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Computational Benchmark for Estimation of Reactivity Margin from Fission Products and Minor Actinides in PWR Burnup Credit

Oak Ridge National Laboratory

U.S. Nuclear Regulatory Commission
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ABSTRACT

This report proposes and documents a computational benchmark problem for the estimation of the additional reactivity margin available in spent nuclear fuel (SNF) from fission products and minor actinides in a burnup-credit storage/transport environment, relative to SNF compositions containing only the major actinides. The benchmark problem/configuration is a generic burnup credit cask designed to hold 32 pressurized water reactor (PWR) assemblies. The purpose of this computational benchmark is to provide a reference configuration for the estimation of the additional reactivity margin, which is encouraged in the U.S. Nuclear Regulatory Commission (NRC) guidance for partial burnup credit (ISG8), and document reference estimations of the additional reactivity margin as a function of initial enrichment, burnup, and cooling time. Consequently, the geometry and material specifications are provided in sufficient detail to enable independent evaluations. Estimates of additional reactivity margin for this reference configuration may be compared to those of similar burnup-credit casks to provide an indication of the validity of design-specific estimates of fission-product margin. The reference solutions were generated with the SAS2H-depletion and CSAS25-criticality sequences of the SCALE 4.4a package. Although the SAS2H and CSAS25 sequences have been extensively validated elsewhere, the reference solutions are not directly or indirectly based on experimental results. Consequently, this computational benchmark cannot be used to satisfy the ANS 8.1 requirements for validation of calculational methods and is not intended to be used to establish biases for burnup credit analyses.

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1 INTRODUCTION

This report proposes and documents a computational benchmark for the estimation of the additional reactivity margin available from fission products and minor actinides, relative to calculations based on major actinides only, in a pressurized water reactor (PWR) burnup credit storage/transport environment. Herein, the major actinides are consistent with those specified in a Department of Energy (DOE) topical report[1] on burnup credit (i.e., ^{234}U, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am). Although the additional reactivity margin is primarily due to fission products, a few minor actinides (i.e., ^{236}U, ^{237}Np, and ^{243}Am) that have been identified as being relevant to burnup credit[2] have been included in this benchmark to provide a more complete assessment of the additional reactivity margin beyond the major actinides. The proposed benchmark problem was developed to be similar to current burnup credit style casks, including similar materials and dimensions. While preserving all of the important features, it approximates (or eliminates) nonessential details and proprietary information. The documentation of this computational benchmark includes all of the necessary geometric and material specifications to permit independent evaluations and sufficiently detailed reference solutions to enable meaningful comparisons. Select isotopic compositions are provided to facilitate comparisons. The reference solutions were generated with the SAS2H-depletion and CSAS25-criticality modules of the SCALE 4.4a package.[3] It is important that the reader and potential users of this report understand that this is a ***computational*** benchmark, and as such, the reference solutions are based on calculations. Although the SAS2H and CSAS25 sequences have been validated using laboratory critical experiments, commercial reactor criticals (CRCs), measured chemical assay data, and reactivity worth measurements with individual fission products important to burnup credit, the reference solutions are not directly or indirectly based on experimental results.

1.1 PURPOSE

The purpose of this computational benchmark is to provide a reference configuration to help normalize the estimation of reactivity margin available from fission products and minor actinides, and document estimates of the additional reactivity margin as a function of initial enrichment, burnup, and cooling time. Estimates of the additional reactivity margin for this reference configuration may be compared to those of similar burnup credit style casks to provide an indication of the validity of design-specific estimates of the additional reactivity margin. Detailed geometry and material specifications are provided to enable independent estimations and comparisons. As reference solutions are provided in terms of differences in effective neutron multiplication factors (Δk values), benchmarking of depletion and criticality codes, individually, is not the intent. Comparison of calculated results to the reference solutions does not satisfy the ANS 8.1 (Ref. 4) requirements for validation of calculational methods, which states that validation of a calculational method by comparing the results with those of another calculational method is unacceptable. Consequently, this computational benchmark is not intended to be used to establish biases for burnup credit analyses.

1.2 BACKGROUND

In the past, criticality safety analyses for commercial light-water reactor (LWR) spent fuel storage and transport canisters[5,6] have assumed the spent nuclear fuel (SNF) to be fresh (unirradiated) fuel with uniform isotopic compositions corresponding to the maximum allowable enrichment. This "*fresh-fuel assumption*" provides a well-defined, bounding approach for the criticality safety analysis that eliminates all concerns related to the fuel operating history, and thus considerably simplifies the safety analysis. However, because this assumption ignores the decrease in reactivity as a result of irradiation, it is very conservative and can limit the SNF capacity for a given package volume.

*The concept of taking credit for the reduction in reactivity due to fuel burnup is commonly referred to as **burnup credit**.* The reduction in reactivity that occurs with fuel burnup is due to the change in concentration (net reduction) of fissile nuclides and the production of actinide and fission-product neutron absorbers. Consequently, it has been recognized that if criticality calculations are performed based on all fissile nuclides and a limited subset of absorbers, the calculated neutron multiplication factor (k_{eff}) is conservative (i.e., k_{eff} is overestimated). To date, the proposed approach[1,7] for burnup credit in storage and transportation casks has been to qualify calculated isotopic predictions via validation against destructive assay measurements from SNF samples. Thus, utilization of nuclides in a safety analysis process has been primarily limited by the availability of measured assay data. An additional consideration has been the chemical characteristics (e.g., volatility) that could potentially allow the nuclide to escape the fuel region.[8]

Isotopic validation studies using the SCALE/SAS2H depletion sequence and available measured assay data have been performed for PWR spent fuel[9,10,11] and boiling water reactor (BWR) spent fuel.[12] For the most part, the fission product data available in the United States for PWR fuel are limited to 3–6 samples,[9] and calculational methods for these nuclides may not be considered to be fully validated. Note that additional chemical assay data are becoming available that will enable improved validation for fission products. However, the paucity of available chemical assay data for fission products is the major reason that only partial or "actinide-only" burnup credit was considered in a topical report[1] prepared by the DOE and the U.S. Nuclear Regulatory Commission (NRC) interim staff guidance (ISG8)[13] on burnup credit. "Actinide-only burnup credit" refers to criticality analyses that include only a limited set of actinide isotopes in the SNF (i.e., fission products and certain other actinides are not included in the criticality analysis). The additional reduction in reactivity due to the presence of the fission products, often referred to as the *fission product margin*, is still present in reality; but since sufficient measured data for isotopic validation do not exist, credit for their negative reactivity worth has not generally been recommended for inclusion in safety analyses for storage and transport.

Studies[14,15,1] have been performed to quantify the incremental reactivity worth of actinides and fission products for an infinite lattice of fuel pins. The results indicate that, for typical discharge burnup values, approximately 2/3 of the reactivity decrease is due to actinides, with the remaining 1/3 due to fission products. However, it is important to note that the competing effect of external absorbers in cask designs affect this ratio for finite cask analysis, resulting in a relative reduction in the reactivity worth of the fission products.[2,16] This reduced effect has been demonstrated and has led to some concerns regarding the estimation of fission product margin in different systems.[16]

1.3 ESTIMATION OF ADDITIONAL REACTIVITY MARGIN

1.3.1 Regulatory Guidance

The NRC interim staff guidance (ISG8)[13] on burnup credit in storage/transport casks permits partial credit for burnup in PWR fuel. ISG8 limits credit for the reactivity reduction associated with burnup to that available from actinide compositions (i.e., actinide-only burnup credit). Moreover, the actinides are limited to those that are established by validation (e.g., benchmarks of applicable fuel assay measurements). Credit for the reactivity reduction due to fission products is not currently included due to the greater uncertainties associated with inventory prediction and cross-section data for fission products. Consequently, an added margin of subcriticality exists due to the presence of fission product and actinide nuclides not included in the design-basis safety analysis. To assess the effect of fission products, and thus gain a greater understanding of the actual subcritical margin, ISG8 calls for design-specific analyses to estimate the additional reactivity margins available from the fission products and actinide nuclides not included in the design-basis safety analysis. Additionally, ISG8 states that, "the analysis methods used for determining the estimated reactivity margins should be verified using available experimental data (e.g., isotopic assay data) and computational benchmarks that demonstrate the performance of the applicant's methods in comparison with independent methods and analyses." Further, ISG8 states that, "design-specific margins should be evaluated over the full range of initial enrichments and burnups on the burnup credit loading curve(s)."

Besides assessing the actual subcritical margin as recommended in the regulatory guidance, the potential utilization of some portion of the additional reactivity margin provides added incentive for its estimation. ISG8 recommends that the estimated margins be assessed against estimates of (a) any uncertainties not directly evaluated in the modeling or validation processes and (b) any potential nonconservatisms in the models for calculating the licensing safety basis actinide inventories.

1.3.2 Available Resources for Meeting the Regulatory Guidance

The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) sponsors an Expert Group tasked with the study of burnup credit issues. The Expert Group on Burnup Credit (EGBUC), formerly known as the BUCWG, defines and analyzes computational benchmarks for the purpose of international comparison of computer code/data packages used for the analysis of spent fuel. The broad scope of international participants enables comparison of a wide range of codes, data, and methods for each benchmark problem. To date, the EGBUC has studied a number of different configurations relevant to burnup credit in LWR fuel.[17] The studies (or phases) relevant to PWR burnup credit include: Phase I, which investigated the calculation of the neutron multiplication factor for an infinite lattice of PWR pins and the prediction of isotopic composition of spent PWR fuel under simplified operating conditions[15,18] and Phase II, which investigated the effect of the axial burnup distribution in a radially infinite array of PWR pins and in a conceptual burnup credit cask.[19,20] The ISG8 refers to the OECD/NEA's EGBUC as a source of computational benchmarks that may be considered.

Another resource for meeting the regulatory guidance is the limited isotopic assay data available for fission products.[9] Finally, it should be noted that this discussion of available resources is not exhaustive. A number of ongoing research projects, both domestically and internationally, have already or soon will contribute to the pool of available resources and experimental data for validating estimations of the additional reactivity margin available from fission product and minor actinide nuclides.

2 BENCHMARK SPECIFICATION

To provide a reference burnup-credit-style cask configuration that is not constrained by unnecessary detail or proprietary information, a generic 32 PWR-assembly burnup credit cask design was developed. This generic cask design is proposed as a reference configuration to normalize analyses and estimations of the additional reactivity margin available from fission product and minor actinide nuclides. A physical description of the generic burnup credit cask, referred to herein as the GBC-32 cask, is provided in this section. Reference fuel assembly dimensions, corresponding to a 17 × 17 Westinghouse optimized fuel assembly (OFA), are also provided in this section.

2.1 GBC-32 CASK SPECIFICATION

The primary motivation for burnup credit is to eliminate the need for flux-traps between PWR assembly storage cells, and thus increase storage and transport cask capacities for a constant canister volume. For the current large, rail-type cask internal dimensions, this could enable an increase in the assembly capacity by as much as one-third (e.g., increasing total assembly capacity from ~24 to ~32). Although individual canister capacities will vary depending on the inner diameter and assembly cell size, typical burnup credit rail casks are expected to accommodate between 24 and 40 assemblies. Canisters designed to accommodate large PWR assemblies (e.g., 15 × 15 & 17 × 17) are expected to have maximum capacities of approximately 32 assemblies, while canisters designed to accommodate the smaller PWR assemblies (e.g., 14 × 14 & 16 × 16) are expected to have maximum capacities nearing 40 assemblies.

With these thoughts in mind, a review of various cask designs, and consideration of the OECD/NEA conceptual PWR spent fuel transportation cask,[20] a generic burnup credit cask design was developed. The design was developed to meet the following criteria: (1) the internal dimensions and geometry should be representative of typical U.S. rail-type casks, (2) the canister must accommodate at least 30 fuel assemblies, (3) the assembly cell size must be large enough to accommodate all common PWR fuel assembly designs, and (4) the design must be general (i.e., no proprietary information and no unique features that would unnecessarily limit its applicability for analyses). The generic design employs features from several U.S. cask vendor's designs (e.g., similar canister inside diameter and Boral[21] for fixed neutron poison), as well as features from the OECD benchmark cask.[20] The generic cask design, designated GBC-32, will accommodate 32 PWR fuel assemblies. Dimensions for the GBC-32 cask are listed in Table 1. For simplicity, the fuel assemblies are centered in the storage cells and the assembly upper and lower hardware are modeled as water. The height of the fuel assembly cell, which includes the Boral panel, is equivalent to the active fuel length, and the upper and lower boundaries are coincident. Material specifications are provided in Table 2.

Table 1 Physical dimensions for the GBC-32 cask

Parameter	inches	cm
Cell inside dimension (I.D.)	8.6614	22.0000
Cell outside dimension (O.D.)	9.2520	23.5000
Cell wall thickness	0.2953	0.7500
Boral panel thickness†	0.1010	0.2565
Boral center thickness	0.0810	0.2057
Boral Al plate thickness	0.0100	0.0254
Cell pitch	9.3530	23.7565
Boral panel width	7.5000	19.0500
Cell height‡	144.0000	365.76
Boral panel height‡	144.0000	365.76
Cask inside diameter (I.D.)	68.8976	175.0000
Cask outside diameter (O.D.)	84.6457	215.0000
Cask radial thickness	7.8740	20.0000
Base plate thickness	11.8110	30.0000
Cask lid thickness	11.8110	30.0000
Cask inside height	161.7165	410.7600
Active fuel height‡	144.0000	365.76
Bottom assembly hardware thickness	5.9055	15.0000
Top assembly hardware thickness	11.8110	30.0000

† Boral is a clad composite of aluminum and boron carbide. A Boral panel or plate consists of three distinct layers. The outer layers are aluminum cladding which form a sandwich with a central layer that consists of a uniform aggregate of fine boron carbide particles within an aluminum alloy matrix.

‡ The cell height, Boral panel height, and active fuel height are all equivalent and their lower boundaries are coincident, 15 cm above the base plate.

Table 2 Material compositions for GBC-32 cask model

Isotope	Atom density (atoms/b-cm)	Weight percent
Water (Density = 0.9983 g/cm^3)		
Hydrogen (H)	0.06674	11.19
Oxygen (O)	0.03337	88.81
Total	0.10011	100.0
Stainless steel 304 (Density = 7.92 g/cm^3) [22]		
Chromium (Cr)	0.01743	19.0
Manganese (Mn)	0.00174	2.0
Iron (Fe)	0.05936	69.5
Nickel (Ni)	0.00772	9.5
Total	0.08625	100.0
Boral panel Aluminum cladding (Density = 2.699 g/cm^3)		
Aluminum (Al)	0.0602 [23]	100.0
Total	0.0602	100.0
Boral panel central layer (0.0225 g B-10/cm^2)†		
Boron-10 (B-10)	6.5794E-03	4.13
Boron-11 (B-11)	2.7260E-02	18.81
Carbon (C)	8.4547E-03	6.37
Aluminum (Al)	4.1795E-02	70.69
Total	8.4089E-02	100.0

† Note: 0.030 g B-10/cm^2 is the loading from the manufacturer (AAR[21]) that corresponds to the modeled Boral panel thickness of 0.101 inches. However, current NRC regulations[5] allow only 75% credit for fixed neutron absorbers, and thus 75% of 0.030, or 0.0225 g B-10/cm^2 is used.

2.2 PWR FUEL ASSEMBLY SPECIFICATION

The reference fuel assembly design used in the GBC-32 cask is the Westinghouse 17 × 17 OFA. This assembly was selected as the reference because it has been shown to be the most reactive assembly in most fresh-fuel cask designs.[5] However, it is acknowledged that this assembly design will likely not be the most reactive in a burnup credit cask design. The characteristic that makes this assembly design so reactive at zero burnup (fresh), namely the high moderator-to-fuel ratio, is also responsible for making this assembly less reactive, as compared to a similar assembly design with lower moderator-to-fuel ratio (e.g., Westinghouse 17 × 17 Standard), at typical discharge burnups. The assembly physical specifications are listed in Table 3. The initial (fresh) fuel material specifications for the various initial enrichments considered are listed in Table 4.

Table 3 PWR fuel assembly specifications

Parameter	inches	cm
Fuel outside diameter	0.3088	0.7844
Cladding inside diameter	0.3150	0.8001
Cladding outside diameter	0.3600	0.9144
Cladding radial thickness	0.0225	0.0572
Rod pitch	0.4960	1.2598
Guide tube/thimble inside diameter	0.4420	1.1227
Guide tube/thimble outside diameter	0.4740	1.2040
Thimble radial thickness	0.0160	0.0406
Instrument tube inside diameter	0.4420	1.1227
Instrument tube outside diameter	0.4740	1.2040
Instrument tube radial thickness	0.0160	0.0406
Active fuel length	144	365.76
Array size	17×17	
Number of fuel rods	264	
Number of guide tubes/thimbles	24	
Number of instrument tubes	1	

Table 4 Material compositions for the fuel assembly

Isotope	Atom density (atoms/b-cm)	Weight percent
Cladding (Density = 6.40 g/cm^3)		
Zirconium (Zr)	0.0423 [23]	100.0
Total	0.0423	100.0
UO_2, 2 wt % ^{235}U enrichment (Density = 10.5216 g/cm^3)		
Oxygen (O)	4.686E-02	11.8519
^{234}U	3.905E-06	0.0144
^{235}U	4.745E-04	1.7630
^{236}U	2.173E-06	0.0081
^{238}U	2.295E-02	86.3626
Total	7.029E-02	100.0
UO_2, 3 wt % ^{235}U enrichment (Density = 10.5216 g/cm^3)		
Oxygen (O)	4.686E-02	11.8532
^{234}U	6.058E-06	0.0224
^{235}U	7.117E-04	2.6444
^{236}U	3.260E-06	0.0122
^{238}U	2.271E-02	85.4678
Total	7.030E-02	100.0
UO_2, 4 wt % ^{235}U enrichment (Density = 10.5216 g/cm^3)		
Oxygen (O)	4.687E-02	11.8545
^{234}U	8.274E-06	0.0306
^{235}U	9.489E-04	3.5258
^{236}U	4.346E-06	0.0162
^{238}U	2.247E-02	84.5728
Total	7.030E-02	100.0
UO_2, 5 wt % ^{235}U enrichment (Density = 10.5216 g/cm^3)		
Oxygen (O)	4.687E-02	11.8558
^{234}U	1.054E-05	0.0390
^{235}U	1.186E-03	4.4072
^{236}U	5.433E-06	0.0203
^{238}U	2.224E-02	83.6777
Total	7.031E-02	100.0

3 ANALYSIS

3.1 COMPUTATIONAL METHODS

The computational methods necessary for this benchmark analysis include codes for depletion and criticality simulation. A prototype control module designed to automate burnup credit criticality safety analyses by coupling the depletion and criticality modules of SCALE (Ref. 3) was used for this analysis. This module, referred to as STARBUCS, couples a number of SCALE code modules, including ARP, ORIGEN-S, CSASI, WAX, and KENO V.a, to achieve this automation. The ARP code prepares cross sections for each irradiation cycle based on interpolation for the fuel enrichment and the mid-cycle burnup. The use of ARP requires that an ARP library containing the required cross sections be available. These may be obtained from pre-made libraries available with SCALE, or the user may generate problem-specific libraries. For this analysis, problem-specific libraries were generated with the SAS2H sequence of SCALE. All SAS2H calculations utilized the SCALE 44-group (ENDF/B-V) library. The depletion calculations were performed using reasonably conservative cycle-average operational parameters for fuel temperature (1000 K), clad temperature (620 K), moderator temperature (600 K), soluble boron concentration (650 ppm) and specific power (60 MW/MTU). The sensitivity of k_{eff} to variations in these parameters is discussed in Ref. 8. However, it should be noted that this is not a safety evaluation, and thus there is no requirement for the depletion parameters to be bounding. A sample SAS2H input file, which was used to generate the ARP libraries, is provided in Appendix A.

