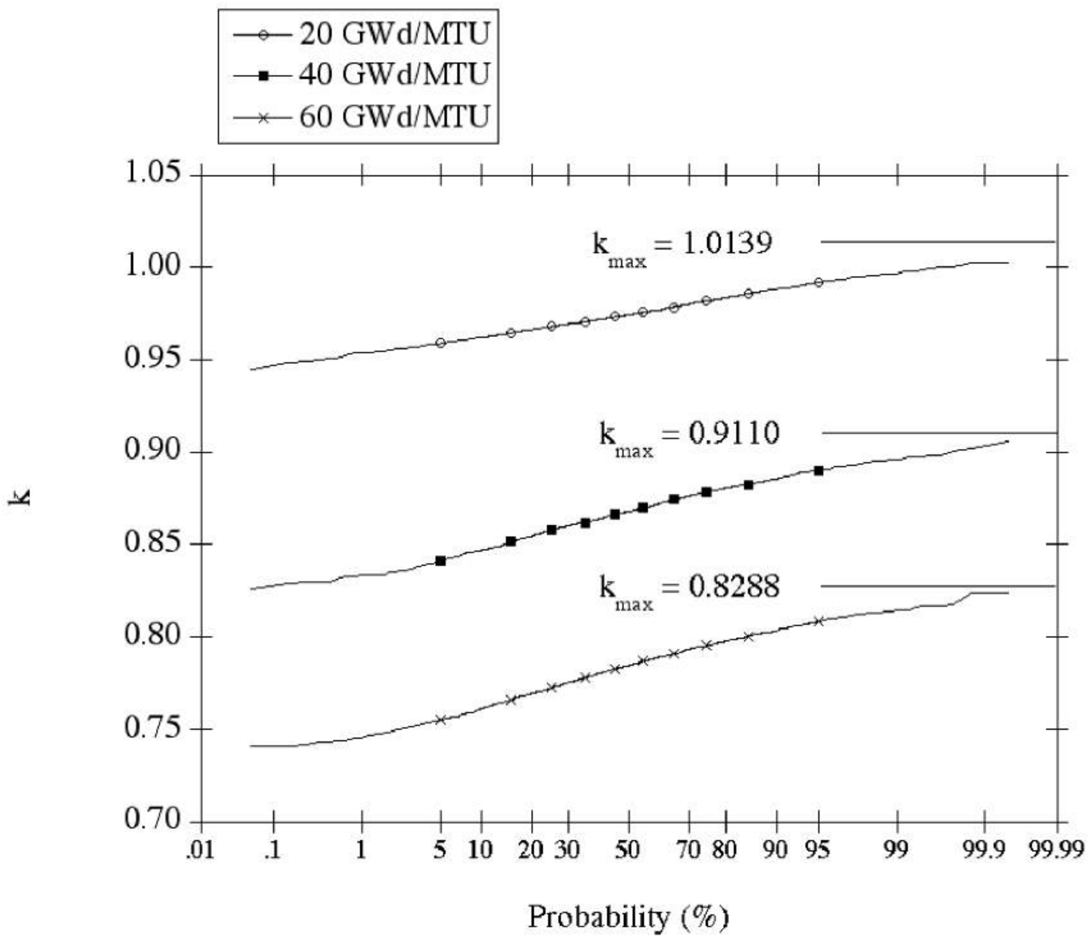

Fig. 8. Probability plot for KENO cask calculations, actinides + fission products.

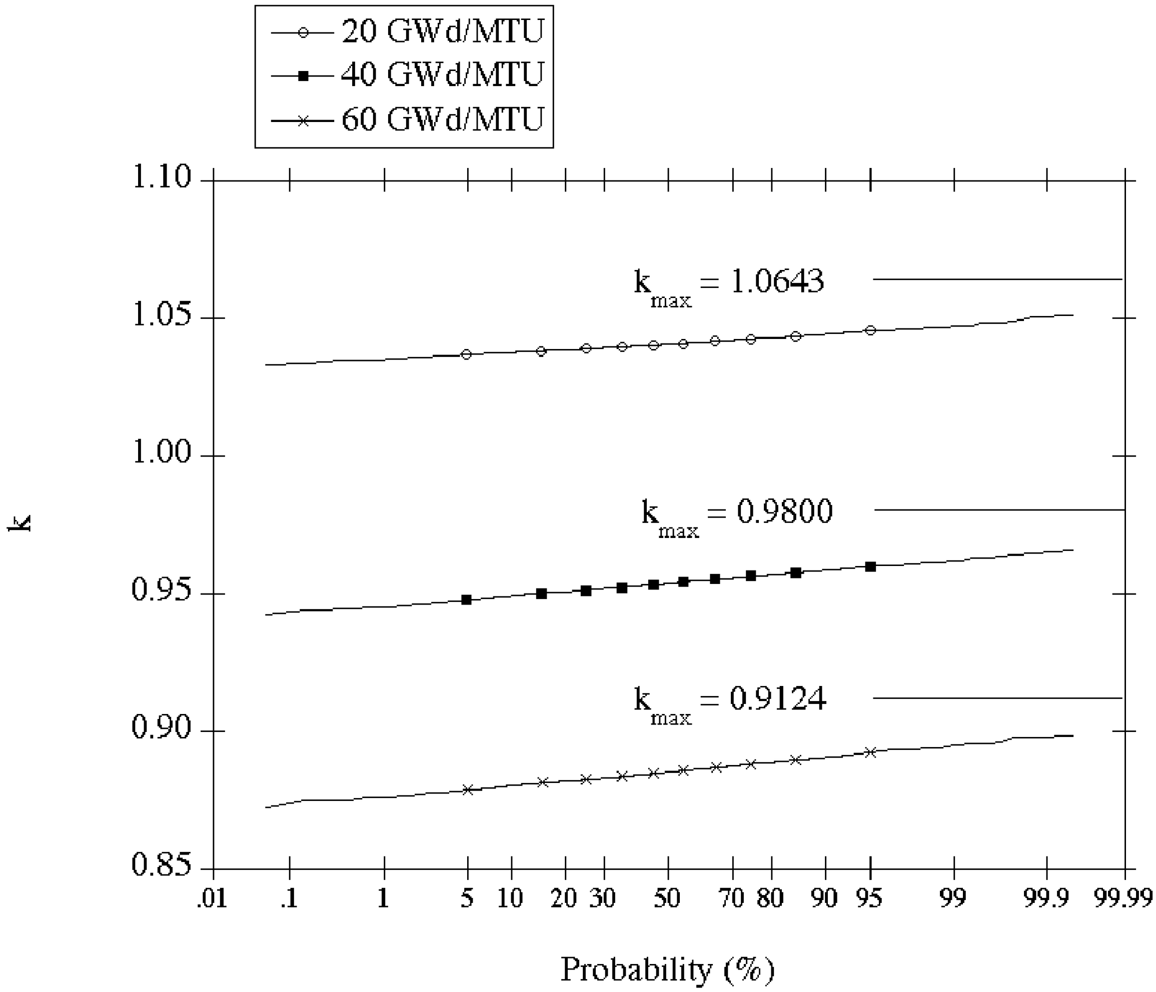

Fig. 9. Probability plot for KENO cask calculations, actinides only.

It is worth noting that the probability distribution function for a normal distribution should be a straight line on a linear-log plot. The results plotted in Fig. 9 are very linear, indicating a normal distribution. The results are linear at low burnup Fig. 8, but departs from linear at the ends as burnup increases. This is consistent with the findings discussed earlier and illustrated in Figs. 3–5, resulting from a non-normal distribution of some nuclides.

Each of the figures shows the value of k_{max} calculated for each model and each burnup. Note that in Fig. 8, the full (actinide + fission product) burnup credit cases have a k_{max} value corresponding to the 99.9 to 99.99% percentile. Such a high probability exceeds that assumed for the analysis of a postulated but highly unlikely accident scenario, typically set at 95%.

Figure 9 shows that the percentiles associated with an assumed bounding value of *k* are greater than 99.999% confidence for all burnups. The increased probability corresponds to the lower uncertainty for actinides relative to fission products.

Assuming a 95% probability is acceptable, and comparing the difference between k_{max} and $k_{95\%}$, it is found that the bounding approach consistently exceeds the 95% probability by roughly 2% Δk for all burnups in both plots. This is a measure of the excess conservatism associated with the bounding approach, but only applies to this cask design, this fuel enrichment, and this modeling approach. Nevertheless, these results indicate a potentially significant reduction in excess conservatism using a statistically derived approach.

6. CONCLUSIONS

A method has been developed to incorporate biases and uncertainties in isotopic predictions into an uncertainty term for neutron multiplication. Uncertainties derived in this manner can be applied in a more realistic yet conservative fashion, without paying the penalties associated with the bounding approach currently recommended in proposed methodologies for transportation and storage.

The results contained herein reflect only three burnup states and a single cask or pin design. This report has been developed to show the utility of the KRONOS approach for the statistical study of the effect of isotopic prediction uncertainties, and to demonstrate the potential magnitude of the effect of those uncertainties on the predicted neutron multiplication factor for a given design. In these results, trends were observed as a function of: fission product vs. actinide-only isotopic models, increasing burnup, and pin-cell vs. cask models. At a 95% percentile, the statistical approach was found to reduce the conservatism associated with a bounding isotopic approach by approximately 2% Δk, irrespective of burnup or the presence of fission products, for the cask models studied. Although heuristically it is expected that general trends noted here would be confirmed in additional analyses, such additional studies have not been performed and there is no technical justification for this. This is especially true in the magnitude of the Δk margin observed. This margin may be dependent on the configuration of the cask, the codes and data used, and certainly will vary as additional assay data becomes available.

The non-normal distributions of k observed with fission product data included result from large uncertainties in fission product measurements and calculations. Modified fission product concentrations of less than zero were set to zero. Since this results in an under population of the upper end of the distribution of k values, the estimated mean value of k and the deviation in k are both slightly underestimated for higher burnups (although the effect is small). This problem could be rectified in two ways. First, it is possible to transform the uncertainties into a log-normal distribution and ensure that all uncertainties are positive, hence no truncation is necessary. A better approach would be to obtain additional fission product data, such that the associated uncertainties would be reduced, and a more realistic estimate of measurement uncertainties could be obtained.

The analyses described herein were detailed and computationally expensive, requiring the use of distributed network computing in order to complete analyses in a reasonable time. However, this relatively simple use of parallel processing was found to be extremely efficient and effective.

7. REFERENCES

1. M. Rahimi, E. Fuentes, and D. Lancaster, *Isotopic and Criticality Validation for PWR Actinide-Only Burnup Credit*, DOE/RW-0497, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, 1997.

2. U.S. Department of Energy, *Topical Report on Actinide-Only Burnup Credit for PWR Spent Nuclear Fuel Packages*, DOE/RW-0472 Rev 2, Office of Civilian Radioactive Waste Management, U.S. Department of Energy, 1998.

3. O. W. Hermann, S. M. Bowman, M. C. Brady, and C. V. Parks, *Validation of the SCALE System for PWR Spent Fuel Isotopic Composition Analyses*, ORNL/TM-12667, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., March 1995.

4. M. D. DeHart and O. W. Hermann, *An Extension of the Validation of SCALE (SAS2H) Isotopic Prediction for PWR Spent Fuel*, ORNL/TM-13317, Lockheed Martin Energy Research Corp., Oak Ridge Natl. Lab., September 1996.

5. M. D. DeHart, *Sensitivity and Parametric Evaluations of Significant Aspects of Burnup Credit for PWR Spent Fuel Packages*, ORNL/TM-12973, Lockheed Martin Energy Research Corp., Oak Ridge Natl. Lab., May 1996.

6. O. W. Hermann and C. V. Parks, "SAS2H: A Coupled One-Dimensional Depletion and Shielding Analysis Module," Vol. I, Sect. S2 of *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, NUREG/CR-0200, Rev. 6 (ORNL/NUREG/CSD-2/R6), Vols. I, II, and III, May 2000. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-545.

7. M. D. DeHart and S. M. Bowman, *Validation of the SCALE Broad Structure 44-Group ENDF/B-V Cross-Section Library for Use in Criticality Safety Analyses*, NUREG/CR-6102 (ORNL/TM-12460), U.S. Nuclear Regulatory Commission, Oak Ridge Natl. Lab., September 1994.