Using an ARP-generated cross-section library, ORIGEN-S performs the depletion calculation to generate the fuel compositions for the burnup and decay time requested for a single axial fuel region. Subsequently, ARP and ORIGEN-S calculations are performed for each of the axial fuel regions. After the fuel compositions from all axial regions have been generated, the CSASI module is called to automate resonance self-shielding and prepare macroscopic fuel cross sections for each axial region. Sequentially with CSASI, the WAX module is executed to append the cross sections into a single cross-section library for all axial fuel regions. Finally, the STARBUCS module executes the three-dimensional (3-D) KENO V.a Monte Carlo criticality code using the generated axially-varying cross sections and isotopic compositions. To ensure proper convergence and reduce statistical uncertainty, the KENO V.a calculations simulated 1100 generations, with 2000 neutron histories per generation, and skipped the first 100 generations before averaging; thus, each calculated k_{eff} value is based on 2 million neutron histories. These calculations utilized the SCALE 238-group cross-section library, which is primarily based on ENDF/B-V data, and required ~18 CPU-minutes for each k_{eff} calculation (on a DEC AlphaStation 500). Since the STARBUCS module is not currently publicly available, and the CSAS25 module is a standard part of SCALE, an equivalent sample input file for CSAS25 is provided in Appendix B.

3.2 GBC-32 COMPUTATIONAL MODEL

Based on the benchmark specification provided in Section 2, a computational model of the GBC-32 cask, loaded with PWR fuel assemblies, was developed for KENO V.a (Ref. 3). Cross-sectional views of the computational model, as generated by KENO V.a, are shown in Figure 1 and Figure 2. A 3-D cutaway view, as generated by KENO3D (Ref. 24), is shown in Figure 3. To aid users of this proposed benchmark in verification of their criticality models, k_{eff} values corresponding to fresh fuel are provided in the next section for initial enrichments of 2, 3, 4, and 5 wt % ^{235}U.

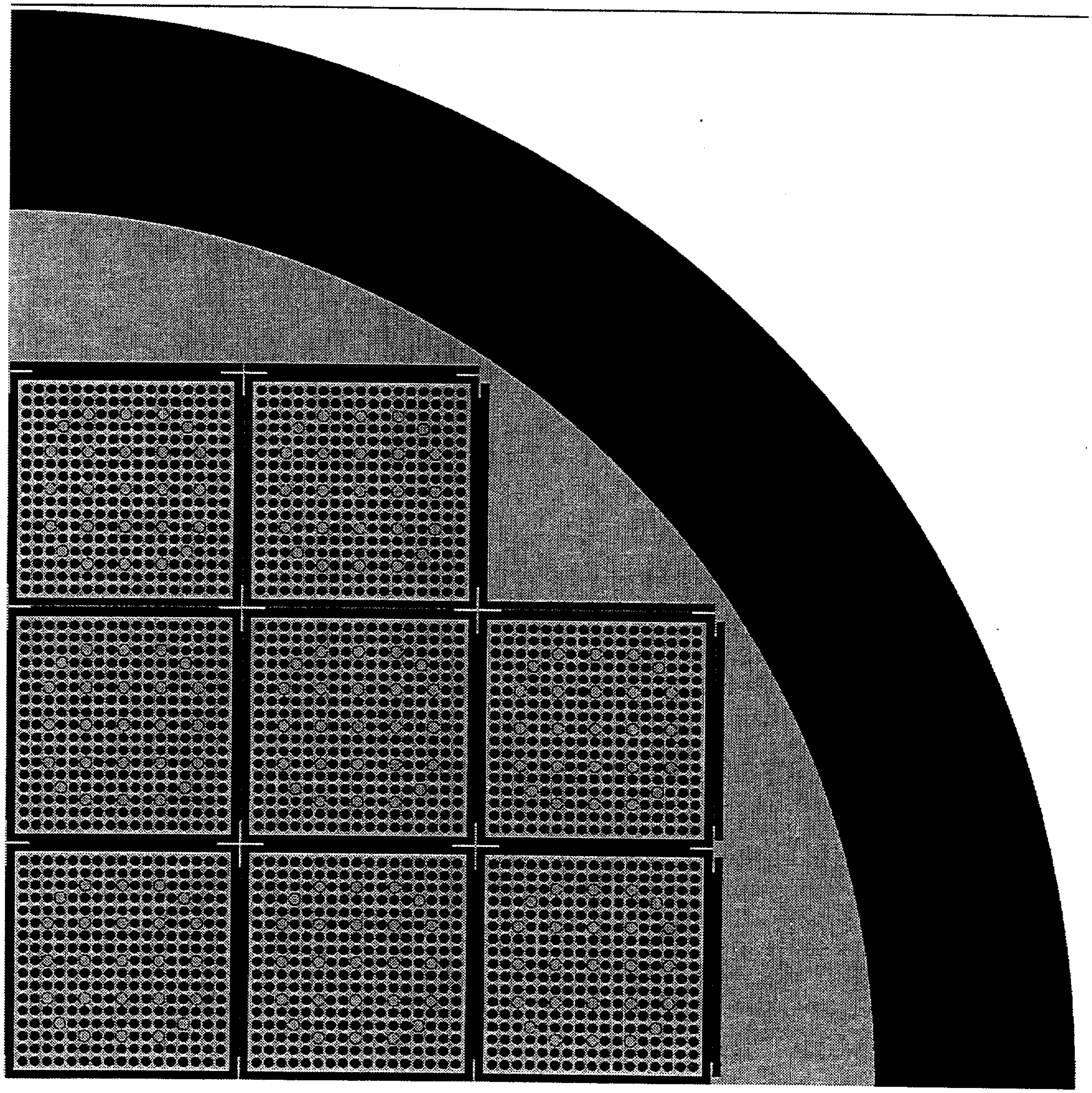

Figure 1 Radial cross section of one quarter of the KENO V.a model for the GBC-32 cask

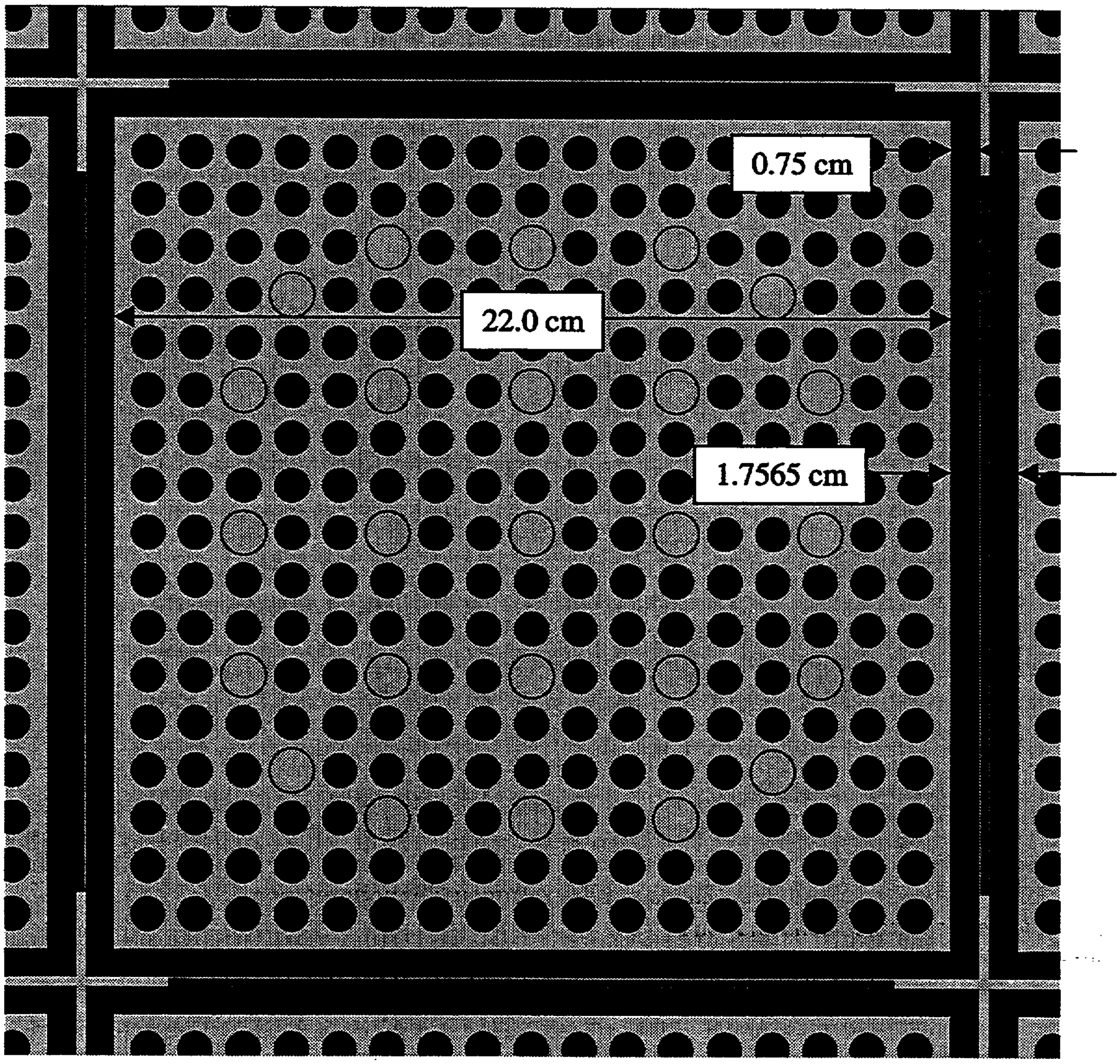

Figure 2 Cross-sectional view of assembly cell in KENO V.a model for the GBC-32 cask

The active fuel length of the assemblies is divided into 18 equal-length axial regions to facilitate the variation in axial composition due to the axial burnup distribution.[25] Although the shape of the axial burnup distribution is known to vary as a function of burnup, a single axial burnup profile was used for this analysis to facilitate the estimation of the additional reactivity margin and corresponding discussion. The profile used corresponds to the bounding profile suggested in Ref. 1 for PWR fuel with average-assembly discharge burnup greater than 30 GWd/MTU. The axial burnup profile is plotted in Figure 4 and the specifications necessary for modeling the axial burnup profile are provided in Table 5. Horizontal variations in burnup are not included in this computational benchmark problem. Finally, for simplicity, isotopic correction factors (used to "correct" predicted isotopic compositions to that determined from comparisons with measured assay data) are not considered for this benchmark problem.

For the criticality calculations, it is necessary to define the isotopes considered. As mentioned, the use of a subset of possible actinides in burnup credit calculations is referred to as "actinide-only" burnup credit. The nuclides used here for actinide-only calculations are consistent with those specified in the DOE topical report on actinide-only burnup credit.[1] Other actinides of minor importance to burnup credit, for which measured assay data are available, are ^{236}U and ^{237}Np (Ref. 26), but these actinides are omitted from the actinide-only calculations due to large deviations between calculated and measured values for ^{237}Np and the lack of sufficient critical experiments with ^{236}U (Ref. 1).

In determining which additional nuclides to include for the estimation of the additional reactivity margin, the following two criteria were considered: (1) reactivity worth and (2) availability of cross-section data. It was recognized that the availability of nuclides in the various cross-section libraries is an important consideration. Thus, it was decided not to consider all of the nuclides for which cross-section data are available (in SCALE), because doing so may make it difficult for others to analyze the benchmark with other codes/data (e.g., other code systems may not have data available for all of the included nuclides).

Regarding reactivity worth, many studies have been performed to rank the reactivity worth of the actinide and fission product nuclides. Based on these analyses, Ref. 2 lists "prime candidates" for inclusion in burnup credit analyses related to dry storage and transport, including several nuclides for which measured chemical assay data are not currently available in the United States. Cross-section data are generally available to the primary criticality codes for all of the nuclides identified in Ref. 2 as being the most important for burnup credit criticality calculations. Therefore, in this benchmark, all of the actinide and fission product nuclides identified in Table 2 of Ref. 2, including those for which no chemical assay data are available, are used in the estimation of the additional reactivity margin. This decision is based on the objective of estimating the residual margins associated with actinide-only burnup credit. Additionally, it should be noted that the selected actinide and fission product nuclides account for less than the total negative worth of all of the nuclides in SNF.[2]

The two "nuclide sets" used here for the estimation of the additional reactivity margin are listed in Table 6. The first set, which corresponds to the major actinides specified in a DOE topical report,[1] is used for the reference actinide-only calculations. The second set includes all of the actinide and fission product nuclides identified in Ref. 2 as being important for burnup credit criticality calculations; the first set is a subset of the second set. For the purpose of this benchmark report and the cited results, the additional reactivity margin available from fission products and minor actinides is due to the nuclides that are exclusive to the second set. These "additional nuclides," which are exclusive to the second set, are listed in Table 7 for clarity and are designated as "set 3." Throughout this report, where reference is made to the additional reactivity margin due to the additional actinide and fission product nuclides, the additional reactivity margin is due to the nuclides listed in Table 7.

Finally, it should be noted that these "nuclide sets" are defined for the purposes of this analysis only; other terminology and specific sets of nuclides have been defined and used by individuals studying burnup credit phenomena.

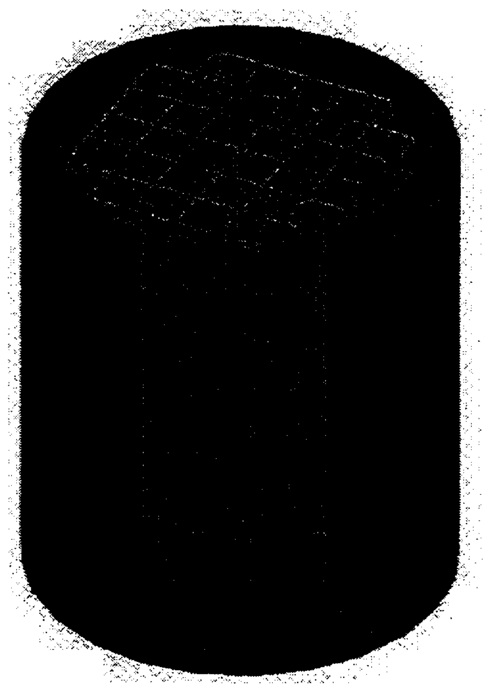

Figure 3 Cutaway view of KENO V.a model for the GBC-32 cask (one-half full height)

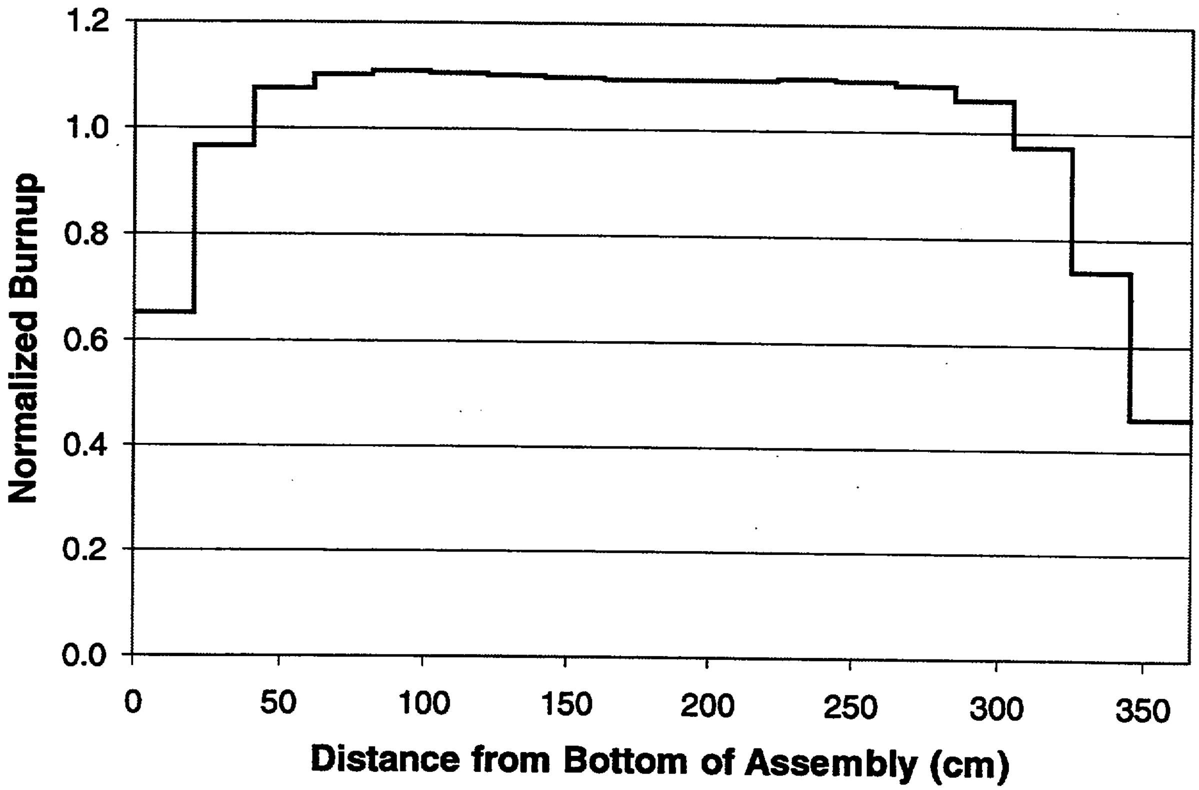

Figure 4 Axial burnup profile used for calculations (Source: Ref. 1)

Table 5 Specification of axial burnup distribution used for benchmark problem (Source: Ref. 1)

Upper bound of axial region, measured from bottom of active fuel (cm)	Normalized burnup
20.32	0.652
40.64	0.967
60.95	1.074
81.27	1.103
101.61	1.108
121.93	1.106
142.28	1.102
162.60	1.097
182.88	1.094
203.20	1.094
223.52	1.095
243.83	1.096
264.15	1.095
284.49	1.086
304.81	1.059
325.12	0.971
345.44	0.738
365.76	0.462

Table 6 Nuclide sets defined for the benchmark problem analysis

set 1: Major actinides (10 total)									
U-234	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	O†

set 2: Actinides and major fission products (29 total)									
U-234	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
Am-243	Np-237	Mo-95	Tc-99	Ru-101	Rh-103	Ag-109	Cs-133	Sm-147	Sm-149
Sm-150	Sm-151	Sm-152	Nd-143	Nd-145	Eu-151	Eu-153	Gd-155	O†	

† Oxygen is neither an actinide nor a fission product, but is included in this list because it is included in the calculations.