8. N. F. Landers and L. M. Petrie, "CSAS: Control Module for Enhanced Criticality Safety Analysis Sequences," Vol. I, Sect. C4 of *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, NUREG/CR-0200, Rev. 6 (ORNL/NUREG/CSD-2/R6), Vols. I, II, and III, May 2000. Available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-545.

9. W. Gropp, E. Lusk, and A. Skjellum, *Using MPI - Portable Parallel Programming with the Message Passing Interface*, The MIT Press, Cambridge, Massachusetts, 1996.

10. J. C. Wagner, *Computational Benchmark for Estimation of Reactivity Margin from Fission Products and Minor Actinides in PWR Burnup Credit*, NUREG/CR-XXXX, ORNL/TM-2000/306, U.S. Nuclear Regulatory Commission, Oak Ridge Natl. Lab., in preparation.

APPENDIX A

KRONOS Fortran-90 Program Listing

```
 module kronos_module
  implicit none
  integer MAXNUCS,MAXCASES,NUMISOS
  parameter (MAXNUCS=31, MAXCASES=5000,NUMISOS=1000)
  integer i, j, k, mat(NUMISOS), nummeas,isocnt,numcases
  character*6 nucnam(MAXNUCS),nuc(NUMISOS)
  character*100 title,xtra(2000)
  character*100 tmpstr
  character*7 type
  real m2c(MAXNUCS), sigma(MAXNUCS), den(NUMISOS), tf(38)
  integer n(MAXNUCS),error,numxtra
  real temp, randen, ranm2c, caseran, mult, sig, ratio, seed, ran, kinf, sum1, sum2, mean, stdv
  real, external :: rnor, rstart
  logical done,fissile(MAXNUCS)
  character*11 filename
!
!  Average m/c ratio (m2c), std deviation (sigma) and measurement count (n) from Table 22 of
!  "An Extension of the Validation of SCALE (SAS2H) Isotopic Predictions for PWR Spent
!  Fuel," ORNL/TM-13317, DeHart and Hermann.
!
  data (nucnam(i),m2c(i),sigma(i),n(i),fissile(i),i=1,MAXNUCS) / &
    'cs-133', 0.9759, 0.009,  3, .false., 'cs-135', 0.9471, 0.029,  9, .false., &
    'nd-143', 1.0000, 0.005,  3, .false., 'nd-145', 1.0032, 0.004,  3, .false., &
    'nd-148', 0.9992, 0.018, 16, .false., 'pm-147', 1.0170, 0.042,  3, .false., &
    'sm-147', 1.0170, 0.042,  3, .false., 'sm-149', 1.5095, 0.406,  3, .false., &
    'sm-150', 1.0018, 0.050,  3, .false., 'sm-151', 0.7584, 0.033,  3, .false., &
    'eu-151', 0.7584, 0.033,  3, .false., 'eu-153', 0.9395, 0.039,  3, .false., &
    'eu-154', 1.2735, 0.070,  9, .false., 'eu-155', 1.3586, 0.109,  3, .false., &
    'gd-154', 1.0144, 0.035,  3, .false., 'gd-155', 1.3586, 0.109,  3, .false., &
    ' u-234', 0.9829, 0.133, 14, .false., ' u-235', 1.0104, 0.035, 38,  .true., &
    ' u-236', 1.0132, 0.048, 38, .false., ' u-238', 1.0026, 0.005, 32, .false., &
    'np-237', 0.9484, 0.094, 13, .false., 'pu-238', 1.0338, 0.077, 24, .false., &
    'pu-239', 1.0142, 0.029, 38,  .true., 'pu-240', 1.0030, 0.027, 38, .false., &
    'pu-241', 1.0119, 0.035, 38,  .true., 'pu-242', 0.9875, 0.064, 34, .false., &
    'am-241', 1.1420, 0.176,  9, .false., &
    'am-243', 1.0491, 0.066,  6, .false., 'cm-242', 1.3916, 0.087, 15, .false., &
    'cm-243', 1.0266, 0.063,  9, .false., 'cm-244', 1.1090, 0.053, 15, .false. /
!
!  Tolerance factors taken from Table 21 of ORNL/TM-13317.
!  A value of -1 is put in the positions that I don't have
```

```
!  data for.  The code later tests to make sure I am not
!  using an untabulated value
!
  data ( tf(i),i=1,38 )/    -1.000, -1.000, 7.6560, 5.1440, -1.000, &
    3.7080, -1.000, -1.000, 3.0310, -1.000, -1.000, -1.000, 2.6710, &
    2.6140, 2.5660, 2.5240, -1.000, -1.000, -1.000, -1.000, -1.000, &
    -1.000, -1.000, 2.3090, -1.000, 2.2750, -1.000, -1.000, -1.000, &
    -1.000, -1.000, 2.1970, -1.000, 2.1760, -1.000, -1.000, -1.000, &
    2.1410/
end
program kronos
!
!  kronos  - Calculated Homogeneous Reactivity Of Nuclides using Ordered Sampling
!
!  Version 1.0  12/8/97   Mark D. DeHart  Oak Ridge National Laboratory
!
!  Version 1.0 of kronos is a first attemt at creating a program to investigate the sensitivity
!  of k-inf to random variations in isotopic concentrations.  Based on an initial XSDRNPM (csas1x)
!  model of a pin cell containing calculated spent fuel isotopic concentrations, estimates
!  of possible 'measured' concentrations are obtained by randomly sampling from a statistically-
!  derived range of expected concentrations.  k-inf is calculated multiple times with varying
!  isotopics to obtain a distribution of k-inf values.
!
!  Version 4.6par 4/10/00 Mark D. DeHart  Oak Ridge National Laboratory
!
!  mpi-based parallel version.
!
! Version 4.7par 10/17/00 Mark D. DeHart  Oak Ridge National Laboratory
!
!  Modified to calculate the best estimate, worst case, and best case first before doing random cases.  Also has some more
!  output to help in debugging.
!
! Version 4.71par 01/11/01 Mark D. DeHart  Oak Ridge National Laboratory
!
!  Modified to read csas1x output if the input is csas1x instead of csas25
!
  use kronos_module
  include "mpif.h"
!
!  MPI-related vars
!
  integer myid,resultlen,ierr,stat(MPI_STATUS_SIZE),sender,err,source
  character*(MPI_MAX_PROCESSOR_NAME) procname
!
!  Initialize MPI
```

```
!
  call MPI_INIT(ierr)
  call MPI_COMM_RANK(MPI_COMM_WORLD,myid,ierr)
  call MPI_COMM_SIZE(MPI_COMM_WORLD,numprocs,ierr)
  call MPI_GET_PROCESSOR_NAME(procname,resultlen,ierr)
  if(myid.eq.0) write(*,*)'numprocs=',numprocs
  write(*,*)myid,procname(1:resultlen)
  write(filename(1:7),'("cases",i2.2)')myid
  open(44,file=filename(1:7),status='unknown')
  write(44,*)procname(1:resultlen)
  if(myid.eq.0)then
    error=0
!
!
    call read_data
!
!  Seed random number generator
!
    call plant_seed
!
!  Open file for saving k-inf values
!
    open(16,file='kinf.kron',status='unknown')
!
!  Begin loop to repeat k-inf calculations a specified number of times
!
    sum1 = 0.0
    sum2 = 0.0
    mean = 0.0
    stdv = 0.0
!
!   set up cases for up to (numprocs-1) processors
!
    firstsweep = min(numprocs-1,numcases-1)
    do k = 1,firstsweep
      write(filename,"('kronos0',i4.4)") k
!
!  Call setup_input to set up the input for this case
!
     call setup_input
     call MPI_SSEND(0,0,MPI_INTEGER,k,k,MPI_COMM_WOR
     numsent = numsent + 1
    end do
    do k = 0,numcases
!      select case (k)
```

```
!      case (0:3)
!        source = k+1
!      case default
         source = MPI_ANY_SOURCE
!      end select
       call MPI_RECV(0,0,MPI_INTEGER,source,MPI_ANY_TAG            RLD,stat,ierr)
       sender = stat(MPI_SOURCE)
       kk = stat(MPI_TAG)
       write(44,*)'Received from ',sender,kk
       if(type(6:6).eq.'2')then
         call read_output25(kk,sender)
       elseif(type(6:6).eq.'1')then
         call read_output1x(kk,sender)
       endif
       if(numsent.le.numcases)then  ! there are more cases to run
         numsent = numsent + 1
         write(filename,"('kronos0',i4.4)") numsent
         call setup_input
         call MPI_SSEND(0,0,MPI_INTEGER,sender,numsent,MPI_COMM_WORLD,ierr)
         write(44,*)'Sent to ',sender,numsent
       elseif(error.eq.1) then ! error condition set in read_output
         call MPI_ABORT(MPI_COMM_WORLD,error)
         call MPI_FINALIZE(ierr)
         close(44)
         stop
       else ! we are done
         call MPI_SSEND(0,0,MPI_INTEGER,sender,0,MPI_COMM_WORLD,ierr)
         write(44,*)'Sent to ',sender,' stop flag (0)'
       endif
     end do
   else  ! this is a slave processor
     done = .false.
     do while (.not.done)
       call MPI_RECV(i,j,MPI_INTEGER,0,MPI_ANY_TAG,MPI_COMM_WORLD,stat,ierr)
       k = stat(MPI_TAG)
       write(44,*)'Received k = ',k
       if(k .eq. 0)then
         done = .true.
       else
         write(filename,"('kronos0',i4.4)") k
         write(6,*)'Filename=',filename,' on node ',procname(1:resultlen)
         write(44,*)filename
         open(19,file='nicelevel',status='old')
         read(19,*)nice
         close(19)
```

```
        open(19,file=filename,status='unknown')
        write(19,"('#!/bin/csh')")
        write(19,"('# ',a)")procname(1:resultlen)
        write(19,"('setenv SCALE /scale4.4')")
        write(19,"('setenv TMPDIR /var/tmp/udq.',i5.5)")k
        write(19,"('nice +',i2.2,' $SCALE/cmds/scale4             ',a11,'.out')")nice,filename,filename
        write(19,"('rm -rf $TMPDIR')")
        write(19,"('sleep 5')")
        close(19)
        call system('chmod 755 '//filename)
        call system(filename)
        call system('rm '//filename)
        call MPI_SSEND(0,0,MPI_INTEGER,0,k,MPI_COMM_WORLD,ierr)
      endif
    end do
  endif
  call MPI_FINALIZE(ierr)
  close(44)
stop
end
real function rnor()
!
!***purpose  generates normal random numbers, with mean zero and
!             unit standard deviation, often denoted n(0,1).
!***description
!
!       rnor generates normal random numbers with zero mean and
!       unit standard deviation, often denoted n(0,1).
!           from the book, "numerical methods and software" by
!                d. kahaner, c. moler, s. nash
!                prentice hall, 1988
!   use
!       first time....
!                   z = rstart(iseed)
!                     here iseed is any  n o n - z e r o  integer.
!                     this causes initialization of the program.
!                     rstart returns a real (single precision) echo of iseed.
!
!       subsequent times...
!                   z = rnor()
!                     causes the next real (single precision) random number
!                           to be returned as z.
!
!.....................................................................
!                 typical usage
```

```
!
!                    real rstart,rnor,z
!                    integer iseed,i
!                    iseed = 305
!                    z = rstart(iseed)
!                    do 1 i = 1,10
!                       z = rnor()
!                       write(*,*) z
!                 1  continue
!                    end
!
!
!***references  marsaglia & tsang, "a fast, easily implemented
!                 method for sampling from decreasing or
!                 symmetric unimodal density functions", to be
!                 published in siam j sisc 1983.
  real aa,b,c,c1,c2,pc,x,y,xn,v(65),rstart,u(17),s,t,un
  integer j,ia,ib,ic,ii,jj,id,iii,jjj
  save u,ii,jj
!
  data aa,b,c/12.37586,.4878992,12.67706/
  data c1,c2,pc,xn/.9689279,1.301198,.1958303e-1,2.776994/
  data v/ .3409450, .4573146, .5397793, .6062427, .6631691 &
    , .7136975, .7596125, .8020356, .8417227, .8792102, .9148948 &
    , .9490791, .9820005, 1.0138492, 1.0447810, 1.0749254, 1.1043917 &
    ,1.1332738, 1.1616530, 1.1896010, 1.2171815, 1.2444516, 1.2714635 &
    ,1.2982650, 1.3249008, 1.3514125, 1.3778399, 1.4042211, 1.4305929 &
    ,1.4569915, 1.4834526, 1.5100121, 1.5367061, 1.5635712, 1.5906454 &
    ,1.6179680, 1.6455802, 1.6735255, 1.7018503, 1.7306045, 1.7598422 &
    ,1.7896223, 1.8200099, 1.8510770, 1.8829044, 1.9155830, 1.9492166 &
    ,1.9839239, 2.0198430, 2.0571356, 2.0959930, 2.1366450, 2.1793713 &
    ,2.2245175, 2.2725185, 2.3239338, 2.3795007, 2.4402218, 2.5075117 &
    ,2.5834658, 2.6713916, 2.7769943, 2.7769943, 2.7769943, 2.7769943/
!      load data array in case user forgets to initialize.
!      this array is the result of calling uni 100000 times
!         with seed 305.
  data u/ &
    0.8668672834288,  0.3697986366357,  0.8008968294805, &
    0.4173889774680,  0.8254561579836,  0.9640965269077, &
    0.4508667414265,  0.6451309529668,  0.1645456024730, &
    0.2787901807898,  0.06761531340295, 0.9663226330820, &
    0.01963343943798, 0.02947398211399, 0.1636231515294, &
    0.3976343250467,  0.2631008574685/
!
  data ii,jj / 17, 5 /
```

```
!
!***first executable statement  rnor
!
! fast part...
!
!
!   basic generator is fibonacci
!
  un = u(ii)-u(jj)
  if(un.lt.0.0) un = un+1.
  u(ii) = un
!          u(ii) and un are uniform on [0,1)
!          vni is uniform on [-1,1)
  vni = un + un -1.
  ii = ii-1
  if(ii.eq.0)ii = 17
  jj = jj-1
  if(jj.eq.0)jj = 17
!       int(un(ii)*128) in range [0,127],  j is in range [1,64]
  j = mod(int(u(ii)*128),64)+1
!       pick sign as vni is positive or negative
  rnor = vni*v(j+1)
  if(abs(rnor).le.v(j))return
!
! slow part; aa is a*f(0)
  x = (abs(rnor)-v(j))/(v(j+1)-v(j))
!         y is uniform on [0,1)
  y = u(ii)-u(jj)
  if(y.lt.0.0) y = y+1.
  u(ii) = y
  ii = ii-1
  if(ii.eq.0)ii = 17
  jj = jj-1
  if(jj.eq.0)jj = 17
!
  s = x+y
  if(s.gt.c2)go to 11
  if(s.le.c1)return
  if(y.gt.c-aa*exp(-.5*(b-b*x)**2))go to 11
  if(exp(-.5*v(j+1)**2)+y*pc/v(j+1).le.exp(-.5*rnor**
!
! tail part; .3601016 is 1./xn
!       y is uniform on [0,1)
  22 y = u(ii)-u(jj)
  if(y.le.0.0) y = y+1.
```

```
  u(ii) = y
  ii = ii-1
  if(ii.eq.0)ii = 17
  jj = jj-1
  if(jj.eq.0)jj = 17
!
  x = 0.3601016*log(y)
!      y is uniform on [0,1)
  y = u(ii)-u(jj)
  if(y.le.0.0) y = y+1.
  u(ii) = y
  ii = ii-1
  if(ii.eq.0)ii = 17
  jj = jj-1
  if(jj.eq.0)jj = 17
  if( -2.*log(y).le.x**2 )go to 22
  rnor = sign(xn-x,rnor)
return
  11 rnor = sign(b-b*x,rnor)
return
!
!
!  fill
entry rstart(iseed)
  if(iseed.ne.0) then
!
!         set up ...
!             generate random bit pattern in array based on given seed
!
  ii = 17
  jj = 5
  ia = mod(abs(iseed),32707)
  ib = 1111
  ic = 1947
  do 2 iii = 1,17
  s = 0.0
  t = .50
!            do for each of the bits of mantissa of word
!            loop  over 64 bits, enough for all known machines
!                  in single precision
  do 3 jjj = 1,64
    id = ic-ia
    if(id.ge.0)goto 4
    id = id+32707
    s = s+t
```

```
4   ia = ib
    ib = ic
    ic = id
3 t = .5*t
2 u(iii) = s
  endif
!       return floating echo of iseed
  rstart=iseed
return
end
subroutine read_data
  use kronos_module
  character*80 instr
!
!  open input file and read initial (calculated) isotopics and problem description from a csas1x file.
!
  open(16,file='numcases',status='old')
  read(16,*)numcases
  close(16)
  Write(6,'(i4," histories will be run.")')numcases
  open(16,file='kronos.dat',status='old')
  read(16,'(a7)')type
  read(16,'(a100)')title
  read(16,*)  !skip library/lattice descriptors
!
!  Read fuel nuclides
!
!!!  do i = 1,NUMISOS
!!!    read(16,'(2x,a6,i5,5x,e11.5,f7.1)')nuc(i),mat(i),den(i),temp  ! all matids and temps are the same
!!!  end do
  isocnt = 0
  done = .false.
  do while (.not. done)
    read(16,'(a80)')instr
    if(instr(1:1).eq."'")cycle
    if(instr(1:3).eq."END")then
      done = .true.
    else
      isocnt = isocnt + 1
      read(instr,'(2x,a6)')nuc(isocnt)
      read(instr(9:80),*)mat(isocnt),idum,den(isocnt)
    endif
  end do
!
!  Read remaining input
```

```
!
  numxtra = 0
  do
    read(16,'(a100)',end=99)xtra(numxtra+1)
    numxtra = numxtra + 1
  end do
99 close(16)
return
end
subroutine plant_seed
  use kronos_module
  seed = 1234567890
  call random_number(HARVEST=seed)
  ran = rstart(seed)
return
end
subroutine setup_input
use kronos_module
!
!  Open an input file and write header information
!
    open(17,file=filename//'.in',status='unknown')
    write(17,'(a7,''    parm=size=5000000'',/,a100,/,''44groupndf5  latticecell'')')type,title
    select case (filename)
      case ('kronos00001')
        write(17,"('''Nominal (unbiased) case')")
      case ('kronos00002')
        write(17,"('''Biased case')")
      case ('kronos00003')
        write(17,"('''Maximum case')")
      case ('kronos00004')
        write(17,"('''Minimum case')")
      case default
        write(17,"('''Random case')")
      end select
!
!  For each nuclide in the input listing, scan thru the list of tabulated nuclides, to see
!  if there is a match.  Compute a randomized m/c ratio, using 1.0 +/- 0.999999 for unmeasured
!  nuclides.  Modify the input value for the isotopic concentration, and write std comp data.
!
    do i = 1,isocnt
      ratio = 1.000
      sig = 1.000000  ! assign sigma = 1.0, mult= 1.0 in case tabulated values are not available  (then 0 < den < 2*nominal
den)
      mult = 1.000
```

```
call random_number(ran)
ran = 2.0*ran - 1.0  ! -1.0 <= ran < 1.0
do j = 1,MAXNUCS
  if(nuc(i).eq.nucnam(j))then
    ratio = m2c(j)
    sig = sigma(j)
    nummeas = n(j)
    mult = tf(nummeas)
    if(mult.lt.0)then
      write(6,*)'Error - invalid value of nummeas found.  nummeas = ',nummeas
      call MPI_FINALIZE(ierr)
      stop
    endif
    exit
  endif
end do
select case (filename)
  case ('kronos00001')
    ranm2c = 1.0
  case ('kronos00002')
    ranm2c = ratio
  case ('kronos00003')
    if(fissile(j))then
      ranm2c = ratio + sig*mult
    else
      ranm2c = ratio - sig*mult
    endif
  case ('kronos00004')
    if(fissile(j))then
      ranm2c = ratio - sig*mult
    else
      ranm2c = ratio + sig*mult
    endif
  case default
    if(nummeas.lt.10) then
      ! Insufficient data to assume a random distribution, so select from a uniform distribution
      ! ranging within +/- T*sigma of the mean m/c ratio
      ranm2c = ratio + sig*ran*mult
    else
      ! Enough m/c ratios are available to assume a good normal distribution.  We need to select
      ! from a normal distribution of random numbers characterized by the std dev of the population
      ranm2c = ratio + sig*rnor()
    endif
end select
randen = ranm2c*den(i)
```

```
      if(randen.le.1.0e-20)randen = 1.0e-20
      write(17,'(2x,a6,i5," 0   ",1pe11.5," end ",t81,"(",0p,f9.2,"%)")')nuc(i),mat(i),randen,(ranm2c-1.0)*100
    end do
!
!  write remaining input
!
    do i = 1,numxtra
      write(17,'(a100)')xtra(i)
    end do
    close(17)
!
return
end
subroutine read_output25(icasenum,sender)
  use kronos_module
  integer casenum,sender
  real twosig
  logical lexist
  write(filename,"('kronos0',i4.4)") icasenum
  open(17,file=filename//'.in',status='old')
  inquire(file='debug',exist=lexist)
  if(lexist)then
    close(17)
    call system ('compress '//filename//'.in')
  else
    close(17,status='delete')
  endif
  open(17,file=filename//'.out',status='old')
  do
    read(17,'(23x,a50)',end=999)tmpstr(1:50)
    if(tmpstr(1:50).eq.'plot of average k-effective by generation skipped.')then
      read(17,"(34x,f6.4,9x,f6.4)")kinf,twosig
      kk = k - 3  !  First four (0-3) values are not included in the mean
      if(k.gt.3)then
        sum1 = sum1 + kinf*kinf
        sum2 = sum2 + kinf
        mean = sum2/kk
      endif
      if(k.gt.4) stdv = ( abs(kk*sum1 - sum2*sum2)/(kk*(kk-1)) )**0.5
      if(k.eq.0)then
        write(16,"('k-eff   sigma   mean k  mean s  case   mach.')")
        write(6,"('k-eff   sigma   mean k  mean s  case   mach.')")
      endif
      select case (icasenum)
      case (1)
```

```
        write(16,124)kinf,twosig,'nominal',icasenum,sender
        write(6,124)kinf,twosig,'nominal',icasenum,sender
      case (2)
        write(16,124)kinf,twosig,'bestest',icasenum,sender
        write(6,124)kinf,twosig,'bestest',icasenum,sender
      case (3)
        write(16,124)kinf,twosig,'maximum',icasenum,sender
        write(6,124)kinf,twosig,'maximum',icasenum,sender
      case (4)
        write(16,124)kinf,twosig,'minimum',icasenum,sender
        write(6,124)kinf,twosig,'minimum',icasenum,sender
      case (5:)
        write(16,123)kinf,twosig,mean,stdv,icasenum,sender
        write(6,123)kinf,twosig,mean,stdv,icasenum,se
      end select
123 format(4(f6.4,2x),2(i5))
124 format(2(f6.4,2x),3x,a7,6x,2(i5))
      exit
    endif
  end do
  if(lexist)then
    close(17)
    call system ('compress '//filename//'.out')
  else
    close(17,status='delete')
  endif
return
999 write(6,*)'%%Error reading "'//filename//'.out"  String "plot of average k-effective by generation skipped." not found.'
close(17,status='keep')
error = 1
return
end
subroutine read_output1x(icasenum,sender)
  use kronos_module
  integer casenum,sender
  logical lexist
  write(filename,"('kronos0',i4.4)") icasenum
  open(17,file=filename//'.in',status='old')
  inquire(file='debug',exist=lexist)
  if(lexist)then
    close(17)
    call system ('compress '//filename//'.in')
  else
    close(17,status='delete')
  endif
```

```
  open(17,file=filename//'.out',status='old')
  do
    read(17,'(13x,a13)',end=999)tmpstr(1:13)
    if(tmpstr(1:13).eq.'final monitor')then
      read(17,"(28x,e11.5)")kinf
      kk = k - 3  !  First four (0-3) values are not included in the mean
      if(k.gt.3)then
        sum1 = sum1 + kinf*kinf
        sum2 = sum2 + kinf
        mean = sum2/kk
      endif
      if(k.gt.4) stdv = ( abs(kk*sum1 - sum2*sum2)/(kk*(kk-1)) )**0.5
      if(k.eq.0)then
        write(16,"('k-eff   mean k  mean s  case   mach.')")
        write(6,"('k-eff   mean k  mean s  case   mach
      endif
      select case (icasenum)
      case (1)
        write(16,124)kinf,'nominal',icasenum,sender
        write(6,124)kinf,'nominal',icasenum,sender
      case (2)
        write(16,124)kinf,'bestest',icasenum,sender
        write(6,124)kinf,'bestest',icasenum,sender
      case (3)
        write(16,124)kinf,'maximum',icasenum,sender
        write(6,124)kinf,'maximum',icasenum,sender
      case (4)
        write(16,124)kinf,'minimum',icasenum,sender
        write(6,124)kinf,'minimum',icasenum,sender
      case (5:)
        write(16,123)kinf,mean,stdv,icasenum,sender
        write(6,123)kinf,mean,stdv,icasenum,sender
      end select
123 format(3(f6.4,2x),2(i5))
124 format(f6.4,2x,3x,a7,6x,2(i5))
      exit
    endif
  end do
  if(lexist)then
    close(17)
    call system ('compress '//filename//'.out')
  else
    close(17,status='delete')
  endif
return
```

```
999 write(6,*)'%%Error reading "'//filename//'.out"  String "final monitor" not found.'
close(17,status='keep')
error = 1
return
end
subroutine read_output2(icasenum,err)
  use kronos_module
  integer casenum,err
  err=0
  write(filename,"('kronos0',i4.4)") icasenum
  open(17,file=filename//'.out',status='old')
  do
    read(17,'(23x,a50)',end=999)tmpstr(1:50)
    if(tmpstr(1:50).eq.'plot of average k-effective by generation skipped.') exit
  end do
  close(17)
return
999 write(6,*)'Error reading "'//filename//'.out"  S            of average k-effective by generation skipped." not found.'
close(17)
err = 1
return
end
```