Table 7 Nuclides in "set 3," on which the additional reactivity margin available from fission products and minor actinides is based

set 3: Minor actinides and major fission products (19 total)									
U-236	Am-243	Np-237	Mo-95	Tc-99	Ru-101	Rh-103	Ag-109	Cs-133	Sm-147
Sm-149	Sm-150	Sm-151	Sm-152	Nd-143	Nd-145	Eu-151	Eu-153	Gd-155	

3.3 RESULTS

Results for the computational benchmark are presented in this section. Based on the nuclide sets identified in the previous section, calculated k_{eff} values are provided as a function of initial enrichment, burnup, and cooling time, within the ranges relevant to storage and transportation. A rather large volume of results is included for completeness. It is not anticipated that users of this benchmark problem will attempt to reproduce the complete set of results, but rather compare to a subset of the reference results that are relevant to their application.

3.3.1 Reference Results

Calculated k_{eff} values for the GBC-32 cask as a function of burnup and cooling time for initial enrichments of 2, 3, 4, and 5 wt % ^{235}U are listed in Tables 8–11. Values are provided for the burnup range of 0-60 GWd/MTU, in increments of 10 GWd/MTU, and for cooling times of 0, 5, 10, 20, and 40 years. Standard deviations are also listed in the tables and are all less than 0.00075. The individual components of k_{eff} reduction (Δk) associated with (a) the major actinides and (b) the additional nuclides as a function of burnup and cooling time are listed in Tables 12–15. The second column from the left in Tables 12–15 lists the Δk reductions (relative to fresh fuel) due to the presence of the major actinides alone (nuclide set 1, see Table 6), while the third column lists the Δk reduction due to the presence of the major fission products and additional actinides (i.e., due to the nuclides present in set 3, see Table 7). Thus, the results listed in the third column may be interpreted as the additional Δk margin associated with the fission products and additional actinides. The fourth column from the left in Tables 12–15 lists the total Δk reduction as a function of burnup for the cooling times considered. Finally, the two columns on the right-hand side of the table list the percent contributions from the two sets of nuclides to the total Δk reduction, and thus provide an assessment of the relative reactivity reduction associated with (a) the major actinides and (b) the additional nuclides.

When associating practical meaning to these results, it is important that the reader and potential users of this report understand that this is a ***computational*** benchmark, and as such, the reference solutions are based on calculations alone (e.g., no isotopic correction factors are applied). The reference solutions are not directly or indirectly based on experimental results. However, note that the computational tools used to generate the reference solutions have been validated elsewhere.[2]

3.3.2 Related Information

Additional results and supplementary discussion, which should not be considered part of this computational benchmark, are available in Appendices C and D. Results for various additional nuclide sets as a function of burnup for each initial enrichment and cooling times of 5 and 20 years are provided in Appendix C. Discussion of the reference results, including graphical representations and relevant observations, is given in Appendix D.

3.3.3 Additional Results with Uniform Axial Burnup

As it is recognized that the presence of the axial burnup distribution in the benchmark problem adds complexity and, depending on the computational tools available to the analyst, may substantially increase the effort associated with analyzing this computational benchmark problem, additional reference results are presented in this section for uniform axial burnup. Note, however, that the reactivity worth of the fission products increases with burnup and that, with the axial burnup distribution present, the lower burnup region near the top of the assembly controls the reactivity. Thus, for a given assembly-average burnup, the reactivity margin due to fission products will be overestimated if the axial burnup distribution is not included in the model. Therefore, it should be emphasized that the computational benchmark results in this section with uniform axial burnup are provided to enable comparison with a simpler benchmark problem, and should not be considered to be representative of actual reactivity margins. This modeling simplification reduces the volume of composition data by a factor of 18 (i.e., the number of axial regions used to represent the axial burnup distribution). Nuclide compositions for fuel with initial enrichment of 4 wt % ^{235}U and various burnup and cooling time combinations are included in Appendix E to enable comparisons of calculated spent fuel compositions.

Calculated k_{eff} values, based on the nuclide sets identified in the Section 2, as a function of burnup and cooling time, within the ranges relevant to storage and transportation, are provided for a single initial fuel enrichment of 4 wt % ^{235}U. The calculated k_{eff} values are listed in Table 16 and the individual components of the reactivity reduction associated with (a) the major actinides and (b) the additional nuclides as a function of burnup and cooling time are listed in Table 17. The second column from the left in Table 17 lists the Δk reactivity reductions (relative to fresh fuel) due to the presence of the major actinides alone (nuclide set 1, see Table 6), while the third column lists the reactivity reduction due to the presence of the major fission products and additional actinides (i.e., due to the nuclides present in set 3, see Table 7). Thus, the results listed in the third column may be interpreted as the additional reactivity margin associated with the fission products and additional actinides. The fourth column from the left in Table 17 lists the total reactivity reduction as a function of burnup for the cooling times considered. Finally, the two columns on the right-hand side of the table list the percent contributions from the two sets of nuclides to the total reactivity reduction, and thus provide an assessment of the relative reactivity reduction associated with (a) the major actinides and (b) the additional nuclides.

Comparison of the results in Table 17 with those listed in Table 14 shows that, with the uniform axial burnup distribution, the calculated total reactivity reduction is overestimated for burnups greater than approximately 10 GWd/MTU. The individual components of reactivity reduction due to (a) the major actinides and (b) the additional nuclides are shown to be overestimated for burnups greater than approximately 20 GWd/MTU and 10 GWd/MTU, respectively. Thus, for typical discharge burnups (30–50 GWd/MTU for 4 wt % ^{235}U enrichment), the individual components of reactivity reduction associated with (a) the major actinides and (b) the additional nuclides are both overestimated with the uniform axial burnup distribution. Further, the overestimation increases with cooling time.

Table 8 k_{eff} values for the GBC-32 cask as a function of burnup and cooling time for 2 wt % ^{235}U initial enrichment

Major actinides (nuclide set 1, see Table 6)										
Cooling time (years)	0		5		10		20		40	
Burnup (GWd/MTU)	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation
0	0.94797	0.00058	0.94797	0.00058	0.94797	0.00058	0.94797	0.00058	0.94797	0.00058
10	0.90142	0.00051	0.89928	0.00046	0.89373	0.00055	0.88818	0.00051	0.88113	0.00050
20	0.85376	0.00049	0.84486	0.00048	0.83519	0.00046	0.82165	0.00055	0.80930	0.00057
30	0.81963	0.00053	0.80657	0.00044	0.79199	0.00053	0.77240	0.00048	0.75355	0.00054
40	0.79629	0.00048	0.77814	0.00049	0.75867	0.00042	0.73439	0.00048	0.70993	0.00044
50	0.78326	0.00054	0.75996	0.00045	0.73669	0.00047	0.70568	0.00051	0.67757	0.00049
60	0.77869	0.00045	0.74930	0.00039	0.72356	0.00041	0.68805	0.00040	0.65382	0.00041
Actinides and major fission products (nuclide set 2, see Table 6)										
0	0.94797	0.00058	0.94797	0.00058	0.94797	0.00058	0.94797	0.00058	0.94797	0.00058
10	0.86946	0.00049	0.85380	0.00048	0.85015	0.00051	0.84444	0.00053	0.83915	0.00048
20	0.80832	0.00048	0.78712	0.00045	0.77769	0.00045	0.76753	0.00052	0.75621	0.00054
30	0.76508	0.00046	0.73685	0.00047	0.72437	0.00043	0.70679	0.00048	0.69188	0.00044
40	0.73163	0.00040	0.70005	0.00046	0.68218	0.00057	0.66012	0.00040	0.64092	0.00051
50	0.70701	0.00043	0.67103	0.00044	0.64977	0.00043	0.62388	0.00044	0.60011	0.00043
60	0.68844	0.00051	0.64783	0.00047	0.62443	0.00041	0.59499	0.00040	0.56896	0.00042

Table 9 k_{eff} values for the GBC-32 cask as a function of burnup and cooling time for 3 wt % ^{235}U initial enrichment

Major actinides (nuclide set 1, see Table 6)										
Cooling time (years)	0		5		10		20		40	
Burnup (GWd/MTU)	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation
0	1.06633	0.00059	1.06633	0.00059	1.06633	0.00059	1.06633	0.00059	1.06633	0.00059
10	1.01277	0.00055	1.01232	0.00058	1.00913	0.00055	1.00438	0.00054	1.00018	0.00051
20	0.95973	0.00055	0.95288	0.00046	0.94668	0.00053	0.93680	0.00047	0.92994	0.00065
30	0.91723	0.00053	0.90684	0.00054	0.89573	0.00052	0.88210	0.00055	0.86925	0.00071
40	0.88025	0.00051	0.86807	0.00058	0.85486	0.00058	0.83711	0.00056	0.81985	0.00052
50	0.85158	0.00053	0.83412	0.00054	0.81885	0.00047	0.79703	0.00047	0.77646	0.00046
60	0.82720	0.00050	0.80870	0.00050	0.78895	0.00046	0.76269	0.00049	0.73765	0.00047
Actinides and major fission products (nuclide set 2, see Table 6)										
0	1.06633	0.00059	1.06633	0.00059	1.06633	0.00059	1.06633	0.00059	1.06633	0.00059
10	0.97915	0.00052	0.96674	0.00044	0.96348	0.00050	0.96000	0.00055	0.95599	0.00055
20	0.91232	0.00054	0.89556	0.00053	0.88923	0.00053	0.87974	0.00060	0.87282	0.00047
30	0.86008	0.00049	0.83836	0.00061	0.82832	0.00056	0.81603	0.00052	0.80503	0.00049
40	0.81703	0.00055	0.79134	0.00060	0.77723	0.00057	0.76236	0.00059	0.74722	0.00049
50	0.78077	0.00053	0.75040	0.00050	0.73375	0.00051	0.71466	0.00043	0.69731	0.00049
60	0.74946	0.00047	0.71563	0.00051	0.69751	0.00047	0.67412	0.00044	0.65359	0.00052

Table 10 k_{eff} values for the GBC-32 cask as a function of burnup and cooling time for 4 wt % ^{235}U initial enrichment

Major actinides (nuclide set 1, see Table 6)										
Cooling time (years)	0		5		10		20		40	
Burnup (GWd/MTU)	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation
0	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065
10	1.09164	0.00058	1.09080	0.00065	1.08835	0.00056	1.08607	0.00061	1.08301	0.00058
20	1.04031	0.00068	1.03480	0.00062	1.03061	0.00061	1.02341	0.00061	1.01529	0.00068
30	0.99712	0.00058	0.98852	0.00057	0.98179	0.00050	0.97011	0.00058	0.96204	0.00063
40	0.96212	0.00056	0.94987	0.00061	0.93875	0.00069	0.92537	0.00054	0.91200	0.00056
50	0.92785	0.00057	0.91323	0.00058	0.90156	0.00053	0.88338	0.00059	0.86689	0.00066
60	0.89973	0.00057	0.88209	0.00057	0.86666	0.00054	0.84654	0.00063	0.82689	0.00055
Actinides and major fission products (nuclide set 2, see Table 6)										
0	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065
10	1.05711	0.00060	1.04583	0.00058	1.04295	0.00062	1.03927	0.00055	1.03682	0.00056
20	0.98981	0.00065	0.97480	0.00054	0.96995	0.00055	0.96340	0.00060	0.95960	0.00060
30	0.93904	0.00055	0.91944	0.00057	0.91224	0.00048	0.90120	0.00061	0.89465	0.00063
40	0.89470	0.00058	0.87156	0.00058	0.86051	0.00053	0.84925	0.00053	0.83745	0.00056
50	0.85564	0.00061	0.82811	0.00056	0.81489	0.00057	0.80009	0.00051	0.78521	0.00056
60	0.82032	0.00053	0.79043	0.00056	0.77525	0.00054	0.75693	0.00062	0.74001	0.00048

Table 11 k_{eff} values for the GBC-32 cask as a function of burnup and cooling time for 5 wt % ^{235}U initial enrichment

Cooling time (years)	0		5		10		20		40	
Burnup (GWd/MTU)	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation
Major actinides (nuclide set 1, see Table 6)										
0	1.19142	0.00056	1.19142	0.00056	1.19142	0.00056	1.19142	0.00056	1.19142	0.00056
10	1.14856	0.00057	1.14808	0.00063	1.14680	0.00058	1.14482	0.00058	1.14173	0.00062
20	1.10288	0.00064	1.09803	0.00059	1.09310	0.00056	1.08810	0.00061	1.08294	0.00055
30	1.06231	0.00057	1.05430	0.00065	1.04805	0.00049	1.03898	0.00054	1.03093	0.00062
40	1.02689	0.00062	1.01604	0.00058	1.00786	0.00059	0.99584	0.00063	0.98577	0.00061
50	0.99396	0.00057	0.98203	0.00064	0.97055	0.00055	0.95624	0.00055	0.94285	0.00058
60	0.96403	0.00056	0.94944	0.00055	0.93655	0.00059	0.91956	0.00056	0.90229	0.00046
Actinides and major fission products (nuclide set 2, see Table 6)										
0	1.19142	0.00056	1.19142	0.00056	1.19142	0.00056	1.19142	0.00056	1.19142	0.00056
10	1.11293	0.00062	1.10270	0.00061	1.10083	0.00060	1.09906	0.00061	1.09871	0.00056
20	1.05132	0.00057	1.03554	0.00055	1.03228	0.00057	1.02738	0.00052	1.02376	0.00051
30	1.00087	0.00059	0.98376	0.00061	0.97800	0.00062	0.96914	0.00063	0.96236	0.00054
40	0.95883	0.00051	0.93748	0.00053	0.92718	0.00060	0.91822	0.00055	0.91042	0.00049
50	0.91844	0.00054	0.89442	0.00058	0.88344	0.00056	0.87030	0.00047	0.85945	0.00065
60	0.88140	0.00048	0.85549	0.00052	0.84317	0.00055	0.82850	0.00050	0.81455	0.00054

Table 12 Individual components of the reduction in k_{eff} as a function of burnup and cooling time for fuel of 2 wt % ^{235}U initial enrichment

	Δk values due to the various nuclide sets			Contribution to total reduction in k_{eff}	
Burnup (GWd/MTU)	Major actinides (set 1)	Additional nuclides (set 3)	Total (set 2)	Major actinides (set 1)	Additional nuclides (set 3)
0-year cooling time					
10	0.04655	0.03196	0.07851	59.29%	40.71%
20	0.09421	0.04544	0.13965	67.46%	32.54%
30	0.12834	0.05455	0.18289	70.17%	29.83%
40	0.15168	0.06466	0.21634	70.11%	29.89%
50	0.16471	0.07625	0.24096	68.36%	31.64%
60	0.16928	0.09025	0.25953	65.23%	34.77%
5-year cooling time					
10	0.04869	0.04548	0.09417	51.70%	48.30%
20	0.10311	0.05774	0.16085	64.10%	35.90%
30	0.14140	0.06972	0.21112	66.98%	33.02%
40	0.16983	0.07809	0.24792	68.50%	31.50%
50	0.18801	0.08893	0.27694	67.89%	32.11%
60	0.19867	0.10147	0.30014	66.19%	33.81%
10-year cooling time					
10	0.05424	0.04358	0.09782	55.45%	44.55%
20	0.11278	0.05750	0.17028	66.23%	33.77%
30	0.15598	0.06762	0.22360	69.76%	30.24%
40	0.18930	0.07649	0.26579	71.22%	28.78%
50	0.21128	0.08692	0.29820	70.85%	29.15%
60	0.22441	0.09913	0.32354	69.36%	30.64%
20-year cooling time					
10	0.05979	0.04374	0.10353	57.75%	42.25%
20	0.12632	0.05412	0.18044	70.01%	29.99%
30	0.17557	0.06561	0.24118	72.80%	27.20%
40	0.21358	0.07427	0.28785	74.20%	25.80%
50	0.24229	0.08180	0.32409	74.76%	25.24%
60	0.25992	0.09306	0.35298	73.64%	26.36%
40-year cooling time					
10	0.06684	0.04198	0.10882	61.42%	38.58%
20	0.13867	0.05309	0.19176	72.31%	27.69%
30	0.19442	0.06167	0.25609	75.92%	24.08%
40	0.23804	0.06901	0.30705	77.52%	22.48%
50	0.27040	0.07746	0.34786	77.73%	22.27%
60	0.29415	0.08486	0.37901	77.61%	22.39%

Table 13 Individual components of the reduction in k_{eff} as a function of burnup and cooling time for fuel of 3 wt % ^{235}U initial enrichment

	Δk values due to the various nuclide sets			Contribution to total reduction in k_{eff}	
Burnup (GWd/MTU)	Major actinides (set 1)	Additional nuclides (set 3)	Total (set 2)	Major actinides (set 1)	Additional nuclides (set 3)
0-year cooling time					
10	0.05356	0.03362	0.08718	61.44%	38.56%
20	0.10660	0.04741	0.15401	69.22%	30.78%
30	0.14910	0.05715	0.20625	72.29%	27.71%
40	0.18608	0.06322	0.24930	74.64%	25.36%
50	0.21475	0.07081	0.28556	75.20%	24.80%
60	0.23913	0.07774	0.31687	75.47%	24.53%
5-year cooling time					
10	0.05401	0.04558	0.09959	54.23%	45.77%
20	0.11345	0.05732	0.17077	66.43%	33.57%
30	0.15949	0.06848	0.22797	69.96%	30.04%
40	0.19826	0.07673	0.27499	72.10%	27.90%
50	0.23221	0.08372	0.31593	73.50%	26.50%
60	0.25763	0.09307	0.35070	73.46%	26.54%
10-year cooling time					
10	0.05720	0.04565	0.10285	55.61%	44.39%
20	0.11965	0.05745	0.17710	67.56%	32.44%
30	0.17060	0.06741	0.23801	71.68%	28.32%
40	0.21147	0.07763	0.28910	73.15%	26.85%
50	0.24748	0.08510	0.33258	74.41%	25.59%
60	0.27738	0.09144	0.36882	75.21%	24.79%
20-year cooling time					
10	0.06195	0.04438	0.10633	58.26%	41.74%
20	0.12953	0.05706	0.18659	69.42%	30.58%
30	0.18423	0.06607	0.25030	73.60%	26.40%
40	0.22922	0.07475	0.30397	75.41%	24.59%
50	0.26930	0.08237	0.35167	76.58%	23.42%
60	0.30364	0.08857	0.39221	77.42%	22.58%
40-year cooling time					
10	0.06615	0.04419	0.11034	59.95%	40.05%
20	0.13639	0.05712	0.19351	70.48%	29.52%
30	0.19708	0.06422	0.26130	75.42%	24.58%
40	0.24648	0.07263	0.31911	77.24%	22.76%
50	0.28987	0.07915	0.36902	78.55%	21.45%
60	0.32868	0.08406	0.41274	79.63%	20.37%

Table 14 Individual components of the reduction in k_{eff} as a function of burnup and cooling time for fuel of 4 wt % ^{235}U initial enrichment

	Δk values due to the various nuclide sets			Contribution to total reduction in k_{eff}	
Burnup (GWd/MTU)	Major actinides (set 1)	Additional nuclides (set 3)	Total (set 2)	Major actinides (set 1)	Additional nuclides (set 3)
0-year cooling time					
10	0.04819	0.03453	0.08272	58.26%	41.74%
20	0.09952	0.05050	0.15002	66.34%	33.66%
30	0.14271	0.05808	0.20079	71.07%	28.93%
40	0.17771	0.06742	0.24513	72.50%	27.50%
50	0.21198	0.07221	0.28419	74.59%	25.41%
60	0.24010	0.07941	0.31951	75.15%	24.85%
5-year cooling time					
10	0.04903	0.04497	0.09400	52.16%	47.84%
20	0.10503	0.06000	0.16503	63.64%	36.36%
30	0.15131	0.06908	0.22039	68.66%	31.34%
40	0.18996	0.07831	0.26827	70.81%	29.19%
50	0.22660	0.08512	0.31172	72.69%	27.31%
60	0.25774	0.09166	0.34940	73.77%	26.23%
10-year cooling time					
10	0.05148	0.04540	0.09688	53.14%	46.86%
20	0.10922	0.06066	0.16988	64.29%	35.71%
30	0.15804	0.06955	0.22759	69.44%	30.56%
40	0.20108	0.07824	0.27932	71.99%	28.01%
50	0.23827	0.08667	0.32494	73.33%	26.67%
60	0.27317	0.09141	0.36458	74.93%	25.07%
20-year cooling time					
10	0.05376	0.04680	0.10056	53.46%	46.54%
20	0.11642	0.06001	0.17643	65.99%	34.01%
30	0.16972	0.06891	0.23863	71.12%	28.88%
40	0.21446	0.07612	0.29058	73.80%	26.20%
50	0.25645	0.08329	0.33974	75.48%	24.52%
60	0.29329	0.08961	0.38290	76.60%	23.40%
40-year cooling time					
10	0.05682	0.04619	0.10301	55.16%	44.84%
20	0.12454	0.05569	0.18023	69.10%	30.90%
30	0.17779	0.06739	0.24518	72.51%	27.49%
40	0.22783	0.07455	0.30238	75.35%	24.65%
50	0.27294	0.08168	0.35462	76.97%	23.03%
60	0.31294	0.08688	0.39982	78.27%	21.73%

Table 15 Individual components of the reduction in k_{eff} as a function of burnup and cooling time for fuel of 5 wt % ^{235}U initial enrichment

	Δk values due to the various nuclide sets			Contribution to total reduction in k_{eff}	
Burnup (GWd/MTU)	Major actinides (set 1)	Additional nuclides (set 3)	Total (set 2)	Major actinides (set 1)	Additional nuclides (set 3)
0-year cooling time					
10	0.04286	0.03563	0.07849	54.61%	45.39%
20	0.08854	0.05156	0.14010	63.20%	36.80%
30	0.12911	0.06144	0.19055	67.76%	32.24%
40	0.16453	0.06806	0.23259	70.74%	29.26%
50	0.19746	0.07552	0.27298	72.33%	27.67%
60	0.22739	0.08263	0.31002	73.35%	26.65%
5-year cooling time					
10	0.04334	0.04538	0.08872	48.85%	51.15%
20	0.09339	0.06249	0.15588	59.91%	40.09%
30	0.13712	0.07054	0.20766	66.03%	33.97%
40	0.17538	0.07856	0.25394	69.06%	30.94%
50	0.20939	0.08761	0.29700	70.50%	29.50%
60	0.24198	0.09395	0.33593	72.03%	27.97%
10-year cooling time					
10	0.04462	0.04597	0.09059	49.25%	50.75%
20	0.09832	0.06082	0.15914	61.78%	38.22%
30	0.14337	0.07005	0.21342	67.18%	32.82%
40	0.18356	0.08068	0.26424	69.47%	30.53%
50	0.22087	0.08711	0.30798	71.72%	28.28%
60	0.25487	0.09338	0.34825	73.19%	26.81%
20-year cooling time					
10	0.04660	0.04576	0.09236	50.45%	49.55%
20	0.10332	0.06072	0.16404	62.98%	37.02%
30	0.15244	0.06984	0.22228	68.58%	31.42%
40	0.19558	0.07762	0.27320	71.59%	28.41%
50	0.23518	0.08594	0.32112	73.24%	26.76%
60	0.27186	0.09106	0.36292	74.91%	25.09%
40-year cooling time					
10	0.04969	0.04302	0.09271	53.60%	46.40%
20	0.10848	0.05918	0.16766	64.70%	35.30%
30	0.16049	0.06857	0.22906	70.06%	29.94%
40	0.20565	0.07535	0.28100	73.19%	26.81%
50	0.24857	0.08340	0.33197	74.88%	25.12%
60	0.28913	0.08774	0.37687	76.72%	23.28%

Table 16 k_{eff} values with UNIFORM axial burnup for the GBC-32 cask as a function of burnup and cooling time for 4 wt % ^{235}U initial enrichment

Major actinides (nuclide set 1, see Table 6)										
Cooling time (years)	0		5		10		20		40	
Burnup (GWd/MTU)	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation	k_{eff}	Standard deviation
0	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065
10	1.09551	0.00062	1.09461	0.00060	1.09357	0.00048	1.09151	0.00062	1.08853	0.00056
20	1.04608	0.00054	1.03990	0.00060	1.03287	0.00060	1.02437	0.00051	1.01612	0.00055
30	0.99684	0.00065	0.98484	0.00055	0.97349	0.00055	0.95796	0.00058	0.94214	0.00058
40	0.94988	0.00059	0.93184	0.00052	0.91554	0.00057	0.89278	0.00056	0.86966	0.00052
50	0.90678	0.00050	0.88361	0.00053	0.86267	0.00050	0.83281	0.00051	0.80460	0.00053
60	0.87012	0.00049	0.84299	0.00047	0.81871	0.00054	0.78489	0.00044	0.75001	0.00048
Actinides and major fission products (nuclide set 2, see Table 6)										
0	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065	1.13983	0.00065
10	1.06057	0.00053	1.05023	0.00058	1.04736	0.00060	1.04493	0.00051	1.04318	0.00056
20	0.99105	0.00053	0.97162	0.00048	0.96457	0.00048	0.95614	0.00054	0.94770	0.00050
30	0.92418	0.00053	0.89802	0.00051	0.88551	0.00052	0.86861	0.00044	0.85387	0.00048
40	0.86305	0.00051	0.82865	0.00045	0.81073	0.00050	0.78732	0.00046	0.76648	0.00043
50	0.80905	0.00050	0.76758	0.00041	0.74515	0.00045	0.71642	0.00041	0.69011	0.00039
60	0.76355	0.00049	0.71736	0.00040	0.69119	0.00038	0.65827	0.00041	0.62781	0.00036

Table 17 Individual components of the reduction in k_{eff} for UNIFORM axial burnup as a function of burnup and cooling time for fuel of 4 wt % ^{235}U initial enrichment

	Δk values due to the various nuclide sets			Contribution to total reduction in k_{eff}	
Burnup (GWd/MTU)	Major actinides (set 1)	Additional nuclides (set 3)	Total (set 2)	Major actinides (set 1)	Additional nuclides (set 3)
0-year cooling time					
10	0.04432	0.03494	0.07926	55.92%	44.08%
20	0.09375	0.05503	0.14878	63.01%	36.99%
30	0.14299	0.07266	0.21565	66.31%	33.69%
40	0.18995	0.08683	0.27678	68.63%	31.37%
50	0.23305	0.09773	0.33078	70.45%	29.55%
60	0.26971	0.10657	0.37628	71.68%	28.32%
5-year cooling time					
10	0.04522	0.04438	0.08960	50.47%	49.53%
20	0.09993	0.06828	0.16821	59.41%	40.59%
30	0.15499	0.08682	0.24181	64.10%	35.90%
40	0.20799	0.10319	0.31118	66.84%	33.16%
50	0.25622	0.11603	0.37225	68.83%	31.17%
60	0.29684	0.12563	0.42247	70.26%	29.74%
10-year cooling time					
10	0.04626	0.04621	0.09247	50.03%	49.97%
20	0.10696	0.06830	0.17526	61.03%	38.97%
30	0.16634	0.08798	0.25432	65.41%	34.59%
40	0.22429	0.10481	0.32910	68.15%	31.85%
50	0.27716	0.11752	0.39468	70.22%	29.78%
60	0.32112	0.12752	0.44864	71.58%	28.42%
20-year cooling time					
10	0.04832	0.04658	0.09490	50.92%	49.08%
20	0.11546	0.06823	0.18369	62.86%	37.14%
30	0.18187	0.08935	0.27122	67.06%	32.94%
40	0.24705	0.10546	0.35251	70.08%	29.92%
50	0.30702	0.11639	0.42341	72.51%	27.49%
60	0.35494	0.12662	0.48156	73.71%	26.29%
40-year cooling time					
10	0.05130	0.04535	0.09665	53.08%	46.92%
20	0.12371	0.06842	0.19213	64.39%	35.61%
30	0.19769	0.08827	0.28596	69.13%	30.87%
40	0.27017	0.10318	0.37335	72.36%	27.64%
50	0.33523	0.11449	0.44972	74.54%	25.46%
60	0.38982	0.12220	0.51202	76.13%	23.87%

4 CONCLUSIONS

This report proposes and documents a computational benchmark problem for the estimation of the additional reactivity margin available from fission products and minor actinides in a PWR burnup credit storage/transport environment, based on a generic 32 PWR-assembly cask. The proposed benchmark problem was developed to be similar to proposed designs for burnup credit casks, including similar materials and dimensions. While preserving all of the important features, the proposed benchmark problem approximates (or eliminates) nonessential details and proprietary information. The documentation of this computational benchmark includes all of the necessary geometric and material specifications to permit independent evaluations and sufficiently detailed reference solutions to enable meaningful comparisons.

The purpose of this computational benchmark is to provide a reference configuration to help normalize the estimation of the additional reactivity margin and document reference estimations of the additional reactivity margin as a function of initial enrichment, burnup, and cooling time. Calculated k_{eff} values for the benchmark problem are provided as a function of burnup and cooling time for initial enrichments of 2, 3, 4, and 5 wt % ^{235}U. Values are provided for the burnup range of 0–60 GWd/MTU, in increments of 10 GWd/MTU, and for cooling times of 0, 5, 10, 20, and 40 years. The individual components of the reactivity reduction associated with (a) the major actinides and (b) the additional nuclides as a function of burnup, cooling time, and initial enrichment are also provided. In addition, reference results for a single initial fuel enrichment of 4 wt % ^{235}U are given for a simplification of the computational benchmark problem involving a uniform axial burnup distribution. The reference estimations were all based on the SCALE4.4a code package.

The reference results are plotted and examined in Appendix D, and in some cases, observations and conclusions are offered. For typical discharge enrichment and burnup combinations, the results show that approximately 70% of the reactivity reduction is due to the major actinides, with the remaining 30% being attributed to the additional nuclides (major fission products and minor actinides). For a given burnup, an increase in the initial enrichment is shown to result in a decrease in the contribution from the major actinides and a simultaneous increase in the contribution from the additional nuclides. During the time frame of interest, the reactivity reduction associated with the major actinides is shown to increase with cooling time. In contrast, the reactivity reduction associated with the fission products and minor actinides is shown to increase initially with cooling time, but then decrease somewhat in the 5- to 40-year time frame. Finally, the minimum additional reactivity margin available from fission products and minor actinides is quantified for the burnup, initial enrichments, and cooling times considered in this report. The minimum values are shown to occur at zero cooling time and increase as a function of burnup from ~0.03 Δk at 10 GWd/MTU to ~0.08 Δk at 60 GWd/MTU.

Where applicable, estimates of the reactivity margin for this reference configuration may be compared to those of actual burnup credit style casks to provide a check of the design-specific estimates. However, when associating practical meaning to these results, it is important that the reader and potential users of this report understand that this is a ***computational*** benchmark, and as such, the reference solutions are based on calculations alone. Although reference solutions are not directly or indirectly based on experimental results, it should be noted that the depletion (SAS2H) and criticality (CSAS25) sequences have been validated using laboratory critical experiments, commercial reactor criticals (CRCs), measured chemical assay data, and reactivity worth measurements with individual fission products important to burnup credit.[2] Although the minor modeling simplifications employed in this evaluation are not expected to have a significant impact on the calculated reactivity margins, analyses to support this assertion have not been performed.

One modeling characteristic that is known to notably impact the calculated reactivity margins, however, is the axial burnup profile. The use a of more bounding profile (i.e., one that results in greater reactivity) than the one specified in Section 2 for this benchmark problem will yield lower estimates for the reactivity margin available from the additional nuclides, as well as from the major actinides. The amount by which the estimates are lower will depend on the actual axial burnup profile.