APPENDIX B

SAMPLE BASELINE INPUT MODELS USED BY KRONOS

APPENDIX B

SAMPLE BASELINE INPUT MODELS USED BY KRONOS

Sample 1: KRONOS KENO Cask model, non-uniform axial profile, actinides only, 20 GWd/MTU

```
=csas25    parm=size=5000000
Generic 32-Assembly Burnup Credit Cask (GC-32) w/Axial Brnp Profile
44groupndf5    latticecell
'
'  Proposed Model Rev. 0
'  Last Updated:
'
' **********  GC-32: Generic 32-Assembly Cask  **********
' *
' * -GC-32 Characteristics-
' *     Basket Cell ID: 22.0 cm
' *     Basket Cell OD: 23.5 cm, basket wall thickness = 0.75 cm
' *     Boral Thickness: 0.2565 cm (0.101 in)
' *     Boral Width: 19.05 cm (7.5 in)
' *     Boral B-10 Loading: 0.0225 g/sqcm (75% of 0.030)
' *     Cask ID: 175.0 cm
' *     Cask OD: 215.0 cm
' *     Cask Top & Bottom Thickness: 30.0 & 15.0 cm, respectively
' *
' * -Assembly Characteristics-
' *     Assembly Type: Westinghouse 17x17 OFA/V5
' *     Assembly Initial Enrichment: 4.0 wt% U-235
' *     Assembly Burnup:          20 GWD/MTU
' *     Assembly Cooling Time:     5 Years
' *
' * -Modeling Characteristics-
' *     18-equi-length node axial profile (365.76cm total fuel height)
' *
' *
' **********  GC-32: Generic 32-Assembly Cask  **********
'
' Axial Zone # 1 Burnup=13.040GWd/MTU
   u-234  101  0  6.9739E-06  end
   u-235  101  0  6.3477E-04  end
   u-238  101  0  2.2321E-02  end
  pu-238  101  0  2.8523E-07  end
  pu-239  101  0  9.7176E-05  end
  pu-240  101  0  1.6719E-05  end
  pu-241  101  0  5.7845E-06  end
  pu-242  101  0  7.2294E-07  end
  am-241  101  0  1.6286E-06  end
   o      101  0  4.6950E-02  end
' Axial Zone # 2 Burnup=19.340GWd/MTU
   u-234  102  0  6.4003E-06  end
   u-235  102  0  5.1664E-04  end
   u-238  102  0  2.2221E-02  end
  pu-238  102  0  7.7701E-07  end
  pu-239  102  0  1.1787E-04  end
  pu-240  102  0  2.7737E-05  end
  pu-241  102  0  1.1519E-05  end
  pu-242  102  0  2.3074E-06  end
  am-241  102  0  3.2940E-06  end
   o      102  0  4.6950E-02  end
```

```
' Axial Zone # 3 Burnup=21.480GWd/MTU
   u-234  103  0  6.2146E-06  end
   u-235  103  0  4.8053E-04  end
   u-238  103  0  2.2186E-02  end
  pu-238  103  0  1.0134E-06  end
  pu-239  103  0  1.2283E-04  end
  pu-240  103  0  3.1408E-05  end
  pu-241  103  0  1.3522E-05  end
  pu-242  103  0  3.0803E-06  end
  am-241  103  0  3.8853E-06  end
   o      103  0  4.6950E-02  end
' Axial Zone # 4 Burnup=22.060GWd/MTU
   u-234  104  0  6.1651E-06  end
   u-235  104  0  4.7107E-04  end
   u-238  104  0  2.2176E-02  end
  pu-238  104  0  1.0839E-06  end
  pu-239  104  0  1.2403E-04  end
  pu-240  104  0  3.2391E-05  end
  pu-241  104  0  1.4060E-05  end
  pu-242  104  0  3.3101E-06  end
  am-241  104  0  4.0450E-06  end
   o      104  0  4.6950E-02  end
' Axial Zone # 5 Burnup=22.160GWd/MTU
   u-234  105  0  6.1566E-06  end
   u-235  105  0  4.6945E-04  end
   u-238  105  0  2.2175E-02  end
  pu-238  105  0  1.0962E-06  end
  pu-239  105  0  1.2422E-04  end
  pu-240  105  0  3.2560E-05  end
  pu-241  105  0  1.4153E-05  end
  pu-242  105  0  3.3506E-06  end
  am-241  105  0  4.0726E-06  end
   o      105  0  4.6950E-02  end
' Axial Zone # 6 Burnup=22.120GWd/MTU
   u-234  106  0  6.1600E-06  end
   u-235  106  0  4.7010E-04  end
   u-238  106  0  2.2175E-02  end
  pu-238  106  0  1.0912E-06  end
  pu-239  106  0  1.2415E-04  end
  pu-240  106  0  3.2492E-05  end
  pu-241  106  0  1.4116E-05  end
  pu-242  106  0  3.3344E-06  end
  am-241  106  0  4.0616E-06  end
   o      106  0  4.6950E-02  end
' Axial Zone # 7 Burnup=22.040GWd/MTU
   u-234  107  0  6.1668E-06  end
   u-235  107  0  4.7140E-04  end
   u-238  107  0  2.2177E-02  end
  pu-238  107  0  1.0814E-06  end
  pu-239  107  0  1.2399E-04  end
  pu-240  107  0  3.2357E-05  end
  pu-241  107  0  1.4041E-05  end
  pu-242  107  0  3.3020E-06  end
  am-241  107  0  4.0394E-06  end
   o      107  0  4.6950E-02  end
' Axial Zone # 8 Burnup=21.940GWd/MTU
   u-234  108  0  6.1753E-06  end
   u-235  108  0  4.7302E-04  end
   u-238  108  0  2.2178E-02  end
  pu-238  108  0  1.0690E-06  end
  pu-239  108  0  1.2379E-04  end
  pu-240  108  0  3.2188E-05  end
  pu-241  108  0  1.3949E-05  end
  pu-242  108  0  3.2618E-06  end
  am-241  108  0  4.0121E-06  end
   o      108  0  4.6950E-02  end
' Axial Zone # 9 Burnup=21.880GWd/MTU
   u-234  109  0  6.1804E-06  end
```

```
  u-235  109  0  4.7399E-04  end
  u-238  109  0  2.2179E-02  end
 pu-238  109  0  1.0617E-06  end
 pu-239  109  0  1.2367E-04  end
 pu-240  109  0  3.2087E-05  end
 pu-241  109  0  1.3894E-05  end
 pu-242  109  0  3.2378E-06  end
 am-241  109  0  3.9956E-06  end
  o      109  0  4.6950E-02  end
' Axial Zone #10 Burnup=21.880GWd/MTU
  u-234  110  0  6.1804E-06  end
  u-235  110  0  4.7399E-04  end
  u-238  110  0  2.2179E-02  end
 pu-238  110  0  1.0617E-06  end
 pu-239  110  0  1.2367E-04  end
 pu-240  110  0  3.2087E-05  end
 pu-241  110  0  1.3894E-05  end
 pu-242  110  0  3.2378E-06  end
 am-241  110  0  3.9956E-06  end
  o      110  0  4.6950E-02  end
' Axial Zone #11 Burnup=21.900GWd/MTU
  u-234  111  0  6.1787E-06  end
  u-235  111  0  4.7367E-04  end
  u-238  111  0  2.2179E-02  end
 pu-238  111  0  1.0641E-06  end
 pu-239  111  0  1.2371E-04  end
 pu-240  111  0  3.2121E-05  end
 pu-241  111  0  1.3912E-05  end
 pu-242  111  0  3.2458E-06  end
 am-241  111  0  4.0009E-06  end
  o      111  0  4.6950E-02  end
' Axial Zone #12 Burnup=21.920GWd/MTU
  u-234  112  0  6.1770E-06  end
  u-235  112  0  4.7334E-04  end
  u-238  112  0  2.2179E-02  end
 pu-238  112  0  1.0666E-06  end
 pu-239  112  0  1.2375E-04  end
 pu-240  112  0  3.2155E-05  end
 pu-241  112  0  1.3931E-05  end
 pu-242  112  0  3.2538E-06  end
 am-241  112  0  4.0065E-06  end
  o      112  0  4.6950E-02  end
' Axial Zone #13 Burnup=21.900GWd/MTU
  u-234  113  0  6.1787E-06  end
  u-235  113  0  4.7367E-04  end
  u-238  113  0  2.2179E-02  end
 pu-238  113  0  1.0641E-06  end
 pu-239  113  0  1.2371E-04  end
 pu-240  113  0  3.2121E-05  end
 pu-241  113  0  1.3912E-05  end
 pu-242  113  0  3.2458E-06  end
 am-241  113  0  4.0009E-06  end
  o      113  0  4.6950E-02  end
' Axial Zone #14 Burnup=21.720GWd/MTU
  u-234  114  0  6.1940E-06  end
  u-235  114  0  4.7660E-04  end
  u-238  114  0  2.2182E-02  end
 pu-238  114  0  1.0422E-06  end
 pu-239  114  0  1.2333E-04  end
 pu-240  114  0  3.1816E-05  end
 pu-241  114  0  1.3745E-05  end
 pu-242  114  0  3.1743E-06  end
 am-241  114  0  3.9515E-06  end
  o      114  0  4.6950E-02  end
' Axial Zone #15 Burnup=21.180GWd/MTU
  u-234  115  0  6.2402E-06  end
  u-235  115  0  4.8548E-04  end
  u-238  115  0  2.2191E-02  end
```

```
  pu-238  115  0  9.7800E-07  end
  pu-239  115  0  1.2219E-04  end
  pu-240  115  0  3.0898E-05  end
  pu-241  115  0  1.3243E-05  end
  pu-242  115  0  2.9648E-06  end
  am-241  115  0  3.8025E-06  end
   o      115  0  4.6950E-02  end
' Axial Zone #16 Burnup=19.420GWd/MTU
   u-234  116  0  6.3932E-06  end
   u-235  116  0  5.1526E-04  end
   u-238  116  0  2.2219E-02  end
  pu-238  116  0  7.8518E-07  end
  pu-239  116  0  1.1807E-04  end
  pu-240  116  0  2.7876E-05  end
  pu-241  116  0  1.1595E-05  end
  pu-242  116  0  2.3341E-06  end
  am-241  116  0  3.3162E-06  end
   o      116  0  4.6950E-02  end
' Axial Zone #17 Burnup=14.760GWd/MTU
   u-234  117  0  6.8133E-06  end
   u-235  117  0  6.0067E-04  end
   u-238  117  0  2.2294E-02  end
  pu-238  117  0  3.9092E-07  end
  pu-239  117  0  1.0389E-04  end
  pu-240  117  0  1.9727E-05  end
  pu-241  117  0  7.2867E-06  end
  pu-242  117  0  1.0542E-06  end
  am-241  117  0  2.0606E-06  end
   o      117  0  4.6950E-02  end
' Axial Zone #18 Burnup= 9.240GWd/MTU
   u-234  118  0  7.3392E-06  end
   u-235  118  0  7.1552E-04  end
   u-238  118  0  2.2377E-02  end
  pu-238  118  0  1.1874E-07  end
  pu-239  118  0  7.8671E-05  end
  pu-240  118  0  1.0254E-05  end
  pu-241  118  0  2.8545E-06  end
  pu-242  118  0  2.4012E-07  end
  am-241  118  0  7.9564E-07  end
   o      118  0  4.6950E-02  end
END
'
'    - Zr cladding
zr      2  0  0.04230         293.0  end
'
'
'    - water moderator
h       3  0  0.06674         293.0  end
o-16    3  0  0.03337         293.0  end
'
'    - Stainless Steel [Ref. LA-12827-M, page C-10]
cr      4  0  0.01743      293.0  end
mn      4  0  0.00174      293.0  end
fe      4  0  0.05936      293.0  end
ni      4  0  0.00772      293.0  end
'
'    - Boral Center - B-10 loading of 0.0225 g/sqcm
b-10    5  0  6.5795E-03   293.0  end
b-11    5  0  2.7260E-02   293.0  end
c       5  0  8.4547E-03   293.0  end
al      5  0  4.1795E-02   293.0  end
'
'    - Stainless Steel [Ref. LA-12827-M, page C-10]
cr      6  0  0.01743      293.0  end
mn      6  0  0.00174      293.0  end
fe      6  0  0.05936      293.0  end
ni      6  0  0.00772      293.0  end
'
```

```
'    - Aluminum  [Ref. Duderstadt & Hamilton]
al      7  0  0.0602       293.0  end
'
end comp
'
'           pitch  fuel OD  mfuel  mmod  clad OD  mclad  cladid  mgap
squarepitch 1.2598  0.7844  101     3     0.9144    2    0.8001   3  end
more data
res=102 cylinder 0.3922 dan(102)=0.22877
res=103 cylinder 0.3922 dan(103)=0.22877
res=104 cylinder 0.3922 dan(104)=0.22877
res=105 cylinder 0.3922 dan(105)=0.22877
res=106 cylinder 0.3922 dan(106)=0.22877
res=107 cylinder 0.3922 dan(107)=0.22877
res=108 cylinder 0.3922 dan(108)=0.22877
res=109 cylinder 0.3922 dan(109)=0.22877
res=110 cylinder 0.3922 dan(110)=0.22877
res=111 cylinder 0.3922 dan(111)=0.22877
res=112 cylinder 0.3922 dan(112)=0.22877
res=113 cylinder 0.3922 dan(113)=0.22877
res=114 cylinder 0.3922 dan(114)=0.22877
res=115 cylinder 0.3922 dan(115)=0.22877
res=116 cylinder 0.3922 dan(116)=0.22877
res=117 cylinder 0.3922 dan(117)=0.22877
res=118 cylinder 0.3922 dan(118)=0.22877  end
Generic 32-Assembly Burnup Credit Cask (GC-32) w/Axial Brnp Profile
read param
tme=10000 gen=1100 nsk=100 npg=1000
end parm
read geom
'
'           Fuel Pin
unit           1
cylinder       101 1  0.3922                                    20.318   0.
cylinder       102 1  0.3922                                    40.636   0.
cylinder       103 1  0.3922                                    60.954   0.
cylinder       104 1  0.3922                                    81.272   0.
cylinder       105 1  0.3922                                   101.608   0.
cylinder       106 1  0.3922                                   121.926   0.
cylinder       107 1  0.3922                                   142.281   0.
cylinder       108 1  0.3922                                   162.599   0.
cylinder       109 1  0.3922                                   192.061   0.
cylinder       110 1  0.3922                                   212.379   0.
cylinder       111 1  0.3922                                   223.516   0.
cylinder       112 1  0.3922                                   243.834   0.
cylinder       113 1  0.3922                                   264.152   0.
cylinder       114 1  0.3922                                   284.488   0.
cylinder       115 1  0.3922                                   304.806   0.
cylinder       116 1  0.3922                                   325.124   0.
cylinder       117 1  0.3922                                   345.442   0.
cylinder       118 1  0.3922                                   365.760   0.
cylinder        3  1  0.4001                                    365.76   0.
cylinder        2  1  0.4572                                    365.76   0.
cuboid          3  1  0.6299   -0.6299    0.6299    -0.6299     365.76   0.
'
'           Guide Thimble/Instrument Tube  (assumed to be same)
unit           2
cylinder        3  1  0.5613                                    365.76   0.
cylinder        2  1  0.6020                                    365.76   0.
cuboid          3  1  0.6299   -0.6299    0.6299    -0.6299     365.76   0.
'
'           Top Half Horizontal Boral Panel
unit           4
cuboid          7  1  9.5250   -9.5250     0.02540   -0.0       365.76   0.
cuboid          5  1  9.5250   -9.5250     0.128270  -0.0       365.76   0.
'
'           Right-Hand Side Half Vertical Boral Panel
unit           5
```

```
cuboid          7  1  0.02540   -0.0       9.5250   -9.5250     365.76   0.
cuboid          5  1  0.128270  -0.0       9.5250   -9.5250     365.76   0.
'
'           Bottom Half Horizontal Boral Panel
unit           6
cuboid          7  1  9.5250   -9.5250     0.0     -0.02540     365.76   0.
cuboid          5  1  9.5250   -9.5250     0.0     -0.128270    365.76   0.
'
'           Left-Hand Side Half Vertical Boral Panel
unit           7
cuboid          7  1   0.0     -0.02540    9.5250   -9.5250      365.76   0.
cuboid          5  1   0.0     -0.128270   9.5250   -9.5250      365.76   0.
'
'
'           Assembly Basket Cell
unit          101  ARRAY 1  -10.7086     -10.7086        0.
cuboid          3  1  11.0000  -11.0000   11.0000  -11.0000     365.76   0.
cuboid          4  1  11.7500  -11.7500   11.7500  -11.7500     365.76   0.
cuboid          3  1  11.87827 -11.87827  11.87827 -11.87827    365.76   0.
hole            4    0.         11.75000    0.
hole            5   11.75000     0.         0.
hole            6  0.          -11.75000    0.
hole            7  -11.75000     0.         0.
'
'
'           Top Boral/Basket Plate
unit          110
cuboid          4  1  11.7500  -11.7500    0.0000   -0.7500     365.76   0.
cuboid          3  1  11.7500  -11.7500    0.0000   -0.8783     365.76   0.
hole            6    0.         -0.7500    0.
'
'           Bottom Boral/Basket Plate
unit          111
cuboid          4  1  11.7500  -11.7500    0.7500   -0.0000     365.76   0.
cuboid          3  1  11.7500  -11.7500    0.8783   -0.0000     365.76   0.
hole            4    0.          0.7500    0.
'
'           Left-Hand Side Boral/Basket Plate
unit          112
cuboid          4  1  0.0000   -0.7500    10.9999  -10.9999     365.76   0.
cuboid          3  1  0.0000   -0.8783    10.9999  -10.9999     365.76   0.
hole            7   -0.75000     0.        0.
'
'           Right-Hand Side Boral/Basket Plate
unit          113
cuboid          4  1  0.7500   -0.0000    10.9999  -10.9999     365.76   0.
cuboid          3  1  0.8783   -0.0000    10.9999  -10.9999     365.76   0.
hole            5    0.75000     0.        0.
'
'
'
'           Cask Inner Volume
global  unit   200
cylinder        3  1  87.500                                  395.76  -15.00
'           Assemblies
hole           101 -35.634840    59.391400     0.
hole           101 -11.878270    59.391400     0.
hole           101  11.878270    59.391400     0.
hole           101  35.634840    59.391400     0.
'
hole           101 -59.391400    35.634840     0.
hole           101 -35.634840    35.634840     0.
hole           101 -11.878270    35.634840     0.
hole           101  11.878270    35.634840     0.
hole           101  35.634840    35.634840     0.
hole           101  59.391400    35.634840     0.
'
hole           101 -59.391400    11.878270     0.
```

```
hole           101 -35.634840    11.878270     0.
hole           101 -11.878270    11.878270     0.
hole           101  11.878270    11.878270     0.
hole           101  35.634840    11.878270     0.
hole           101  59.391400    11.878270     0.
'
hole           101 -59.391400   -11.878270     0.
hole           101 -35.634840   -11.878270     0.
hole           101 -11.878270   -11.878270     0.
hole           101  11.878270   -11.878270     0.
hole           101  35.634840   -11.878270     0.
hole           101  59.391400   -11.878270     0.
'
hole           101 -59.391400   -35.634840     0.
hole           101 -35.634840   -35.634840     0.
hole           101 -11.878270   -35.634840     0.
hole           101  11.878270   -35.634840     0.
hole           101  35.634840   -35.634840     0.
hole           101  59.391400   -35.634840     0.
'
hole           101 -35.634840   -59.391400     0.
hole           101 -11.878270   -59.391400     0.
hole           101  11.878270   -59.391400     0.
hole           101  35.634840   -59.391400     0.
'
'
'           Exterior Half Boral Panels
'       Top Plates
hole           110 -35.634840    72.147980     0.
hole           110 -11.878270    72.147980     0.
hole           110  11.878270    72.147980     0.
hole           110  35.634840    72.147980     0.
hole           110  59.391400    48.391420     0.
hole           110 -59.391400    48.391420     0.
'       Bottom Plates
hole           111 -35.634840   -72.147980     0.
hole           111 -11.878270   -72.147980     0.
hole           111  11.878270   -72.147980     0.
hole           111  35.634840   -72.147980     0.
hole           111  59.391400   -48.391420     0.
hole           111 -59.391400   -48.391420     0.
'       Left-Hand Side Plates
hole           112 -48.391420    59.391400     0.
hole           112 -72.147980    35.634840     0.
hole           112 -72.147980    11.878270     0.
hole           112 -72.147980   -11.878270     0.
hole           112 -72.147980   -35.634840     0.
hole           112 -48.391420   -59.391400     0.
'       Right-Hand Side Plates
hole           113  48.391420    59.391400     0.
hole           113  72.147980    35.634840     0.
hole           113  72.147980    11.878270     0.
hole           113  72.147980   -11.878270     0.
hole           113  72.147980   -35.634840     0.
hole           113  48.391420   -59.391400     0.
'
'           Steel Cask/Overpack
cylinder        6  1  107.5                     415.76   -45.
'
'           Cube of Water Surrounding Cask
cuboid          0  1  108  -108   108   -108    415.76   -45.
end geom
'
'
'      Assembly Type: Westinghouse 17x17 OFA/V5
read array
ara=1  nux=17  nuy=17  nuz=1
fill
```

```
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 2 1 1 2 1 1 2 1 1 1 1 1 1
 1 1 1 2 1 1 1 1 1 1 1 1 1 1 2 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 2 1 1 1 1 1 1 1 1 1 1 2 1 1 1
 1 1 1 1 1 2 1 1 2 1 1 2 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
end fill
end array
read bounds  xyf=specular   end bounds
end data
end
```