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APPENDIX A

SAMPLE INPUT FILE FOR SAS2H

```
=sas2       parm='halt31,skipshipdata'
sas2  pwr-buc westinghouse 17x17OFA, 4.0 wt % U-235, B_total=60 GWd/MTU
44groupndf5       latticecell
'
'   ASS= Westinghouse 17x17 OFA assembly design
'   IE = initial enrichment of 4.0 wt % U-235
'   Tm = moderator temperature = 600K
'   Tf = fuel temperature = 1000K
'   SB = soluble boron concentration = 650ppm
'   SP = Specific Power = 60 MW/MTU
'
'   mixtures of fuel-pin-unit-cell
'
'   U-234, U-236, & U-238 isotopics calculated based on relations
'   in NUREG/CR-5625(ORNL-6698)
'   Fuel Density reduced to account for pellet expansion
uo2  1 den=10.5216
 1  1000.0  92234 0.03473
                              92235 4.0
                              92236 0.01840
                              92238 95.94687   end
'
'     Following list contains all Important nuclides from
'     Table 1 of ORNL/TM-12294/V1
u-232     1 0 1.00e-20 1000.0 end
u-233     1 0 1.00e-20 1000.0 end
u-237     1 0 1.00e-20 1000.0 end
np-237    1 0 1.00e-20 1000.0 end
pu-236    1 0 1.00e-20 1000.0 end
pu-237    1 0 1.00e-20 1000.0 end
pu-238    1 0 1.00e-20 1000.0 end
pu-239    1 0 1.00e-20 1000.0 end
pu-240    1 0 1.00e-20 1000.0 end
pu-241    1 0 1.00e-20 1000.0 end
pu-242    1 0 1.00e-20 1000.0 end
pu-243    1 0 1.00e-20 1000.0 end
pu-244    1 0 1.00e-20 1000.0 end
am-241    1 0 1.00e-20 1000.0 end
am-242m   1 0 1.00e-20 1000.0 end
am-243    1 0 1.00e-20 1000.0 end
cm-241    1 0 1.00e-20 1000.0 end
cm-242    1 0 1.00e-20 1000.0 end
cm-243    1 0 1.00e-20 1000.0 end
cm-244    1 0 1.00e-20 1000.0 end
cm-245    1 0 1.00e-20 1000.0 end
cm-246    1 0 1.00e-20 1000.0 end
cm-247    1 0 1.00e-20 1000.0 end
cm-248    1 0 1.00e-20 1000.0 end
ge-72     1 0 1.00e-20 1000.0 end
ge-73     1 0 1.00e-20 1000.0 end
ge-74     1 0 1.00e-20 1000.0 end
as-75     1 0 1.00e-20 1000.0 end
ge-76     1 0 1.00e-20 1000.0 end
se-76     1 0 1.00e-20 1000.0 end
se-77     1 0 1.00e-20 1000.0 end
se-78     1 0 1.00e-20 1000.0 end
br-79     1 0 1.00e-20 1000.0 end
se-80     1 0 1.00e-20 1000.0 end
kr-80     1 0 1.00e-20 1000.0 end
br-81     1 0 1.00e-20 1000.0 end
se-82     1 0 1.00e-20 1000.0 end
kr-82     1 0 1.00e-20 1000.0 end
kr-83     1 0 1.00e-20 1000.0 end
kr-84     1 0 1.00e-20 1000.0 end
kr-85     1 0 1.00e-20 1000.0 end
rb-85     1 0 1.00e-20 1000.0 end
kr-86     1 0 1.00e-20 1000.0 end
rb-86     1 0 1.00e-20 1000.0 end
sr-86     1 0 1.00e-20 1000.0 end
rb-87     1 0 1.00e-20 1000.0 end
sr-87     1 0 1.00e-20 1000.0 end
```

```
sr-88     1 0 1.00e-20 1000.0 end
sr-89     1 0 1.00e-20 1000.0 end
y-89      1 0 1.00e-20 1000.0 end
sr-90     1 0 1.00e-20 1000.0 end
y-90      1 0 1.00e-20 1000.0 end
zr-90     1 0 1.00e-20 1000.0 end
y-91      1 0 1.00e-20 1000.0 end
zr-91     1 0 1.00e-20 1000.0 end
zr-92     1 0 1.00e-20 1000.0 end
zr-93     1 0 1.00e-20 1000.0 end
nb-93     1 0 1.00e-20 1000.0 end
zr-94     1 0 1.00e-20 1000.0 end
nb-94     1 0 1.00e-20 1000.0 end
zr-95     1 0 1.00e-20 1000.0 end
nb-95     1 0 1.00e-20 1000.0 end
mo-95     1 0 1.00e-20 1000.0 end
zr-96     1 0 1.00e-20 1000.0 end
mo-96     1 0 1.00e-20 1000.0 end
mo-97     1 0 1.00e-20 1000.0 end
mo-98     1 0 1.00e-20 1000.0 end
mo-99     1 0 1.00e-20 1000.0 end
tc-99     1 0 1.00e-20 1000.0 end
ru-99     1 0 1.00e-20 1000.0 end
mo-100    1 0 1.00e-20 1000.0 end
ru-100    1 0 1.00e-20 1000.0 end
ru-101    1 0 1.00e-20 1000.0 end
ru-102    1 0 1.00e-20 1000.0 end
pd-102    1 0 1.00e-20 1000.0 end
ru-103    1 0 1.00e-20 1000.0 end
rh-103    1 0 1.00e-20 1000.0 end
ru-104    1 0 1.00e-20 1000.0 end
pd-104    1 0 1.00e-20 1000.0 end
ru-105    1 0 1.00e-20 1000.0 end
rh-105    1 0 1.00e-20 1000.0 end
pd-105    1 0 1.00e-20 1000.0 end
ru-106    1 0 1.00e-20 1000.0 end
pd-106    1 0 1.00e-20 1000.0 end
pd-107    1 0 1.00e-20 1000.0 end
ag-107    1 0 1.00e-20 1000.0 end
pd-108    1 0 1.00e-20 1000.0 end
cd-108    1 0 1.00e-20 1000.0 end
ag-109    1 0 1.00e-20 1000.0 end
pd-110    1 0 1.00e-20 1000.0 end
cd-110    1 0 1.00e-20 1000.0 end
ag-111    1 0 1.00e-20 1000.0 end
cd-111    1 0 1.00e-20 1000.0 end
cd-112    1 0 1.00e-20 1000.0 end
cd-113    1 0 1.00e-20 1000.0 end
in-113    1 0 1.00e-20 1000.0 end
cd-114    1 0 1.00e-20 1000.0 end
sn-114    1 0 1.00e-20 1000.0 end
cd-115m   1 0 1.00e-20 1000.0 end
in-115    1 0 1.00e-20 1000.0 end
sn-115    1 0 1.00e-20 1000.0 end
cd-116    1 0 1.00e-20 1000.0 end
sn-116    1 0 1.00e-20 1000.0 end
sn-117    1 0 1.00e-20 1000.0 end
sn-118    1 0 1.00e-20 1000.0 end
sn-119    1 0 1.00e-20 1000.0 end
sn-120    1 0 1.00e-20 1000.0 end
sb-121    1 0 1.00e-20 1000.0 end
sn-122    1 0 1.00e-20 1000.0 end
te-122    1 0 1.00e-20 1000.0 end
sn-123    1 0 1.00e-20 1000.0 end
sb-123    1 0 1.00e-20 1000.0 end
te-123    1 0 1.00e-20 1000.0 end
sn-124    1 0 1.00e-20 1000.0 end
sb-124    1 0 1.00e-20 1000.0 end
te-124    1 0 1.00e-20 1000.0 end
sn-125    1 0 1.00e-20 1000.0 end
```

```
sb-125    1 0 1.00e-20 1000.0 end
te-125    1 0 1.00e-20 1000.0 end
sn-126    1 0 1.00e-20 1000.0 end
sb-126    1 0 1.00e-20 1000.0 end
te-126    1 0 1.00e-20 1000.0 end
xe-126    1 0 1.00e-20 1000.0 end
te-127m   1 0 1.00e-20 1000.0 end
i-127     1 0 1.00e-20 1000.0 end
te-128    1 0 1.00e-20 1000.0 end
xe-128    1 0 1.00e-20 1000.0 end
te-129m   1 0 1.00e-20 1000.0 end
i-129     1 0 1.00e-20 1000.0 end
xe-129    1 0 1.00e-20 1000.0 end
te-130    1 0 1.00e-20 1000.0 end
i-130     1 0 1.00e-20 1000.0 end
xe-130    1 0 1.00e-20 1000.0 end
i-131     1 0 1.00e-20 1000.0 end
xe-131    1 0 1.00e-20 1000.0 end
te-132    1 0 1.00e-20 1000.0 end
xe-132    1 0 1.00e-20 1000.0 end
xe-133    1 0 1.00e-20 1000.0 end
cs-133    1 0 1.00e-20 1000.0 end
xe-134    1 0 1.00e-20 1000.0 end
cs-134    1 0 1.00e-20 1000.0 end
ba-134    1 0 1.00e-20 1000.0 end
i-135     1 0 1.00e-20 1000.0 end
xe-135    1 0 1.00e-20 1000.0 end
cs-135    1 0 1.00e-20 1000.0 end
ba-135    1 0 1.00e-20 1000.0 end
xe-136    1 0 1.00e-20 1000.0 end
cs-136    1 0 1.00e-20 1000.0 end
ba-136    1 0 1.00e-20 1000.0 end
cs-137    1 0 1.00e-20 1000.0 end
ba-137    1 0 1.00e-20 1000.0 end
ba-138    1 0 1.00e-20 1000.0 end
la-139    1 0 1.00e-20 1000.0 end
ba-140    1 0 1.00e-20 1000.0 end
la-140    1 0 1.00e-20 1000.0 end
ce-140    1 0 1.00e-20 1000.0 end
ce-141    1 0 1.00e-20 1000.0 end
pr-141    1 0 1.00e-20 1000.0 end
ce-142    1 0 1.00e-20 1000.0 end
pr-142    1 0 1.00e-20 1000.0 end
nd-142    1 0 1.00e-20 1000.0 end
ce-143    1 0 1.00e-20 1000.0 end
pr-143    1 0 1.00e-20 1000.0 end
nd-143    1 0 1.00e-20 1000.0 end
ce-144    1 0 1.00e-20 1000.0 end
nd-144    1 0 1.00e-20 1000.0 end
nd-145    1 0 1.00e-20 1000.0 end
nd-146    1 0 1.00e-20 1000.0 end
nd-147    1 0 1.00e-20 1000.0 end
pm-147    1 0 1.00e-20 1000.0 end
sm-147    1 0 1.00e-20 1000.0 end
nd-148    1 0 1.00e-20 1000.0 end
pm-148    1 0 1.00e-20 1000.0 end
pm-148m   1 0 1.00e-20 1000.0 end
sm-148    1 0 1.00e-20 1000.0 end
pm-149    1 0 1.00e-20 1000.0 end
sm-149    1 0 1.00e-20 1000.0 end
nd-150    1 0 1.00e-20 1000.0 end
sm-150    1 0 1.00e-20 1000.0 end
pm-151    1 0 1.00e-20 1000.0 end
sm-151    1 0 1.00e-20 1000.0 end
eu-151    1 0 1.00e-20 1000.0 end
sm-152    1 0 1.00e-20 1000.0 end
eu-152    1 0 1.00e-20 1000.0 end
gd-152    1 0 1.00e-20 1000.0 end
sm-153    1 0 1.00e-20 1000.0 end
eu-153    1 0 1.00e-20 1000.0 end
sm-154    1 0 1.00e-20 1000.0 end
```

```
eu-154   1 0 1.00e-20 1000.0 end
gd-154   1 0 1.00e-20 1000.0 end
eu-155   1 0 1.00e-20 1000.0 end
gd-155   1 0 1.00e-20 1000.0 end
eu-156   1 0 1.00e-20 1000.0 end
gd-156   1 0 1.00e-20 1000.0 end
eu-157   1 0 1.00e-20 1000.0 end
gd-157   1 0 1.00e-20 1000.0 end
gd-158   1 0 1.00e-20 1000.0 end
tb-159   1 0 1.00e-20 1000.0 end
gd-160   1 0 1.00e-20 1000.0 end
tb-160   1 0 1.00e-20 1000.0 end
dy-160   1 0 1.00e-20 1000.0 end
dy-161   1 0 1.00e-20 1000.0 end
dy-162   1 0 1.00e-20 1000.0 end
dy-163   1 0 1.00e-20 1000.0 end
dy-164   1 0 1.00e-20 1000.0 end
ho-165   1 0 1.00e-20 1000.0 end
er-166   1 0 1.00e-20 1000.0 end
er-167   1 0 1.00e-20 1000.0 end
'
zirc2  2  1          620.0 end
h2o    3 den=0.670 1 600.0 end
arbm-bormod  0.670 1 1 0 0 5000 100 3 650.0E-06 600.0 end
end comp
'
'   base reactor lattice specification
squarepitch 1.2598  0.7844  1  3  0.9144 2  0.8001  3  end
more data szf=0.50 end
'
'     assembly and cycle parameters
npin/assembly=264  fuelngth=845.0  ncycles=21 nlib/cyc=1
printlevel=2  lightel=9  inplevel=1
numinstr=1  ortube=0.60198  srtube=0.56134  asmpitch=21.5
facmesh=0.50  end
'
'     assembly depletion/decay parameters
power=60.0  burn=1.0e-15  down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
power=60.0  burn=50.0     down=0.0        end
'
'    light-elements taken from SAS2H input listing in
'    ORNL/TM-12294/V5  Appendix B, not verified to be accurate
 o  135     cr  5.9     mn  0.33
 fe  12.9   co  0.075   ni  9.9
 zr 221     nb  0.71    sn  3.60
'
'   end of input
end
```

APPENDIX B

SAMPLE INPUT FILE FOR CSAS25

```
=csas25    parm=size=5000000
Generic 32-Assembly Burnup Credit Cask (GBC-32) w/Axial Brnp Profile
238groupndf5    latticecell
'
' **********  GBC-32: Generic 32-Assembly Cask  **********
' *
' * -GBC-32 Characteristics-
' *      Basket Cell ID: 22.0 cm
' *      Basket Cell OD: 23.5 cm, basket wall thickness = 0.75 cm
' *      Basket Cell Height: 365.76
' *      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)
' *      Boral Panel Height: 365.76
' *      Cask ID: 175.0 cm
' *      Cask OD: 215.0 cm
' *      Cask Top & Bottom Thickness: 30.0 cm
' *
' * -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)
' *       Axial Burnup Profile consistent with that suggested in
' *       DOE TR Rev. 2 for Burnups > 30 GWd/MTU
' *
' **********  GBC-32: Generic 32-Assembly Cask  **********
'
'  Node-01 Burnup=26.08GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  101 0  5.8176E-06   293.0 end
  u-235  101 0  4.0950E-04   293.0 end
  u-236  101 0  9.9756E-05   293.0 end
  u-238  101 0  2.2105E-02   293.0 end
 np-237  101 0  7.9002E-06   293.0 end
 pu-238  101 0  1.6561E-06   293.0 end
 pu-239  101 0  1.3192E-04   293.0 end
 pu-240  101 0  3.9078E-05   293.0 end
 pu-241  101 0  1.7872E-05   293.0 end
 pu-242  101 0  5.1651E-06   293.0 end
 am-241  101 0  5.1831E-06   293.0 end
 am-243  101 0  7.5598E-07   293.0 end
'  fission products
 mo-95   101 0  3.7734E-05   293.0 end
 tc-99   101 0  3.7770E-05   293.0 end
 ru-101  101 0  3.3623E-05   293.0 end
 rh-103  101 0  2.1908E-05   293.0 end
 ag-109  101 0  2.8370E-06   293.0 end
 cs-133  101 0  3.9691E-05   293.0 end
 nd-143  101 0  2.9313E-05   293.0 end
 nd-145  101 0  2.1983E-05   293.0 end
 sm-147  101 0  7.0810E-06   293.0 end
 sm-149  101 0  2.0986E-07   293.0 end
 sm-150  101 0  8.8377E-06   293.0 end
 sm-151  101 0  5.9274E-07   293.0 end
 eu-151  101 0  2.3732E-08   293.0 end
 sm-152  101 0  3.8060E-06   293.0 end
 eu-153  101 0  2.8524E-06   293.0 end
 gd-155  101 0  6.3214E-08   293.0 end
  o-16   101 0  4.6948E-02   293.0 end
'  Node-02 Burnup=38.68 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  102 0  4.8790E-06   293.0 end
  u-235  102 0  2.5447E-04   293.0 end
  u-236  102 0  1.2187E-04   293.0 end
  u-238  102 0  2.1873E-02   293.0 end
 np-237  102 0  1.3147E-05   293.0 end
```

```
 pu-238   102 0  4.2966E-06   293.0 end
 pu-239   102 0  1.4269E-04   293.0 end
 pu-240   102 0  5.7000E-05   293.0 end
 pu-241   102 0  2.7388E-05   293.0 end
 pu-242   102 0  1.3158E-05   293.0 end
 am-241   102 0  8.0958E-06   293.0 end
 am-243   102 0  2.8810E-06   293.0 end
'  fission products
 mo-95    102 0  5.3059E-05   293.0 end
 tc-99    102 0  5.3269E-05   293.0 end
 ru-101   102 0  4.9411E-05   293.0 end
 rh-103   102 0  3.0421E-05   293.0 end
 ag-109   102 0  4.9976E-06   293.0 end
 cs-133   102 0  5.5684E-05   293.0 end
 nd-143   102 0  3.7678E-05   293.0 end
 nd-145   102 0  3.0398E-05   293.0 end
 sm-147   102 0  8.5409E-06   293.0 end
 sm-149   102 0  2.1895E-07   293.0 end
 sm-150   102 0  1.3693E-05   293.0 end
 sm-151   102 0  6.9918E-07   293.0 end
 eu-151   102 0  2.7946E-08   293.0 end
 sm-152   102 0  5.3941E-06   293.0 end
 eu-153   102 0  4.9658E-06   293.0 end
 gd-155   102 0  1.2078E-07   293.0 end
  o-16    102 0  4.6946E-02   293.0 end
'  Node-03 Burnup=42.96 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   103 0  4.5993E-06   293.0 end
  u-235   103 0  2.1363E-04   293.0 end
  u-236   103 0  1.2668E-04   293.0 end
  u-238   103 0  2.1790E-02   293.0 end
 np-237   103 0  1.4857E-05   293.0 end
 pu-238   103 0  5.4578E-06   293.0 end
 pu-239   103 0  1.4399E-04   293.0 end
 pu-240   103 0  6.1987E-05   293.0 end
 pu-241   103 0  2.9794E-05   293.0 end
 pu-242   103 0  1.6465E-05   293.0 end
 am-241   103 0  8.8447E-06   293.0 end
 am-243   103 0  3.9712E-06   293.0 end
'  fission products
 mo-95    103 0  5.7866E-05   293.0 end
 tc-99    103 0  5.8118E-05   293.0 end
 ru-101   103 0  5.4667E-05   293.0 end
 rh-103   103 0  3.2880E-05   293.0 end
 ag-109   103 0  5.7639E-06   293.0 end
 cs-133   103 0  6.0625E-05   293.0 end
 nd-143   103 0  3.9755E-05   293.0 end
 nd-145   103 0  3.2959E-05   293.0 end
 sm-147   103 0  8.8457E-06   293.0 end
 sm-149   103 0  2.1999E-07   293.0 end
 sm-150   103 0  1.5298E-05   293.0 end
 sm-151   103 0  7.3084E-07   293.0 end
 eu-151   103 0  2.9194E-08   293.0 end
 sm-152   103 0  5.8819E-06   293.0 end
 eu-153   103 0  5.7012E-06   293.0 end
 gd-155   103 0  1.4254E-07   293.0 end
  o-16    103 0  4.6945E-02   293.0 end
'  Node-04 Burnup=44.12 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   104 0  4.5268E-06   293.0 end
  u-235   104 0  2.0350E-04   293.0 end
  u-236   104 0  1.2777E-04   293.0 end
  u-238   104 0  2.1766E-02   293.0 end
 np-237   104 0  1.5307E-05   293.0 end
 pu-238   104 0  5.7912E-06   293.0 end
 pu-239   104 0  1.4422E-04   293.0 end
 pu-240   104 0  6.3243E-05   293.0 end
 pu-241   104 0  3.0374E-05   293.0 end
 pu-242   104 0  1.7398E-05   293.0 end
 am-241   104 0  9.0255E-06   293.0 end
 am-243   104 0  4.2966E-06   293.0 end
```

```
'  fission products
 mo-95    104 0  5.9135E-05   293.0 end
 tc-99    104 0  5.9395E-05   293.0 end
 ru-101   104 0  5.6081E-05   293.0 end
 rh-103   104 0  3.3508E-05   293.0 end
 ag-109   104 0  5.9725E-06   293.0 end
 cs-133   104 0  6.1921E-05   293.0 end
 nd-143   104 0  4.0255E-05   293.0 end
 nd-145   104 0  3.3628E-05   293.0 end
 sm-147   104 0  8.9143E-06   293.0 end
 sm-149   104 0  2.2014E-07   293.0 end
 sm-150   104 0  1.5726E-05   293.0 end
 sm-151   104 0  7.3907E-07   293.0 end
 eu-151   104 0  2.9518E-08   293.0 end
 sm-152   104 0  6.0099E-06   293.0 end
 eu-153   104 0  5.8995E-06   293.0 end
 gd-155   104 0  1.4852E-07   293.0 end
  o-16    104 0  4.6945E-02   293.0 end
'  Node-05 Burnup=44.32 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   105 0  4.5145E-06   293.0 end
  u-235   105 0  2.0179E-04   293.0 end
  u-236   105 0  1.2795E-04   293.0 end
  u-238   105 0  2.1762E-02   293.0 end
 np-237   105 0  1.5384E-05   293.0 end
 pu-238   105 0  5.8494E-06   293.0 end
 pu-239   105 0  1.4426E-04   293.0 end
 pu-240   105 0  6.3455E-05   293.0 end
 pu-241   105 0  3.0471E-05   293.0 end
 pu-242   105 0  1.7560E-05   293.0 end
 am-241   105 0  9.0558E-06   293.0 end
 am-243   105 0  4.3539E-06   293.0 end
'  fission products
 mo-95    105 0  5.9352E-05   293.0 end
 tc-99    105 0  5.9614E-05   293.0 end
 ru-101   105 0  5.6324E-05   293.0 end
 rh-103   105 0  3.3615E-05   293.0 end
 ag-109   105 0  6.0084E-06   293.0 end
 cs-133   105 0  6.2142E-05   293.0 end
 nd-143   105 0  4.0338E-05   293.0 end
 nd-145   105 0  3.3742E-05   293.0 end
 sm-147   105 0  8.9256E-06   293.0 end
 sm-149   105 0  2.2016E-07   293.0 end
 sm-150   105 0  1.5799E-05   293.0 end
 sm-151   105 0  7.4047E-07   293.0 end
 eu-151   105 0  2.9573E-08   293.0 end
 sm-152   105 0  6.0317E-06   293.0 end
 eu-153   105 0  5.9336E-06   293.0 end
 gd-155   105 0  1.4955E-07   293.0 end
  o-16    105 0  4.6945E-02   293.0 end
'  Node-06 Burnup=44.24 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   106 0  4.5194E-06   293.0 end
  u-235   106 0  2.0247E-04   293.0 end
  u-236   106 0  1.2788E-04   293.0 end
  u-238   106 0  2.1764E-02   293.0 end
 np-237   106 0  1.5353E-05   293.0 end
 pu-238   106 0  5.8261E-06   293.0 end
 pu-239   106 0  1.4424E-04   293.0 end
 pu-240   106 0  6.3371E-05   293.0 end
 pu-241   106 0  3.0432E-05   293.0 end
 pu-242   106 0  1.7495E-05   293.0 end
 am-241   106 0  9.0437E-06   293.0 end
 am-243   106 0  4.3309E-06   293.0 end
'  fission products
 mo-95    106 0  5.9265E-05   293.0 end
 tc-99    106 0  5.9526E-05   293.0 end
 ru-101   106 0  5.6227E-05   293.0 end
 rh-103   106 0  3.3572E-05   293.0 end
 ag-109   106 0  5.9940E-06   293.0 end
 cs-133   106 0  6.2054E-05   293.0 end
```

```
 nd-143  106 0  4.0305E-05   293.0 end
 nd-145  106 0  3.3696E-05   293.0 end
 sm-147  106 0  8.9211E-06   293.0 end
 sm-149  106 0  2.2016E-07   293.0 end
 sm-150  106 0  1.5770E-05   293.0 end
 sm-151  106 0  7.3991E-07   293.0 end
 eu-151  106 0  2.9551E-08   293.0 end
 sm-152  106 0  6.0230E-06   293.0 end
 eu-153  106 0  5.9200E-06   293.0 end
 gd-155  106 0  1.4914E-07   293.0 end
  o-16   106 0  4.6945E-02   293.0 end
'  Node-07 Burnup=44.08 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  107 0  4.5293E-06   293.0 end
  u-235  107 0  2.0384E-04   293.0 end
  u-236  107 0  1.2773E-04   293.0 end
  u-238  107 0  2.1767E-02   293.0 end
 np-237  107 0  1.5292E-05   293.0 end
 pu-238  107 0  5.7796E-06   293.0 end
 pu-239  107 0  1.4421E-04   293.0 end
 pu-240  107 0  6.3200E-05   293.0 end
 pu-241  107 0  3.0354E-05   293.0 end
 pu-242  107 0  1.7366E-05   293.0 end
 am-241  107 0  9.0195E-06   293.0 end
 am-243  107 0  4.2852E-06   293.0 end
'  fission products
 mo-95   107 0  5.9091E-05   293.0 end
 tc-99   107 0  5.9351E-05   293.0 end
 ru-101  107 0  5.6032E-05   293.0 end
 rh-103  107 0  3.3487E-05   293.0 end
 ag-109  107 0  5.9653E-06   293.0 end
 cs-133  107 0  6.1876E-05   293.0 end
 nd-143  107 0  4.0238E-05   293.0 end
 nd-145  107 0  3.3605E-05   293.0 end
 sm-147  107 0  8.9120E-06   293.0 end
 sm-149  107 0  2.2014E-07   293.0 end
 sm-150  107 0  1.5711E-05   293.0 end
 sm-151  107 0  7.3879E-07   293.0 end
 eu-151  107 0  2.9507E-08   293.0 end
 sm-152  107 0  6.0055E-06   293.0 end
 eu-153  107 0  5.8927E-06   293.0 end
 gd-155  107 0  1.4831E-07   293.0 end
  o-16   107 0  4.6945E-02   293.0 end
'  Node-08 Burnup=43.88 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  108 0  4.5417E-06   293.0 end
  u-235  108 0  2.0556E-04   293.0 end
  u-236  108 0  1.2755E-04   293.0 end
  u-238  108 0  2.1771E-02   293.0 end
 np-237  108 0  1.5215E-05   293.0 end
 pu-238  108 0  5.7216E-06   293.0 end
 pu-239  108 0  1.4418E-04   293.0 end
 pu-240  108 0  6.2987E-05   293.0 end
 pu-241  108 0  3.0256E-05   293.0 end
 pu-242  108 0  1.7204E-05   293.0 end
 am-241  108 0  8.9888E-06   293.0 end
 am-243  108 0  4.2282E-06   293.0 end
'  fission products
 mo-95   108 0  5.8873E-05   293.0 end
 tc-99   108 0  5.9132E-05   293.0 end
 ru-101  108 0  5.5789E-05   293.0 end
 rh-103  108 0  3.3379E-05   293.0 end
 ag-109  108 0  5.9293E-06   293.0 end
 cs-133  108 0  6.1654E-05   293.0 end
 nd-143  108 0  4.0153E-05   293.0 end
 nd-145  108 0  3.3490E-05   293.0 end
 sm-147  108 0  8.9006E-06   293.0 end
 sm-149  108 0  2.2012E-07   293.0 end
 sm-150  108 0  1.5638E-05   293.0 end
 sm-151  108 0  7.3737E-07   293.0 end
 eu-151  108 0  2.9451E-08   293.0 end
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 sm-152  108 0  5.9835E-06   293.0 end
 eu-153  108 0  5.8585E-06   293.0 end
 gd-155  108 0  1.4728E-07   293.0 end
  o-16   108 0  4.6945E-02   293.0 end
'  Node-09 Burnup=43.76 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  109 0  4.5491E-06   293.0 end
  u-235  109 0  2.0660E-04   293.0 end
  u-236  109 0  1.2744E-04   293.0 end
  u-238  109 0  2.1774E-02   293.0 end
 np-237  109 0  1.5168E-05   293.0 end
 pu-238  109 0  5.6869E-06   293.0 end
 pu-239  109 0  1.4416E-04   293.0 end
 pu-240  109 0  6.2858E-05   293.0 end
 pu-241  109 0  3.0197E-05   293.0 end
 pu-242  109 0  1.7107E-05   293.0 end
 am-241  109 0  8.9703E-06   293.0 end
 am-243  109 0  4.1943E-06   293.0 end
'  fission products
 mo-95   109 0  5.8743E-05   293.0 end
 tc-99   109 0  5.9000E-05   293.0 end
 ru-101  109 0  5.5642E-05   293.0 end
 rh-103  109 0  3.3315E-05   293.0 end
 ag-109  109 0  5.9077E-06   293.0 end
 cs-133  109 0  6.1521E-05   293.0 end
 nd-143  109 0  4.0102E-05   293.0 end
 nd-145  109 0  3.3421E-05   293.0 end
 sm-147  109 0  8.8936E-06   293.0 end
 sm-149  109 0  2.2010E-07   293.0 end
 sm-150  109 0  1.5593E-05   293.0 end
 sm-151  109 0  7.3653E-07   293.0 end
 eu-151  109 0  2.9418E-08   293.0 end
 sm-152  109 0  5.9703E-06   293.0 end
 eu-153  109 0  5.8380E-06   293.0 end
 gd-155  109 0  1.4666E-07   293.0 end
  o-16   109 0  4.6945E-02   293.0 end
'  Node-10 Burnup=43.76 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  110 0  4.5491E-06   293.0 end
  u-235  110 0  2.0660E-04   293.0 end
  u-236  110 0  1.2744E-04   293.0 end
  u-238  110 0  2.1774E-02   293.0 end
 np-237  110 0  1.5168E-05   293.0 end
 pu-238  110 0  5.6869E-06   293.0 end
 pu-239  110 0  1.4416E-04   293.0 end
 pu-240  110 0  6.2858E-05   293.0 end
 pu-241  110 0  3.0197E-05   293.0 end
 pu-242  110 0  1.7107E-05   293.0 end
 am-241  110 0  8.9703E-06   293.0 end
 am-243  110 0  4.1943E-06   293.0 end
'  fission products
 mo-95   110 0  5.8743E-05   293.0 end
 tc-99   110 0  5.9000E-05   293.0 end
 ru-101  110 0  5.5642E-05   293.0 end
 rh-103  110 0  3.3315E-05   293.0 end
 ag-109  110 0  5.9077E-06   293.0 end
 cs-133  110 0  6.1521E-05   293.0 end
 nd-143  110 0  4.0102E-05   293.0 end
 nd-145  110 0  3.3421E-05   293.0 end
 sm-147  110 0  8.8936E-06   293.0 end
 sm-149  110 0  2.2010E-07   293.0 end
 sm-150  110 0  1.5593E-05   293.0 end
 sm-151  110 0  7.3653E-07   293.0 end
 eu-151  110 0  2.9418E-08   293.0 end
 sm-152  110 0  5.9703E-06   293.0 end
 eu-153  110 0  5.8380E-06   293.0 end
 gd-155  110 0  1.4666E-07   293.0 end
  o-16   110 0  4.6945E-02   293.0 end
'  Node-11 Burnup=43.80 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
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  u-234   111 0  4.5466E-06   293.0 end
  u-235   111 0  2.0625E-04   293.0 end
  u-236   111 0  1.2748E-04   293.0 end
  u-238   111 0  2.1773E-02   293.0 end
 np-237   111 0  1.5184E-05   293.0 end
 pu-238   111 0  5.6985E-06   293.0 end
 pu-239   111 0  1.4416E-04   293.0 end
 pu-240   111 0  6.2901E-05   293.0 end
 pu-241   111 0  3.0216E-05   293.0 end
 pu-242   111 0  1.7139E-05   293.0 end
 am-241   111 0  8.9765E-06   293.0 end
 am-243   111 0  4.2056E-06   293.0 end
'  fission products
 mo-95    111 0  5.8786E-05   293.0 end
 tc-99    111 0  5.9044E-05   293.0 end
 ru-101   111 0  5.5691E-05   293.0 end
 rh-103   111 0  3.3336E-05   293.0 end
 ag-109   111 0  5.9149E-06   293.0 end
 cs-133   111 0  6.1565E-05   293.0 end
 nd-143   111 0  4.0119E-05   293.0 end
 nd-145   111 0  3.3444E-05   293.0 end
 sm-147   111 0  8.8959E-06   293.0 end
 sm-149   111 0  2.2011E-07   293.0 end
 sm-150   111 0  1.5608E-05   293.0 end
 sm-151   111 0  7.3681E-07   293.0 end
 eu-151   111 0  2.9429E-08   293.0 end
 sm-152   111 0  5.9747E-06   293.0 end
 eu-153   111 0  5.8449E-06   293.0 end
 gd-155   111 0  1.4687E-07   293.0 end
  o-16    111 0  4.6945E-02   293.0 end
'  Node-12 Burnup=43.84 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   112 0  4.5442E-06   293.0 end
  u-235   112 0  2.0591E-04   293.0 end
  u-236   112 0  1.2751E-04   293.0 end
  u-238   112 0  2.1772E-02   293.0 end
 np-237   112 0  1.5199E-05   293.0 end
 pu-238   112 0  5.7100E-06   293.0 end
 pu-239   112 0  1.4417E-04   293.0 end
 pu-240   112 0  6.2944E-05   293.0 end
 pu-241   112 0  3.0236E-05   293.0 end
 pu-242   112 0  1.7172E-05   293.0 end
 am-241   112 0  8.9827E-06   293.0 end
 am-243   112 0  4.2169E-06   293.0 end
'  fission products
 mo-95    112 0  5.8830E-05   293.0 end
 tc-99    112 0  5.9088E-05   293.0 end
 ru-101   112 0  5.5740E-05   293.0 end
 rh-103   112 0  3.3358E-05   293.0 end
 ag-109   112 0  5.9221E-06   293.0 end
 cs-133   112 0  6.1610E-05   293.0 end
 nd-143   112 0  4.0136E-05   293.0 end
 nd-145   112 0  3.3467E-05   293.0 end
 sm-147   112 0  8.8983E-06   293.0 end
 sm-149   112 0  2.2011E-07   293.0 end
 sm-150   112 0  1.5623E-05   293.0 end
 sm-151   112 0  7.3709E-07   293.0 end
 eu-151   112 0  2.9440E-08   293.0 end
 sm-152   112 0  5.9791E-06   293.0 end
 eu-153   112 0  5.8517E-06   293.0 end
 gd-155   112 0  1.4707E-07   293.0 end
  o-16    112 0  4.6945E-02   293.0 end
'  Node-13 Burnup=43.80 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   113 0  4.5466E-06   293.0 end
  u-235   113 0  2.0625E-04   293.0 end
  u-236   113 0  1.2748E-04   293.0 end
  u-238   113 0  2.1773E-02   293.0 end
 np-237   113 0  1.5184E-05   293.0 end
 pu-238   113 0  5.6985E-06   293.0 end
 pu-239   113 0  1.4416E-04   293.0 end
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 pu-240  113 0  6.2901E-05   293.0 end
 pu-241  113 0  3.0216E-05   293.0 end
 pu-242  113 0  1.7139E-05   293.0 end
 am-241  113 0  8.9765E-06   293.0 end
 am-243  113 0  4.2056E-06   293.0 end
'  fission products
 mo-95   113 0  5.8786E-05   293.0 end
 tc-99   113 0  5.9044E-05   293.0 end
 ru-101  113 0  5.5691E-05   293.0 end
 rh-103  113 0  3.3336E-05   293.0 end
 ag-109  113 0  5.9149E-06   293.0 end
 cs-133  113 0  6.1565E-05   293.0 end
 nd-143  113 0  4.0119E-05   293.0 end
 nd-145  113 0  3.3444E-05   293.0 end
 sm-147  113 0  8.8959E-06   293.0 end
 sm-149  113 0  2.2011E-07   293.0 end
 sm-150  113 0  1.5608E-05   293.0 end
 sm-151  113 0  7.3681E-07   293.0 end
 eu-151  113 0  2.9429E-08   293.0 end
 sm-152  113 0  5.9747E-06   293.0 end
 eu-153  113 0  5.8449E-06   293.0 end
 gd-155  113 0  1.4687E-07   293.0 end
  o-16   113 0  4.6945E-02   293.0 end
'  Node-14 Burnup=43.44 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  114 0  4.5691E-06   293.0 end
  u-235  114 0  2.0939E-04   293.0 end
  u-236  114 0  1.2714E-04   293.0 end
  u-238  114 0  2.1780E-02   293.0 end
 np-237  114 0  1.5044E-05   293.0 end
 pu-238  114 0  5.5948E-06   293.0 end
 pu-239  114 0  1.4409E-04   293.0 end
 pu-240  114 0  6.2512E-05   293.0 end
 pu-241  114 0  3.0038E-05   293.0 end
 pu-242  114 0  1.6850E-05   293.0 end
 am-241  114 0  8.9207E-06   293.0 end
 am-243  114 0  4.1044E-06   293.0 end
'  fission products
 mo-95   114 0  5.8393E-05   293.0 end
 tc-99   114 0  5.8648E-05   293.0 end
 ru-101  114 0  5.5252E-05   293.0 end
 rh-103  114 0  3.3142E-05   293.0 end
 ag-109  114 0  5.8502E-06   293.0 end
 cs-133  114 0  6.1163E-05   293.0 end
 nd-143  114 0  3.9965E-05   293.0 end
 nd-145  114 0  3.3237E-05   293.0 end
 sm-147  114 0  8.8748E-06   293.0 end
 sm-149  114 0  2.2006E-07   293.0 end
 sm-150  114 0  1.5475E-05   293.0 end
 sm-151  114 0  7.3426E-07   293.0 end
 eu-151  114 0  2.9329E-08   293.0 end
 sm-152  114 0  5.9351E-06   293.0 end
 eu-153  114 0  5.7833E-06   293.0 end
 gd-155  114 0  1.4501E-07   293.0 end
  o-16   114 0  4.6945E-02   293.0 end
'  Node-15 Burnup=42.36 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  115 0  4.6373E-06   293.0 end
  u-235  115 0  2.1903E-04   293.0 end
  u-236  115 0  1.2608E-04   293.0 end
  u-238  115 0  2.1802E-02   293.0 end
 np-237  115 0  1.4622E-05   293.0 end
 pu-238  115 0  5.2882E-06   293.0 end
 pu-239  115 0  1.4385E-04   293.0 end
 pu-240  115 0  6.1322E-05   293.0 end
 pu-241  115 0  2.9482E-05   293.0 end
 pu-242  115 0  1.5988E-05   293.0 end
 am-241  115 0  8.7473E-06   293.0 end
 am-243  115 0  3.8077E-06   293.0 end
'  fission products
 mo-95   115 0  5.7204E-05   293.0 end
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 tc-99    115 0  5.7451E-05   293.0 end
 ru-101   115 0  5.3934E-05   293.0 end
 rh-103   115 0  3.2549E-05   293.0 end
 ag-109   115 0  5.6561E-06   293.0 end
 cs-133   115 0  5.9947E-05   293.0 end
 nd-143   115 0  3.9486E-05   293.0 end
 nd-145   115 0  3.2609E-05   293.0 end
 sm-147   115 0  8.8079E-06   293.0 end
 sm-149   115 0  2.1988E-07   293.0 end
 sm-150   115 0  1.5076E-05   293.0 end
 sm-151   115 0  7.2652E-07   293.0 end
 eu-151   115 0  2.9024E-08   293.0 end
 sm-152   115 0  5.8150E-06   293.0 end
 eu-153   115 0  5.5984E-06   293.0 end
 gd-155   115 0  1.3946E-07   293.0 end
  o-16    115 0  4.6946E-02   293.0 end
'  Node-16 Burnup=38.84 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   116 0  4.8682E-06   293.0 end
  u-235   116 0  2.5284E-04   293.0 end
  u-236   116 0  1.2207E-04   293.0 end
  u-238   116 0  2.1870E-02   293.0 end
 np-237   116 0  1.3212E-05   293.0 end
 pu-238   116 0  4.3378E-06   293.0 end
 pu-239   116 0  1.4275E-04   293.0 end
 pu-240   116 0  5.7196E-05   293.0 end
 pu-241   116 0  2.7486E-05   293.0 end
 pu-242   116 0  1.3277E-05   293.0 end
 am-241   116 0  8.1262E-06   293.0 end
 am-243   116 0  2.9185E-06   293.0 end
'  fission products
 mo-95    116 0  5.3242E-05   293.0 end
 tc-99    116 0  5.3454E-05   293.0 end
 ru-101   116 0  4.9608E-05   293.0 end
 rh-103   116 0  3.0517E-05   293.0 end
 ag-109   116 0  5.0261E-06   293.0 end
 cs-133   116 0  5.5873E-05   293.0 end
 nd-143   116 0  3.7763E-05   293.0 end
 nd-145   116 0  3.0496E-05   293.0 end
 sm-147   116 0  8.5538E-06   293.0 end
 sm-149   116 0  2.1900E-07   293.0 end
 sm-150   116 0  1.3754E-05   293.0 end
 sm-151   116 0  7.0040E-07   293.0 end
 eu-151   116 0  2.7994E-08   293.0 end
 sm-152   116 0  5.4127E-06   293.0 end
 eu-153   116 0  4.9933E-06   293.0 end
 gd-155   116 0  1.2158E-07   293.0 end
  o-16    116 0  4.6946E-02   293.0 end
'  Node-17 Burnup=29.52 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234   117 0  5.5443E-06   293.0 end
  u-235   117 0  3.6164E-04   293.0 end
  u-236   117 0  1.0706E-04   293.0 end
  u-238   117 0  2.2044E-02   293.0 end
 np-237   117 0  9.3347E-06   293.0 end
 pu-238   117 0  2.2501E-06   293.0 end
 pu-239   117 0  1.3627E-04   293.0 end
 pu-240   117 0  4.4429E-05   293.0 end
 pu-241   117 0  2.0813E-05   293.0 end
 pu-242   117 0  7.0354E-06   293.0 end
 am-241   117 0  6.0735E-06   293.0 end
 am-243   117 0  1.1752E-06   293.0 end
'  fission products
 mo-95    117 0  4.2096E-05   293.0 end
 tc-99    117 0  4.2180E-05   293.0 end
 ru-101   117 0  3.7975E-05   293.0 end
 rh-103   117 0  2.4415E-05   293.0 end
 ag-109   117 0  3.4048E-06   293.0 end
 cs-133   117 0  4.4270E-05   293.0 end
 nd-143   117 0  3.1943E-05   293.0 end
 nd-145   117 0  2.4412E-05   293.0 end
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 sm-147  117 0  7.5738E-06   293.0 end
 sm-149  117 0  2.1350E-07   293.0 end
 sm-150  117 0  1.0170E-05   293.0 end
 sm-151  117 0  6.2399E-07   293.0 end
 eu-151  117 0  2.4972E-08   293.0 end
 sm-152  117 0  4.2632E-06   293.0 end
 eu-153  117 0  3.4113E-06   293.0 end
 gd-155  117 0  7.7532E-08   293.0 end
  o-16   117 0  4.6947E-02   293.0 end
'  Node-18 Burnup=18.48 GWd/MTU w17x17 pwr 18-axial nodes gbc-32 model
'  actinides
  u-234  118 0  6.4660E-06   293.0 end
  u-235  118 0  5.3166E-04   293.0 end
  u-236  118 0  7.9832E-05   293.0 end
  u-238  118 0  2.2234E-02   293.0 end
 np-237  118 0  4.8683E-06   293.0 end
 pu-238  118 0  6.9462E-07   293.0 end
 pu-239  118 0  1.1629E-04   293.0 end
 pu-240  118 0  2.6299E-05   293.0 end
 pu-241  118 0  1.0804E-05   293.0 end
 pu-242  118 0  2.0446E-06   293.0 end
 am-241  118 0  3.0829E-06   293.0 end
 am-243  118 0  2.0341E-07   293.0 end
'  fission products
 mo-95   118 0  2.7605E-05   293.0 end
 tc-99   118 0  2.6628E-05   293.0 end
 ru-101  118 0  2.3913E-05   293.0 end
 rh-103  118 0  1.5926E-05   293.0 end
 ag-109  118 0  1.6800E-06   293.0 end
 cs-133  118 0  2.9023E-05   293.0 end
 nd-143  118 0  2.2535E-05   293.0 end
 nd-145  118 0  1.6246E-05   293.0 end
 sm-147  118 0  5.6918E-06   293.0 end
 sm-149  118 0  1.9729E-07   293.0 end
 sm-150  118 0  5.9405E-06   293.0 end
 sm-151  118 0  5.1675E-07   293.0 end
 eu-151  118 0  2.0704E-08   293.0 end
 sm-152  118 0  2.7262E-06   293.0 end
 eu-153  118 0  1.7157E-06   293.0 end
 gd-155  118 0  3.6864E-08   293.0 end
  o-16   118 0  4.6947E-02   293.0 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 (GBC-32) w/Axial Brnp Profile
read param tme=10000 gen=1100 nsk=100 npg=2000  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                                       182.880   0.
cylinder     110 1  0.3922                                       203.198   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  -30.00
'           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           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.
'        Right-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.
'
'            Steel Cask/Overpack
cylinder        6  1  107.5                    425.76    -60.
'
'            Cube of Water Surrounding Cask
cuboid          0  1  108  -108   108   -108   425.76    -60.
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 2 1 1 2 1 1 2 1 1 1 1 1
 1 1 1 2 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 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 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 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 2 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
end fill
end array
read bounds  xyf=specular   end bounds
end data
end
```