Sample 2: KRONOS KENO pin model, non-uniform axial profile, actinides + fission products, 40 GWd/MTU

```
=csas25    parm=size=5000000
Pin model from Generic 32-Assembly Burnup Credit Cask (GC-32) w/Axial Brnp Profile
44groupndf5    latticecell
'
'  Proposed Model Rev. 0
'  Last Updated:
'
' * -Assembly Characteristics-
' *     Assembly Type: Westinghouse 17x17 OFA/V5
' *     Assembly Initial Enrichment: 4.0 wt% U-235
' *     Assembly Burnup:          40 GWD/MTU
' *     Assembly Cooling Time:     5 Years
' *
' * -Modeling Characteristics-
' *     18-equi-length node axial profile (365.76cm total fuel height)
' *
' *
' **********  GC-32: Generic 32-Assembly Cask  **********
'
' Axial Zone # 1 Burnup=26.080GWd/MTU
   u-234  101  0  5.8340E-06  end
   u-235  101  0  4.0973E-04  end
   u-236  101  0  9.9617E-05  end
   u-238  101  0  2.2108E-02  end
  pu-238  101  0  1.6433E-06  end
  pu-239  101  0  1.3084E-04  end
  pu-240  101  0  3.9002E-05  end
  pu-241  101  0  1.7628E-05  end
  pu-242  101  0  5.1131E-06  end
  am-241  101  0  5.1130E-06  end
  am-243  101  0  7.3917E-07  end
  np-237  101  0  7.9119E-06  end
  mo-95   101  0  3.7671E-05  end
  tc-99   101  0  3.7533E-05  end
  ru-101  101  0  3.3545E-05  end
  rh-103  101  0  2.1865E-05  end
  ag-109  101  0  2.8280E-06  end
  cs-133  101  0  3.9656E-05  end
  sm-147  101  0  7.0944E-06  end
  sm-149  101  0  2.1069E-07  end
  sm-150  101  0  8.8869E-06  end
  sm-151  101  0  5.8802E-07  end
  sm-152  101  0  3.8126E-06  end
  nd-143  101  0  2.9264E-05  end
  nd-145  101  0  2.1952E-05  end
  eu-153  101  0  2.8369E-06  end
  gd-155  101  0  6.2970E-08  end
' Axial Zone # 2 Burnup=38.680GWd/MTU
   u-234  102  0  4.9188E-06  end
   u-235  102  0  2.5698E-04  end
   u-236  102  0  1.2146E-04  end
   u-238  102  0  2.1885E-02  end
  pu-238  102  0  4.1894E-06  end
  pu-239  102  0  1.4086E-04  end
  pu-240  102  0  5.6579E-05  end
  pu-241  102  0  2.6799E-05  end
  pu-242  102  0  1.2858E-05  end
  am-241  102  0  7.9204E-06  end
  am-243  102  0  2.7610E-06  end
  np-237  102  0  1.3067E-05  end
  mo-95   102  0  5.2660E-05  end
  tc-99   102  0  5.2704E-05  end
  ru-101  102  0  4.8949E-05  end
  rh-103  102  0  3.0205E-05  end
```

```
  ag-109  102  0  4.9333E-06  end
  cs-133  102  0  5.5312E-05  end
  sm-147  102  0  8.5494E-06  end
  sm-149  102  0  2.1912E-07  end
  sm-150  102  0  1.3676E-05  end
  sm-151  102  0  6.8884E-07  end
  sm-152  102  0  5.3830E-06  end
  nd-143  102  0  3.7423E-05  end
  nd-145  102  0  3.0193E-05  end
  eu-153  102  0  4.8979E-06  end
  gd-155  102  0  1.1895E-07  end
' Axial Zone # 3 Burnup=42.960GWd/MTU
   u-234  103  0  4.6211E-06  end
   u-235  103  0  2.1310E-04  end
   u-236  103  0  1.2666E-04  end
   u-238  103  0  2.1796E-02  end
  pu-238  103  0  5.4103E-06  end
  pu-239  103  0  1.4206E-04  end
  pu-240  103  0  6.1895E-05  end
  pu-241  103  0  2.9309E-05  end
  pu-242  103  0  1.6363E-05  end
  am-241  103  0  8.7020E-06  end
  am-243  103  0  3.8968E-06  end
  np-237  103  0  1.4903E-05  end
  mo-95   103  0  5.7775E-05  end
  tc-99   103  0  5.7883E-05  end
  ru-101  103  0  5.4529E-05  end
  rh-103  103  0  3.2827E-05  end
  ag-109  103  0  5.7469E-06  end
  cs-133  103  0  6.0577E-05  end
  sm-147  103  0  8.8820E-06  end
  sm-149  103  0  2.1997E-07  end
  sm-150  103  0  1.5398E-05  end
  sm-151  103  0  7.2112E-07  end
  sm-152  103  0  5.9097E-06  end
  nd-143  103  0  3.9613E-05  end
  nd-145  103  0  3.2922E-05  end
  eu-153  103  0  5.6810E-06  end
  gd-155  103  0  1.4204E-07  end
' Axial Zone # 4 Burnup=44.120GWd/MTU
   u-234  104  0  4.5487E-06  end
   u-235  104  0  2.0292E-04  end
   u-236  104  0  1.2776E-04  end
   u-238  104  0  2.1773E-02  end
  pu-238  104  0  5.7409E-06  end
  pu-239  104  0  1.4223E-04  end
  pu-240  104  0  6.3146E-05  end
  pu-241  104  0  2.9874E-05  end
  pu-242  104  0  1.7295E-05  end
  am-241  104  0  8.8784E-06  end
  am-243  104  0  4.2176E-06  end
  np-237  104  0  1.5358E-05  end
  mo-95   104  0  5.9042E-05  end
  tc-99   104  0  5.9165E-05  end
  ru-101  104  0  5.5940E-05  end
  rh-103  104  0  3.3455E-05  end
  ag-109  104  0  5.9552E-06  end
  cs-133  104  0  6.1872E-05  end
  sm-147  104  0  8.9518E-06  end
  sm-149  104  0  2.2008E-07  end
  sm-150  104  0  1.5828E-05  end
  sm-151  104  0  7.2899E-07  end
  sm-152  104  0  6.0394E-06  end
  nd-143  104  0  4.0103E-05  end
  nd-145  104  0  3.3590E-05  end
  eu-153  104  0  5.8797E-06  end
  gd-155  104  0  1.4801E-07  end
' Axial Zone # 5 Burnup=44.320GWd/MTU
```

```
  u-234  105  0  4.5364E-06  end
  u-235  105  0  2.0120E-04  end
  u-236  105  0  1.2794E-04  end
  u-238  105  0  2.1769E-02  end
 pu-238  105  0  5.7986E-06  end
 pu-239  105  0  1.4225E-04  end
 pu-240  105  0  6.3358E-05  end
 pu-241  105  0  2.9968E-05  end
 pu-242  105  0  1.7458E-05  end
 am-241  105  0  8.9078E-06  end
 am-243  105  0  4.2742E-06  end
 np-237  105  0  1.5435E-05  end
 mo-95   105  0  5.9260E-05  end
 tc-99   105  0  5.9384E-05  end
 ru-101  105  0  5.6182E-05  end
 rh-103  105  0  3.3562E-05  end
 ag-109  105  0  5.9910E-06  end
 cs-133  105  0  6.2094E-05  end
 sm-147  105  0  8.9633E-06  end
 sm-149  105  0  2.2009E-07  end
 sm-150  105  0  1.5902E-05  end
 sm-151  105  0  7.3033E-07  end
 sm-152  105  0  6.0615E-06  end
 nd-143  105  0  4.0185E-05  end
 nd-145  105  0  3.3705E-05  end
 eu-153  105  0  5.9139E-06  end
 gd-155  105  0  1.4904E-07  end
' Axial Zone # 6 Burnup=44.240GWd/MTU
  u-234  106  0  4.5413E-06  end
  u-235  106  0  2.0188E-04  end
  u-236  106  0  1.2787E-04  end
  u-238  106  0  2.1771E-02  end
 pu-238  106  0  5.7756E-06  end
 pu-239  106  0  1.4224E-04  end
 pu-240  106  0  6.3273E-05  end
 pu-241  106  0  2.9930E-05  end
 pu-242  106  0  1.7393E-05  end
 am-241  106  0  8.8960E-06  end
 am-243  106  0  4.2515E-06  end
 np-237  106  0  1.5404E-05  end
 mo-95   106  0  5.9173E-05  end
 tc-99   106  0  5.9296E-05  end
 ru-101  106  0  5.6085E-05  end
 rh-103  106  0  3.3519E-05  end
 ag-109  106  0  5.9767E-06  end
 cs-133  106  0  6.2005E-05  end
 sm-147  106  0  8.9587E-06  end
 sm-149  106  0  2.2009E-07  end
 sm-150  106  0  1.5873E-05  end
 sm-151  106  0  7.2979E-07  end
 sm-152  106  0  6.0527E-06  end
 nd-143  106  0  4.0153E-05  end
 nd-145  106  0  3.3659E-05  end
 eu-153  106  0  5.9001E-06  end
 gd-155  106  0  1.4863E-07  end
' Axial Zone # 7 Burnup=44.080GWd/MTU
  u-234  107  0  4.5511E-06  end
  u-235  107  0  2.0326E-04  end
  u-236  107  0  1.2772E-04  end
  u-238  107  0  2.1774E-02  end
 pu-238  107  0  5.7294E-06  end
 pu-239  107  0  1.4222E-04  end
 pu-240  107  0  6.3104E-05  end
 pu-241  107  0  2.9855E-05  end
 pu-242  107  0  1.7263E-05  end
 am-241  107  0  8.8725E-06  end
 am-243  107  0  4.2063E-06  end
 np-237  107  0  1.5342E-05  end
```

```
  mo-95   107  0  5.8999E-05  end
  tc-99   107  0  5.9121E-05  end
  ru-101  107  0  5.5891E-05  end
  rh-103  107  0  3.3434E-05  end
  ag-109  107  0  5.9480E-06  end
  cs-133  107  0  6.1828E-05  end
  sm-147  107  0  8.9495E-06  end
  sm-149  107  0  2.2008E-07  end
  sm-150  107  0  1.5814E-05  end
  sm-151  107  0  7.2872E-07  end
  sm-152  107  0  6.0349E-06  end
  nd-143  107  0  4.0087E-05  end
  nd-145  107  0  3.3568E-05  end
  eu-153  107  0  5.8728E-06  end
  gd-155  107  0  1.4781E-07  end
' Axial Zone # 8 Burnup=43.880GWd/MTU
   u-234  108  0  4.5635E-06  end
   u-235  108  0  2.0499E-04  end
   u-236  108  0  1.2754E-04  end
   u-238  108  0  2.1778E-02  end
  pu-238  108  0  5.6719E-06  end
  pu-239  108  0  1.4219E-04  end
  pu-240  108  0  6.2891E-05  end
  pu-241  108  0  2.9759E-05  end
  pu-242  108  0  1.7101E-05  end
  am-241  108  0  8.8425E-06  end
  am-243  108  0  4.1502E-06  end
  np-237  108  0  1.5264E-05  end
  mo-95   108  0  5.8781E-05  end
  tc-99   108  0  5.8901E-05  end
  ru-101  108  0  5.5648E-05  end
  rh-103  108  0  3.3326E-05  end
  ag-109  108  0  5.9120E-06  end
  cs-133  108  0  6.1605E-05  end
  sm-147  108  0  8.9378E-06  end
  sm-149  108  0  2.2006E-07  end
  sm-150  108  0  1.5740E-05  end
  sm-151  108  0  7.2737E-07  end
  sm-152  108  0  6.0127E-06  end
  nd-143  108  0  4.0004E-05  end
  nd-145  108  0  3.3453E-05  end
  eu-153  108  0  5.8387E-06  end
  gd-155  108  0  1.4678E-07  end
' Axial Zone # 9 Burnup=43.760GWd/MTU
   u-234  109  0  4.5923E-06  end
   u-235  109  0  2.0904E-04  end
   u-236  109  0  1.2710E-04  end
   u-238  109  0  2.1787E-02  end
  pu-238  109  0  5.5398E-06  end
  pu-239  109  0  1.4213E-04  end
  pu-240  109  0  6.2394E-05  end
  pu-241  109  0  2.9535E-05  end
  pu-242  109  0  1.6729E-05  end
  am-241  109  0  8.7726E-06  end
  am-243  109  0  4.0218E-06  end
  np-237  109  0  1.5083E-05  end
  mo-95   109  0  5.8276E-05  end
  tc-99   109  0  5.8390E-05  end
  ru-101  109  0  5.5086E-05  end
  rh-103  109  0  3.3077E-05  end
  ag-109  109  0  5.8289E-06  end
  cs-133  109  0  6.1089E-05  end
  sm-147  109  0  8.9102E-06  end
  sm-149  109  0  2.2002E-07  end
  sm-150  109  0  1.5568E-05  end
  sm-151  109  0  7.2424E-07  end
  sm-152  109  0  5.9610E-06  end
  nd-143  109  0  3.9809E-05  end
```

```
  nd-145  109  0  3.3187E-05  end
  eu-153  109  0  5.7594E-06  end
  gd-155  109  0  1.4439E-07  end
' Axial Zone #10 Burnup=43.760GWd/MTU
   u-234  110  0  4.5923E-06  end
   u-235  110  0  2.0904E-04  end
   u-236  110  0  1.2710E-04  end
   u-238  110  0  2.1787E-02  end
  pu-238  110  0  5.5398E-06  end
  pu-239  110  0  1.4213E-04  end
  pu-240  110  0  6.2394E-05  end
  pu-241  110  0  2.9535E-05  end
  pu-242  110  0  1.6729E-05  end
  am-241  110  0  8.7726E-06  end
  am-243  110  0  4.0218E-06  end
  np-237  110  0  1.5083E-05  end
  mo-95   110  0  5.8276E-05  end
  tc-99   110  0  5.8390E-05  end
  ru-101  110  0  5.5086E-05  end
  rh-103  110  0  3.3077E-05  end
  ag-109  110  0  5.8289E-06  end
  cs-133  110  0  6.1089E-05  end
  sm-147  110  0  8.9102E-06  end
  sm-149  110  0  2.2002E-07  end
  sm-150  110  0  1.5568E-05  end
  sm-151  110  0  7.2424E-07  end
  sm-152  110  0  5.9610E-06  end
  nd-143  110  0  3.9809E-05  end
  nd-145  110  0  3.3187E-05  end
  eu-153  110  0  5.7594E-06  end
  gd-155  110  0  1.4439E-07  end
' Axial Zone #11 Burnup=43.800GWd/MTU
   u-234  111  0  4.5923E-06  end
   u-235  111  0  2.0904E-04  end
   u-236  111  0  1.2710E-04  end
   u-238  111  0  2.1787E-02  end
  pu-238  111  0  5.5398E-06  end
  pu-239  111  0  1.4213E-04  end
  pu-240  111  0  6.2394E-05  end
  pu-241  111  0  2.9535E-05  end
  pu-242  111  0  1.6729E-05  end
  am-241  111  0  8.7726E-06  end
  am-243  111  0  4.0218E-06  end
  np-237  111  0  1.5083E-05  end
  mo-95   111  0  5.8276E-05  end