APPENDIX C

SUPPLEMENTARY RESULTS FOR ADDITIONAL NUCLIDE SETS

APPENDIX C

SUPPLEMENTARY RESULTS FOR ADDITIONAL NUCLIDE SETS

This appendix contains supplementary results for nuclide sets in addition to those defined in the main body of this report. One of the more difficult decisions that was required during the preparation of this computational benchmark was the decision related to which nuclides to consider for the estimation of the additional reactivity margin. Given the number of nuclides that have been identified as being important to burnup credit, one could group them in many different ways. It has become a common practice for the nuclides to be divided in terms of actinides and fission products. Another useful guideline for dividing the nuclides into subsets is the existence of measured chemical assay data. In this appendix, the nuclides that have been previous identified as being important to burnup credit are divided into 4 subsets and reactivity comparisons are made between calculations with these nuclide subsets and calculations using all nuclides for which cross-section data are available, which corresponds to 233 nuclides in the SCALE 238-group library. The nuclides are divided into subsets according to their classification as actinide or fission product, and based on the existence of measured assay data.

Reference C.1 lists "prime candidates" for inclusion in burnup credit analyses related to dry storage and transport, including several nuclides for which measured chemical assay data are not currently available in the United States. Therefore, for this benchmark, all of the actinide and fission product nuclides identified in Ref. C.1, including those for which no chemical assay data are available, were used in the estimation of the additional reactivity margin. This decision was based on the objective of estimating the residual margins with actinide-only burnup credit. However, questions often arise regarding the reactivity margin associated with various subsets of the actinides and fission products. To investigate the reactivity worth of the nuclides in a bit more detail, results were also generated for the computational benchmark problem using additional nuclide sets, based on those listed in Table C.1.

Calculated k_{eff} values for the benchmark problem (the GBC-32 cask) for various nuclide sets as a function of burnup for initial enrichments of 2, 3, 4, and 5 wt % ^{235}U and cooling times of 5- and 20-years are plotted in Figures C.1–C.8.

Table C.1 Nuclides used for supplementary analysis of the benchmark problem

<u>U-234</u>	<u>U-235</u>	U-236	<u>U-238</u>	<u>Pu-238</u>	<u>Pu-239</u>	<u>Pu-240</u>	<u>Pu-241</u>	<u>Pu-242</u>	<u>Am-241</u>
Am-243*	Np-237	Mo-95*	Tc-99	Ru-101*	Rh-103*	Ag-109*	Cs-133	Sm-147	Sm-149
Sm-150	Sm-151	Sm-152	Nd-143	Nd-145	Eu-151*	Eu-153	Gd-155		

Notes: (1) Underlined nuclides are consistent with those specified in a DOE Topical Report.[C.2]
(2) Nuclides identified with asterisks are nuclides for which measured chemical assay data are not currently available or are not readily available at this time in the United States.

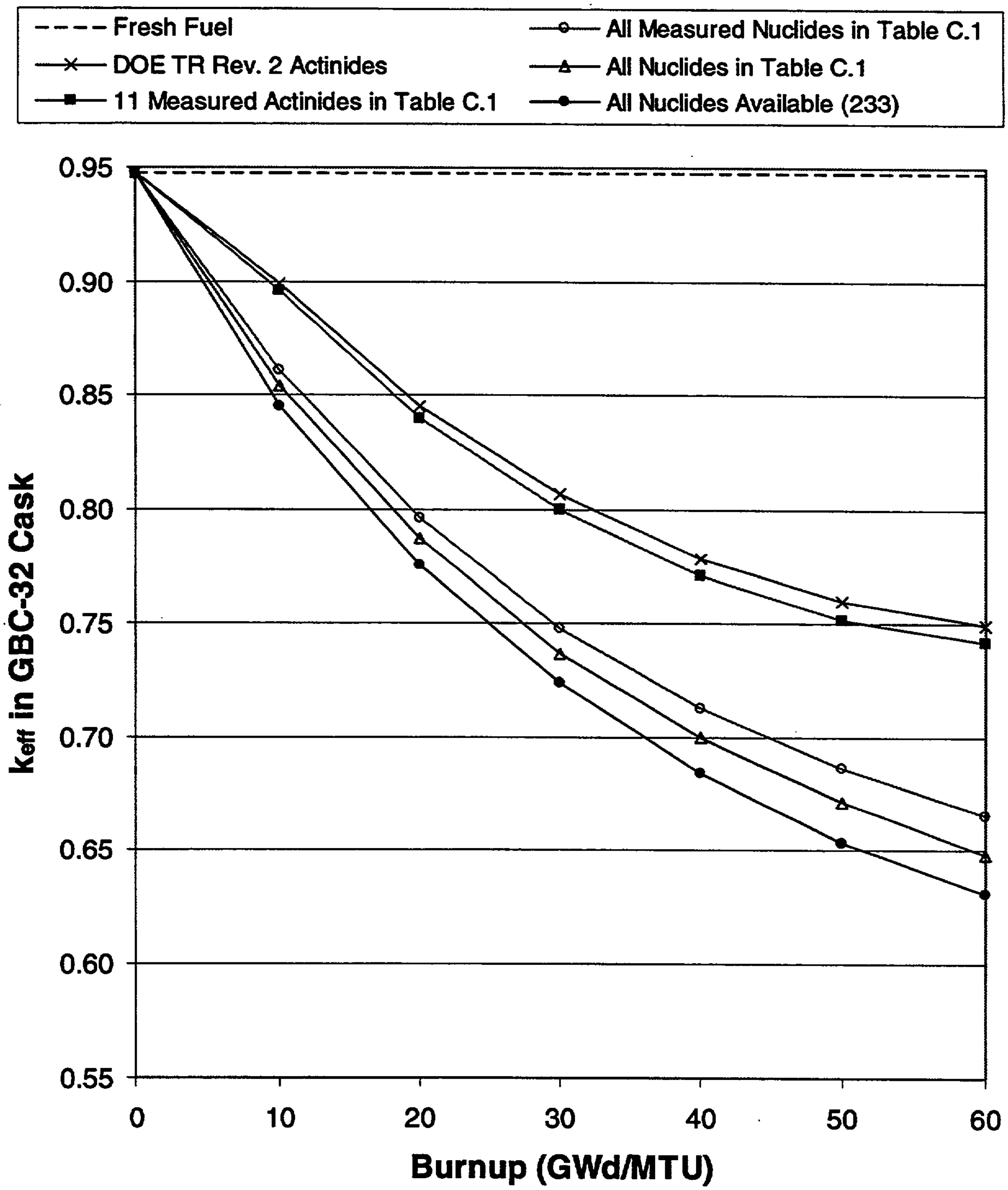

Figure C.1 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 5-year cooling time for fuel of 2 wt % ^{235}U initial enrichment

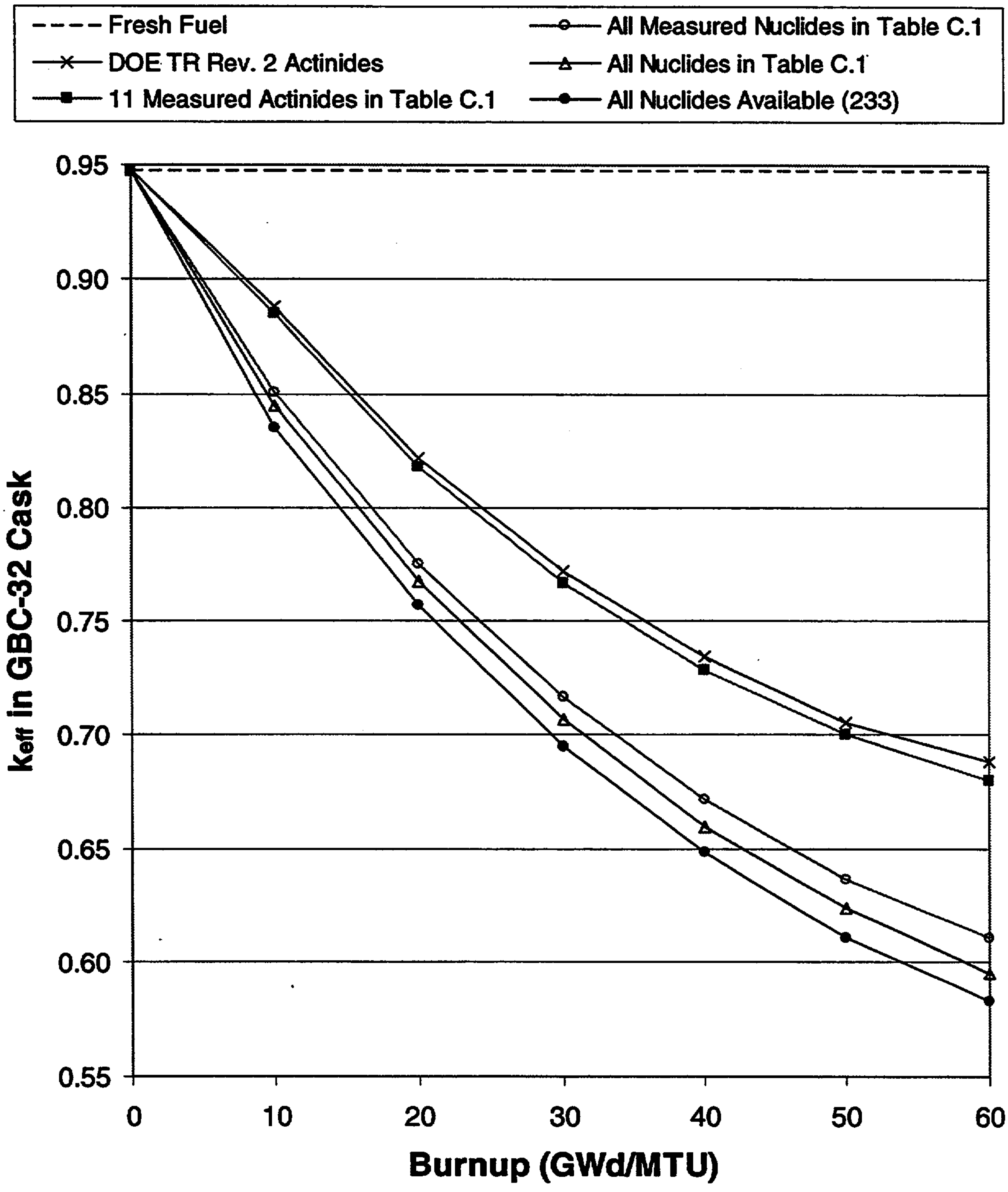

Figure C.2 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 20-year cooling time for fuel of 2 wt % ^{235}U initial enrichment