  tc-99   111  0  5.8390E-05  end
  ru-101  111  0  5.5086E-05  end
  rh-103  111  0  3.3077E-05  end
  ag-109  111  0  5.8289E-06  end
  cs-133  111  0  6.1089E-05  end
  sm-147  111  0  8.9102E-06  end
  sm-149  111  0  2.2002E-07  end
  sm-150  111  0  1.5568E-05  end
  sm-151  111  0  7.2424E-07  end
  sm-152  111  0  5.9610E-06  end
  nd-143  111  0  3.9809E-05  end
  nd-145  111  0  3.3187E-05  end
  eu-153  111  0  5.7594E-06  end
  gd-155  111  0  1.4439E-07  end
' Axial Zone #12 Burnup=43.840GWd/MTU
   u-234  112  0  4.5923E-06  end
   u-235  112  0  2.0904E-04  end
   u-236  112  0  1.2710E-04  end
   u-238  112  0  2.1787E-02  end
  pu-238  112  0  5.5398E-06  end
  pu-239  112  0  1.4213E-04  end
  pu-240  112  0  6.2394E-05  end
  pu-241  112  0  2.9535E-05  end
```

```
  pu-242  112  0  1.6729E-05  end
  am-241  112  0  8.7726E-06  end
  am-243  112  0  4.0218E-06  end
  np-237  112  0  1.5083E-05  end
  mo-95   112  0  5.8276E-05  end
  tc-99   112  0  5.8390E-05  end
  ru-101  112  0  5.5086E-05  end
  rh-103  112  0  3.3077E-05  end
  ag-109  112  0  5.8289E-06  end
  cs-133  112  0  6.1089E-05  end
  sm-147  112  0  8.9102E-06  end
  sm-149  112  0  2.2002E-07  end
  sm-150  112  0  1.5568E-05  end
  sm-151  112  0  7.2424E-07  end
  sm-152  112  0  5.9610E-06  end
  nd-143  112  0  3.9809E-05  end
  nd-145  112  0  3.3187E-05  end
  eu-153  112  0  5.7594E-06  end
  gd-155  112  0  1.4439E-07  end
' Axial Zone #13 Burnup=43.800GWd/MTU
   u-234  113  0  4.5923E-06  end
   u-235  113  0  2.0904E-04  end
   u-236  113  0  1.2710E-04  end
   u-238  113  0  2.1787E-02  end
  pu-238  113  0  5.5398E-06  end
  pu-239  113  0  1.4213E-04  end
  pu-240  113  0  6.2394E-05  end
  pu-241  113  0  2.9535E-05  end
  pu-242  113  0  1.6729E-05  end
  am-241  113  0  8.7726E-06  end
  am-243  113  0  4.0218E-06  end
  np-237  113  0  1.5083E-05  end
  mo-95   113  0  5.8276E-05  end
  tc-99   113  0  5.8390E-05  end
  ru-101  113  0  5.5086E-05  end
  rh-103  113  0  3.3077E-05  end
  ag-109  113  0  5.8289E-06  end
  cs-133  113  0  6.1089E-05  end
  sm-147  113  0  8.9102E-06  end
  sm-149  113  0  2.2002E-07  end
  sm-150  113  0  1.5568E-05  end
  sm-151  113  0  7.2424E-07  end
  sm-152  113  0  5.9610E-06  end
  nd-143  113  0  3.9809E-05  end
  nd-145  113  0  3.3187E-05  end
  eu-153  113  0  5.7594E-06  end
  gd-155  113  0  1.4439E-07  end
' Axial Zone #14 Burnup=43.440GWd/MTU
   u-234  114  0  4.5923E-06  end
   u-235  114  0  2.0904E-04  end
   u-236  114  0  1.2710E-04  end
   u-238  114  0  2.1787E-02  end
  pu-238  114  0  5.5398E-06  end
  pu-239  114  0  1.4213E-04  end
  pu-240  114  0  6.2394E-05  end
  pu-241  114  0  2.9535E-05  end
  pu-242  114  0  1.6729E-05  end
  am-241  114  0  8.7726E-06  end
  am-243  114  0  4.0218E-06  end
  np-237  114  0  1.5083E-05  end
  mo-95   114  0  5.8276E-05  end
  tc-99   114  0  5.8390E-05  end
  ru-101  114  0  5.5086E-05  end
  rh-103  114  0  3.3077E-05  end
  ag-109  114  0  5.8289E-06  end
  cs-133  114  0  6.1089E-05  end
  sm-147  114  0  8.9102E-06  end
  sm-149  114  0  2.2002E-07  end
```

```
  sm-150  114  0  1.5568E-05  end
  sm-151  114  0  7.2424E-07  end
  sm-152  114  0  5.9610E-06  end
  nd-143  114  0  3.9809E-05  end
  nd-145  114  0  3.3187E-05  end
  eu-153  114  0  5.7594E-06  end
  gd-155  114  0  1.4439E-07  end
' Axial Zone #15 Burnup=42.360GWd/MTU
   u-234  115  0  4.6590E-06  end
   u-235  115  0  2.1853E-04  end
   u-236  115  0  1.2605E-04  end
   u-238  115  0  2.1808E-02  end
  pu-238  115  0  5.2422E-06  end
  pu-239  115  0  1.4195E-04  end
  pu-240  115  0  6.1232E-05  end
  pu-241  115  0  2.9005E-05  end
  pu-242  115  0  1.5887E-05  end
  am-241  115  0  8.6072E-06  end
  am-243  115  0  3.7357E-06  end
  np-237  115  0  1.4666E-05  end
  mo-95   115  0  5.7113E-05  end
  tc-99   115  0  5.7213E-05  end
  ru-101  115  0  5.3798E-05  end
  rh-103  115  0  3.2496E-05  end
  ag-109  115  0  5.6392E-06  end
  cs-133  115  0  5.9899E-05  end
  sm-147  115  0  8.8436E-06  end
  sm-149  115  0  2.1991E-07  end
  sm-150  115  0  1.5174E-05  end
  sm-151  115  0  7.1700E-07  end
  sm-152  115  0  5.8419E-06  end
  nd-143  115  0  3.9348E-05  end
  nd-145  115  0  3.2572E-05  end
  eu-153  115  0  5.5781E-06  end
  gd-155  115  0  1.3897E-07  end
' Axial Zone #16 Burnup=38.840GWd/MTU
   u-234  116  0  4.8895E-06  end
   u-235  116  0  2.5252E-04  end
   u-236  116  0  1.2202E-04  end
   u-238  116  0  2.1877E-02  end
  pu-238  116  0  4.3002E-06  end
  pu-239  116  0  1.4101E-04  end
  pu-240  116  0  5.7114E-05  end
  pu-241  116  0  2.7059E-05  end
  pu-242  116  0  1.3180E-05  end
  am-241  116  0  8.0012E-06  end
  am-243  116  0  2.8605E-06  end
  np-237  116  0  1.3245E-05  end
  mo-95   116  0  5.3158E-05  end
  tc-99   116  0  5.3207E-05  end
  ru-101  116  0  4.9484E-05  end
  rh-103  116  0  3.0465E-05  end
  ag-109  116  0  5.0105E-06  end
  cs-133  116  0  5.5827E-05  end
  sm-147  116  0  8.5854E-06  end
  sm-149  116  0  2.1924E-07  end
  sm-150  116  0  1.3842E-05  end
  sm-151  116  0  6.9203E-07  end
  sm-152  116  0  5.4345E-06  end
  nd-143  116  0  3.7651E-05  end
  nd-145  116  0  3.0461E-05  end
  eu-153  116  0  4.9726E-06  end
  gd-155  116  0  1.2112E-07  end
' Axial Zone #17 Burnup=29.520GWd/MTU
   u-234  117  0  5.5626E-06  end
   u-235  117  0  3.6174E-04  end
   u-236  117  0  1.0694E-04  end
   u-238  117  0  2.2048E-02  end
```

```
  pu-238  117  0  2.2316E-06  end
  pu-239  117  0  1.3500E-04  end
  pu-240  117  0  4.4351E-05  end
  pu-241  117  0  2.0518E-05  end
  pu-242  117  0  6.9686E-06  end
  am-241  117  0  5.9884E-06  end
  am-243  117  0  1.1495E-06  end
  np-237  117  0  9.3498E-06  end
  mo-95   117  0  4.2027E-05  end
  tc-99   117  0  4.1935E-05  end
  ru-101  117  0  3.7885E-05  end
  rh-103  117  0  2.4369E-05  end
  ag-109  117  0  3.3938E-06  end
  cs-133  117  0  4.4229E-05  end
  sm-147  117  0  7.5922E-06  end
  sm-149  117  0  2.1422E-07  end
  sm-150  117  0  1.0229E-05  end
  sm-151  117  0  6.1836E-07  end
  sm-152  117  0  4.2733E-06  end
  nd-143  117  0  3.1881E-05  end
  nd-145  117  0  2.4379E-05  end
  eu-153  117  0  3.3935E-06  end
  gd-155  117  0  7.7217E-08  end
' Axial Zone #18 Burnup=18.480GWd/MTU
   u-234  118  0  6.4886E-06  end
   u-235  118  0  5.3420E-04  end
   u-236  118  0  7.9326E-05  end
   u-238  118  0  2.2237E-02  end
  pu-238  118  0  6.7916E-07  end
  pu-239  118  0  1.1528E-04  end
  pu-240  118  0  2.6025E-05  end
  pu-241  118  0  1.0558E-05  end
  pu-242  118  0  1.9856E-06  end
  am-241  118  0  3.0123E-06  end
  am-243  118  0  1.9430E-07  end
  np-237  118  0  4.8310E-06  end
  mo-95   118  0  2.7393E-05  end
  tc-99   118  0  2.7188E-05  end
  ru-101  118  0  2.3708E-05  end
  rh-103  118  0  1.5795E-05  end
  ag-109  118  0  1.6590E-06  end
  cs-133  118  0  2.8824E-05  end
  sm-147  118  0  5.6700E-06  end
  sm-149  118  0  1.9789E-07  end
  sm-150  118  0  5.9210E-06  end
  sm-151  118  0  5.1262E-07  end
  sm-152  118  0  2.7095E-06  end
  nd-143  118  0  2.2392E-05  end
  nd-145  118  0  1.6130E-05  end
  eu-153  118  0  1.6900E-06  end
  gd-155  118  0  3.6424E-08  end
END
   o      101  0  4.6950E-02  end
   o      102  0  4.6950E-02  end
   o      103  0  4.6950E-02  end
   o      104  0  4.6950E-02  end
   o      105  0  4.6950E-02  end
   o      106  0  4.6950E-02  end
   o      107  0  4.6950E-02  end
   o      108  0  4.6950E-02  end
   o      109  0  4.6950E-02  end
   o      110  0  4.6950E-02  end
   o      111  0  4.6950E-02  end
   o      112  0  4.6950E-02  end
   o      113  0  4.6950E-02  end
   o      114  0  4.6950E-02  end
   o      115  0  4.6950E-02  end
   o      116  0  4.6950E-02  end
```

```
   o      117  0  4.6950E-02  end
   o      118  0  4.6950E-02  end
'
'    - Zr cladding
zr      2  0  0.04230         293.0  end
'
'
'    - water moderator
h       3  0  0.06674         293.0  end
o-16    3  0  0.03337         293.0  end
end comp
'
'           pitch  fuel OD  mfuel  mmod  clad OD  mclad  cladid  mgap
squarepitch 1.2598  0.7844  101     3     0.9144    2    0.8001   3  end
more data
res=102 cylinder 0.3922 dan(102)=0.22877
res=103 cylinder 0.3922 dan(103)=0.22877
res=104 cylinder 0.3922 dan(104)=0.22877
res=105 cylinder 0.3922 dan(105)=0.22877
res=106 cylinder 0.3922 dan(106)=0.22877
res=107 cylinder 0.3922 dan(107)=0.22877
res=108 cylinder 0.3922 dan(108)=0.22877
res=109 cylinder 0.3922 dan(109)=0.22877
res=110 cylinder 0.3922 dan(110)=0.22877
res=111 cylinder 0.3922 dan(111)=0.22877
res=112 cylinder 0.3922 dan(112)=0.22877
res=113 cylinder 0.3922 dan(113)=0.22877
res=114 cylinder 0.3922 dan(114)=0.22877
res=115 cylinder 0.3922 dan(115)=0.22877
res=116 cylinder 0.3922 dan(116)=0.22877
res=117 cylinder 0.3922 dan(117)=0.22877
res=118 cylinder 0.3922 dan(118)=0.22877  end
Generic 32-Assembly Burnup Credit Cask (GC-32) w/Axial Brnp Profile
read param
tme=100000 gen=1100 nsk=100 npg=1000
end parm
read geom
'
'           Fuel Pin
global unit           1
cylinder       101 1  0.3922                                    20.318   0.
cylinder       102 1  0.3922                                    40.636   0.
cylinder       103 1  0.3922                                    60.954   0.
cylinder       104 1  0.3922                                    81.272   0.
cylinder       105 1  0.3922                                   101.608   0.
cylinder       106 1  0.3922                                   121.926   0.
cylinder       107 1  0.3922                                   142.281   0.
cylinder       108 1  0.3922                                   162.599   0.
cylinder       109 1  0.3922                                   192.061   0.
cylinder       110 1  0.3922                                   212.379   0.
cylinder       111 1  0.3922                                   223.516   0.
cylinder       112 1  0.3922                                   243.834   0.
cylinder       113 1  0.3922                                   264.152   0.
cylinder       114 1  0.3922                                   284.488   0.
cylinder       115 1  0.3922                                   304.806   0.
cylinder       116 1  0.3922                                   325.124   0.
cylinder       117 1  0.3922                                   345.442   0.
cylinder       118 1  0.3922                                   365.760   0.
cylinder         3  1  0.4001                                   365.76   0.
cylinder         2  1  0.4572                                   365.76   0.
cuboid           3  1  0.6299   -0.6299    0.6299    -0.6299     365.76   0.
end geom
read bounds  xyf=specular   end bounds
end data
end
```

Sample 3: KRONOS XSDRN pin-cell model, actinides + fission products, 60 GWd/MTU

```
=csas1x    parm=size=5000000
1D Pin Cell based on Generic 32-Assembly Burnup Credit Cask (GC-32)
44groupndf5    latticecell
'
'  Proposed Model Rev. 0
'  Last Updated:
'
' * -Assembly Characteristics-
' *      Assembly Type: Westinghouse 17x17 OFA/V5
' *      Assembly Initial Enrichment: 4.0 wt% U-235
' *      Assembly Burnup:          60 GWD/MTU
' *      Assembly Cooling Time:     5 Years
' *
' **********  GC-32: Generic 32-Assembly Cask  **********
'
' Axial Zone # 1 Burnup=60.000GWd/MTU
   u-234  101  0  3.7059E-06  end
   u-235  101  0  9.9874E-05  end
   u-236  101  0  1.3500E-04  end
   u-238  101  0  2.1447E-02  end
  pu-238  101  0  1.0666E-05  end
  pu-239  101  0  1.4200E-04  end
  pu-240  101  0  7.6215E-05  end
  pu-241  101  0  3.5028E-05  end
  pu-242  101  0  3.0719E-05  end
  am-241  101  0  1.0482E-05  end
  am-243  101  0  9.5428E-06  end
  np-237  101  0  2.0692E-05  end
  mo-95   101  0  7.4788E-05  end
  tc-99   101  0  7.4645E-05  end
  ru-101  101  0  7.4458E-05  end
  rh-103  101  0  4.0351E-05  end
  ag-109  101  0  8.7300E-06  end
  cs-133  101  0  7.9475E-05  end
  sm-147  101  0  9.4362E-06  end
  sm-149  101  0  2.1861E-07  end
  sm-150  101  0  2.1208E-05  end
  sm-151  101  0  8.2419E-07  end
  sm-152  101  0  7.6169E-06  end
  nd-143  101  0  4.4382E-05  end
  nd-145  101  0  4.1600E-05  end
  eu-153  101  0  8.4315E-06  end
  gd-155  101  0  2.2731E-07  end
END
   o      101  0  4.6950E-02  end
'
'    - Zr cladding
zr      2  0  0.04230         293.0  end
'
'
'    - water moderator
h       3  0  0.06674         293.0  end
o-16    3  0  0.03337         293.0  end
end comp
'
'           pitch  fuel OD  mfuel  mmod  clad OD  mclad  cladid  mgap
squarepitch 1.2598  0.7844  101     3     0.9144    2    0.8001   3  end
end
```

INTERNAL DISTRIBUTION

1. C. K. Bayne, 6011, MS-6418
2. S. M. Bowman, 6011, MS-6370
3. B. L. Broadhead, 6011, MS-6370
4. W. C. Carter, 6011, MS-6370
5. M. E. Dunn, 6011, MS-6370
6. M. D. DeHart, 6011, MS-6370
7. K. R. Elam, 6011, MS-6370
8. R. J. Ellis, 6025, MS-6363
9. M. B. Emmett, 6011, MS-6370
10. I. C. Gauld, 6011, MS-6370
11. S. Goluoglu, 6011, MS-6370
12. D. F. Hollenbach, 6011, MS-6370
13. C. M. Hopper, 6011, MS-6370
14. D. T. Ingersoll, 6025, MS-6363
15. B. L. Kirk, 6025, MS-6362
16. M. A. Kuliasha, 6025, MS-6435
17. L. C. Leal, 6011, MS-6370
18. C. V. Parks, 6011, MS-6370
19. L. M. Petrie, 6011, MS-6370
20. R. T. Primm, 6025, MS-6363
21. B. T. Rearden, 6011, MS-6370
22. C. E. Sanders, 6011, MS-6370
23. J. C. Wagner, 6011, MS-6370
24. R. M. Westfall, 6011, MS-6370
25. Central Research Library
    4500N, MS-6191
26. ORNL Laboratory Records - RC
    4500N- MS-6254

EXTERNAL DISTRIBUTION

27. J-H. Baik, Korea Power Engineering Company, Inc. (KOPEC), 150 Duckjin-Dong, Yusong, Taejon, South Korea 305-353
28. M. C. Brady Raap, Battelle, Pacific Northwest National Laboratory, P.O. Box 999 / MSK8-34, Richland, WA 99352
29. D. E. Carlson, RES/DSARE/REAHFB, U.S. Nuclear Regulatory Commission, MS T10F-13A, Washington, DC 20555-0001
30. C. W. Connell, Framatome-ANP, PO Box 10935, Lynchburg, VA 24506-0935
31. J. Conde, Consejo de Seguridad Nuclear, Justo Dorado, 11, 28040 Madrid, Spain
32. T. W. Doering, Framatome Cogema Fuels, 1261 Town Center Drive, Las Vegas, Nevada 89144
33. D. Henderson, Framatome-ANP, PO Box 10935, Lynchburg, VA 24506-0935
34. H-R. Hwang, Radiation Safety Analysis Group Manager, Korea Power Engineering Company,Inc.(KOPEC), 150 Duckjin-Dong, Yusong, Taejon, South Korea 305-353
35. R. A. Kochendarfer, Framatome-ANP, PO Box 10935, Lynchburg, VA 24506-0935
36. D. B. Lancaster, NuclearConsultants.com, 320 South Corl Street, State College, PA 16801
37. C. W. Mays, Framatome-ANP, PO Box 10935, Lynchburg, VA 24506-0935
38. J. McClure, BSC, Inc., 1261 Town Center Drive, Las Vegas, NV 89144
39. D. Mennerdahl, E. Mennerdahl Systems, Starvägen 12, S-183 57 Täby, Sweden

40. J-C. Neuber, Framatome-ANP, Dept. NDM3, P.O. Box 101063, D-63010 Offenbach, Germany
41. R. L. Murray, North Carolina State University, P.O. Box 5596, State University Station, Raleigh, North Carolina 27650
42. P. Noel, BSC, Inc., 1261 Town Center Drive, Las Vegas, NV 89144
43. A. Nouri, OECD Nuclear Energy Agency, 12, Bd des Iles, 92130 Issy-les-Moulineaux, FRANCE
44. H. Okuno, Japan Atomic Energy Research Institute, 2-4 Shirakara-shirane, Tokai-mura, Ibaraki-ken, JAPAN 319-1195

45B46. Office of Scientific and Technical Information, U.S. Department of Energy, P.O. Box 62, Oak Ridge, TN 37831

47. J. Pegram, Framatome-ANP, PO Box 10935, Lynchburg, VA 24506-0935
48. R. E. Pevey, University of Tennessee, Nuclear Engineering Dept., 214 Pasqua Engineering Bldg., Knoxville, TN 37922
49. M. Rahimi, NMSS/DWM/HLWB, U.S. Nuclear Regulatory Commission, MS T7-F3, Washington, DC 20555-0001
50. J. Sapyta, Framatome-ANP, PO Box 10935, Lynchburg, VA 24506-0935
51. E. Sartori, OECD Nuclear Energy Agency, 12, Bd des Iles, 92130 Issy-les-Moulineaux, FRANCE
52. J. Scaglione, BSC, Inc., 1261 Town Center Drive, Las Vegas, NV 89144
53. D. A. Thomas, BSC, Inc., 1261 Town Center Drive, Las Vegas, NV 89144
54. C. J. Withee, NMSS/SFPO/TRD, U.S. Nuclear Regulatory Commission, MS O13-D13, Washington, DC 20555-0001