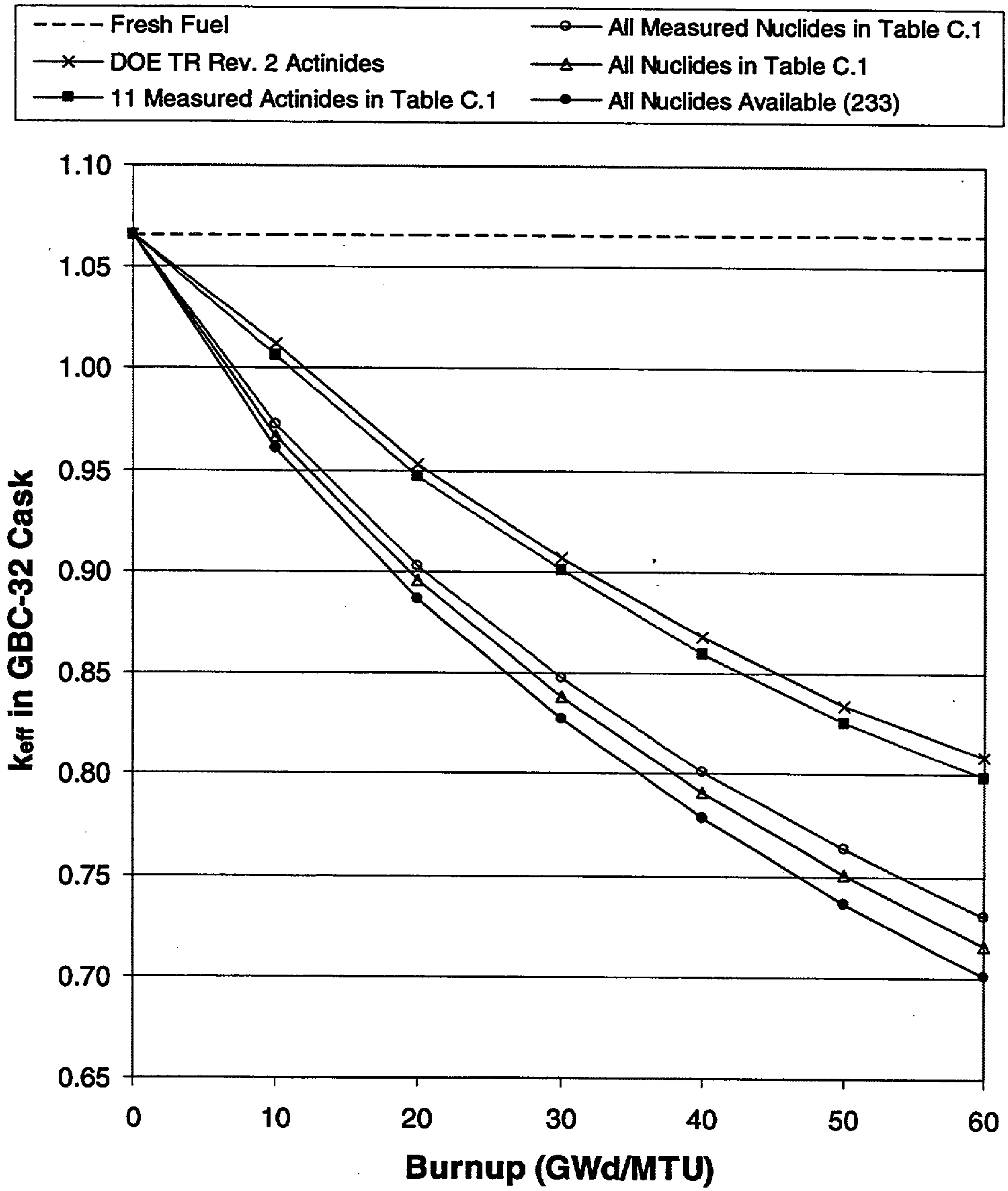

Figure C.3 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 5-year cooling time for fuel of 3 wt % ^{235}U initial enrichment

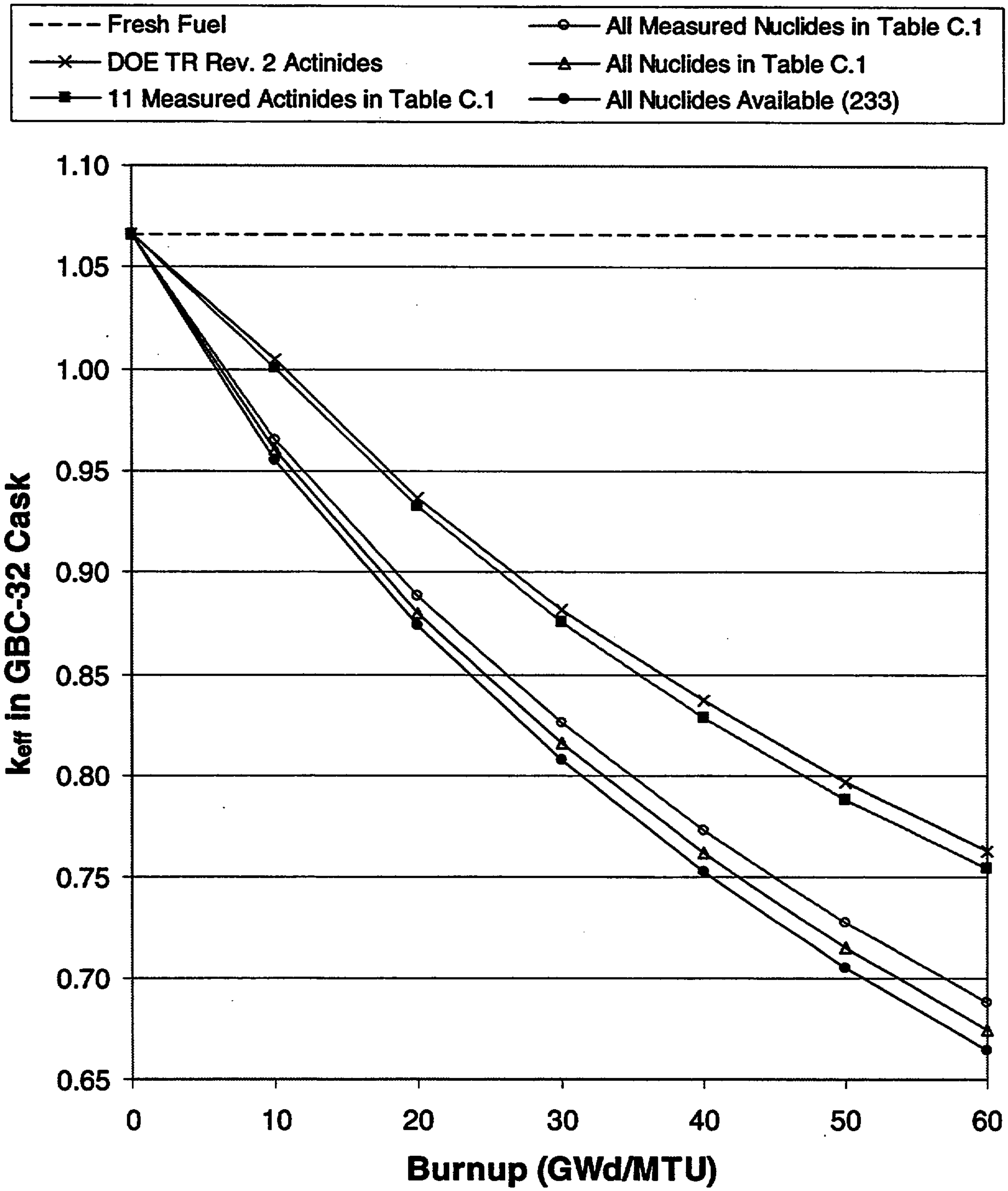

Figure C.4 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 20-year cooling time for fuel of 3 wt % ^{235}U initial enrichment

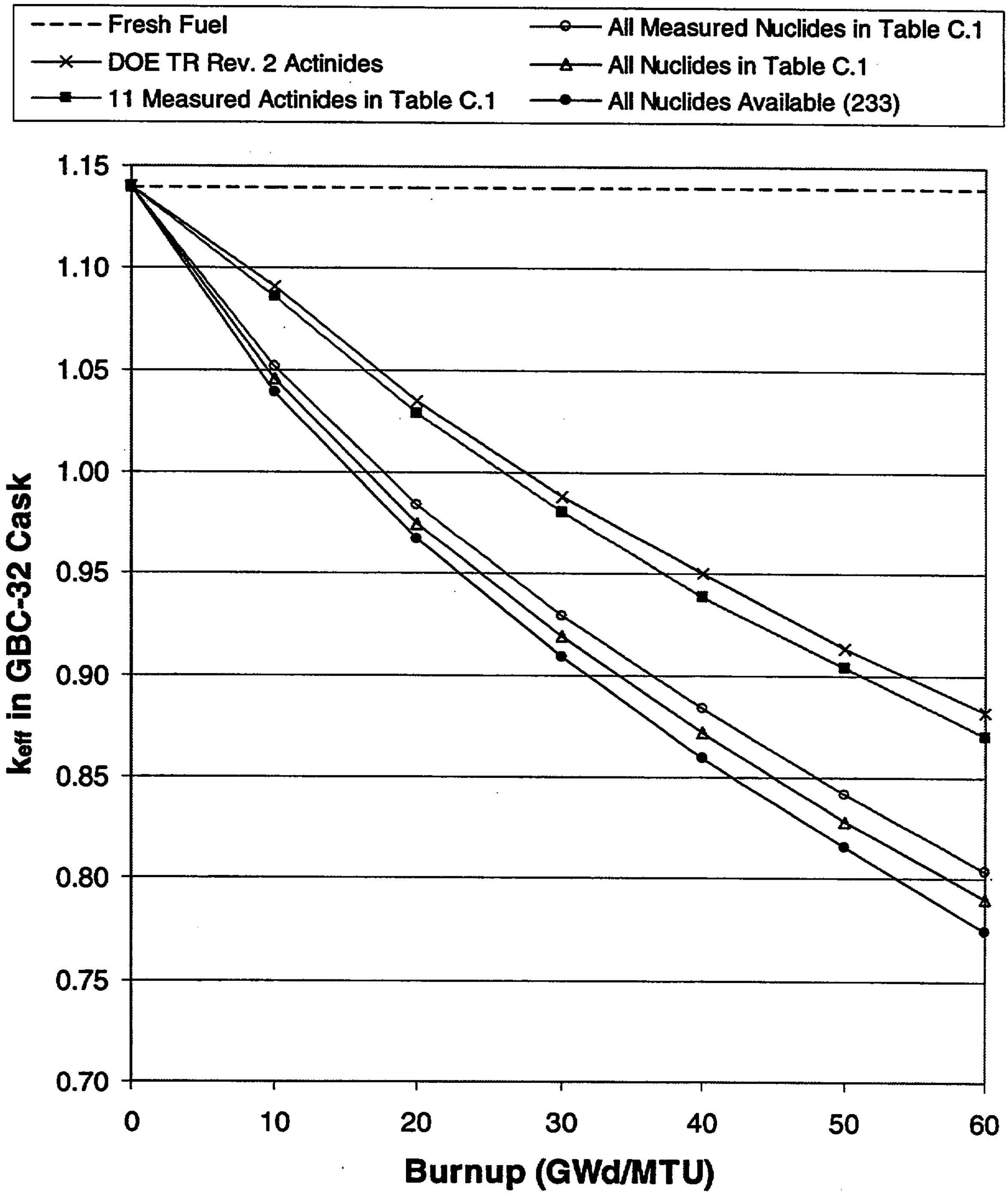

Figure C.5 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 5-year cooling time for fuel of 4 wt % ^{235}U initial enrichment

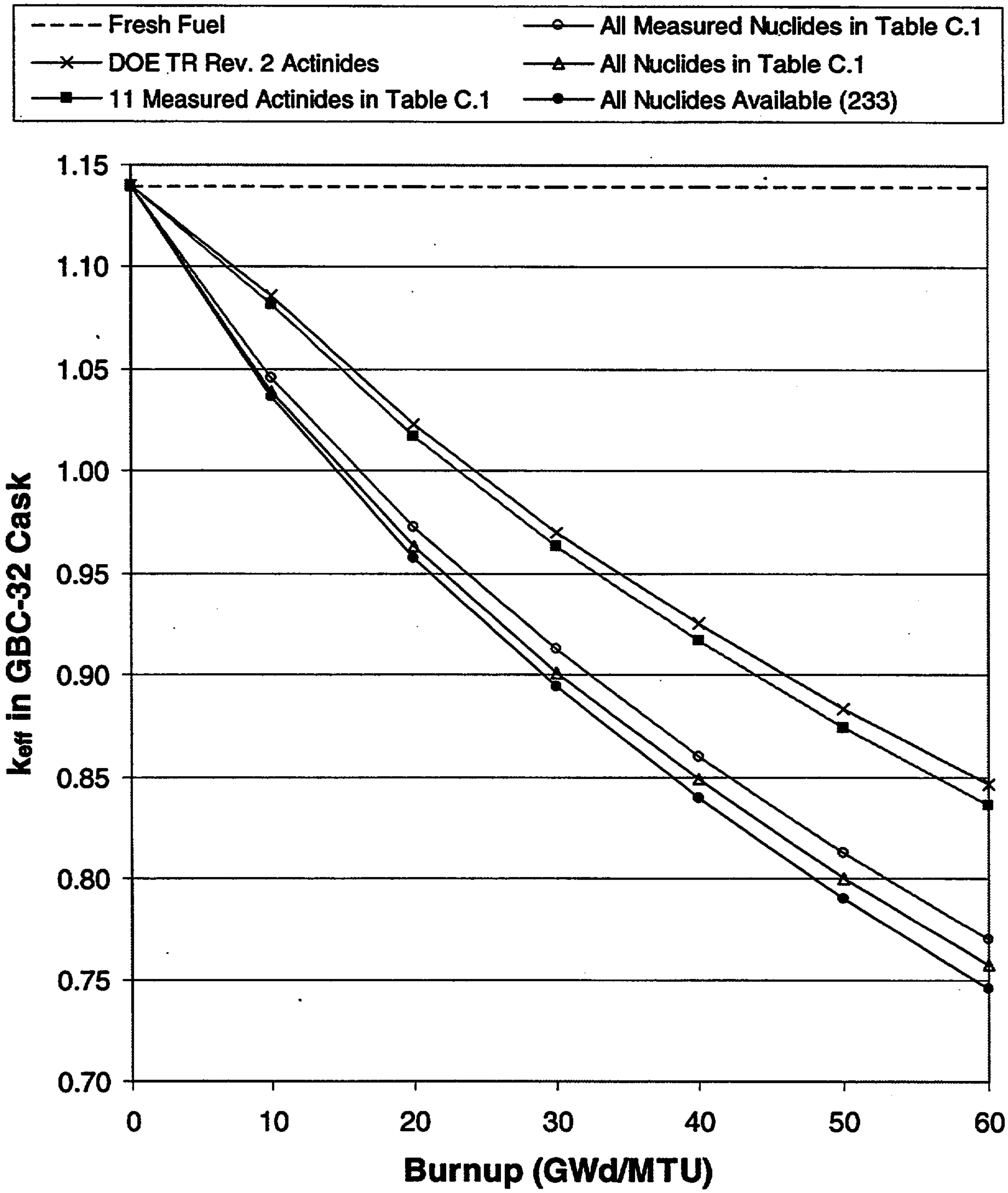

Figure C.6 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 20-year cooling time for fuel of 4 wt % ^{235}U initial enrichment

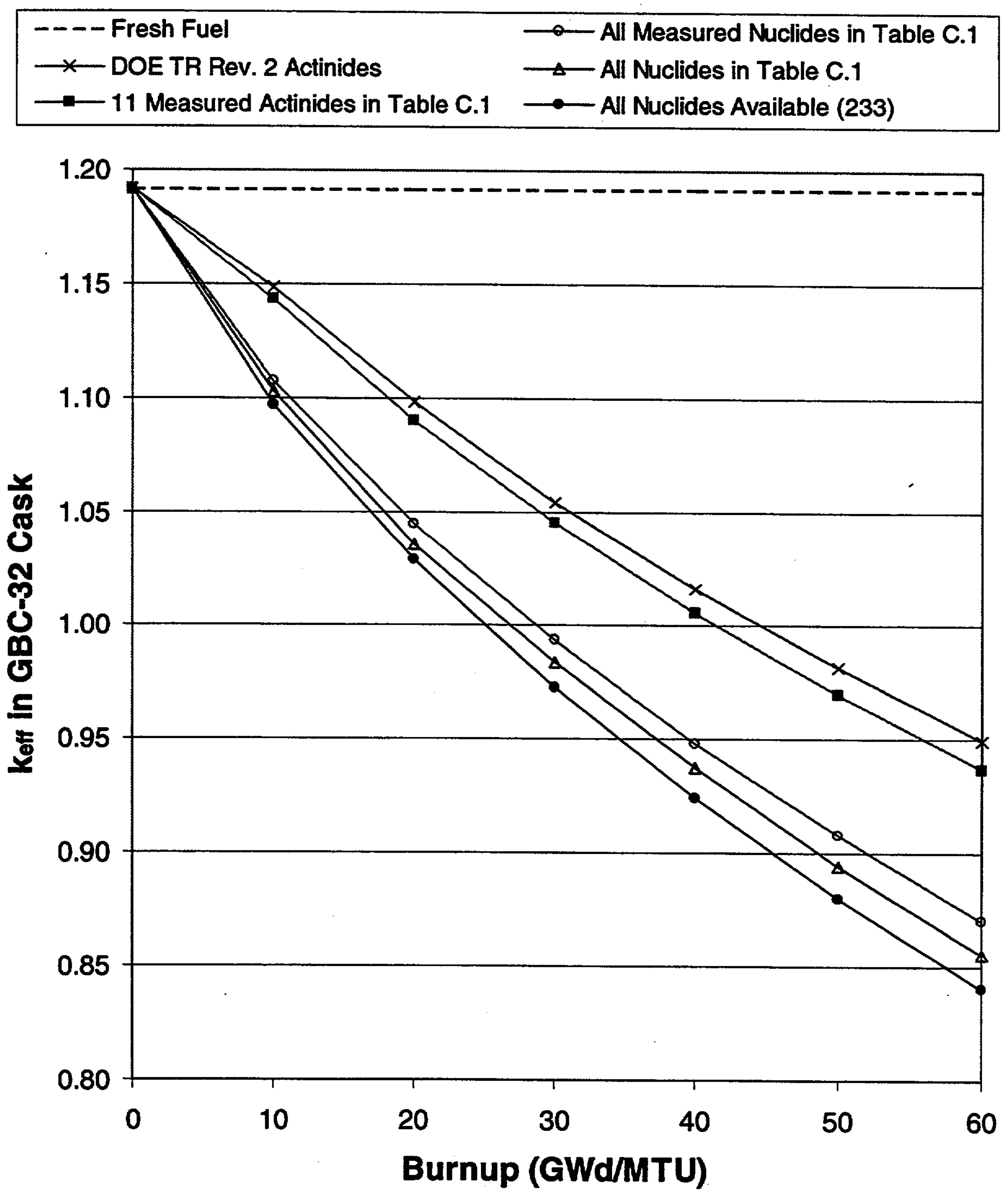

Figure C.7 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 5-year cooling time for fuel of 5 wt % ^{235}U initial enrichment

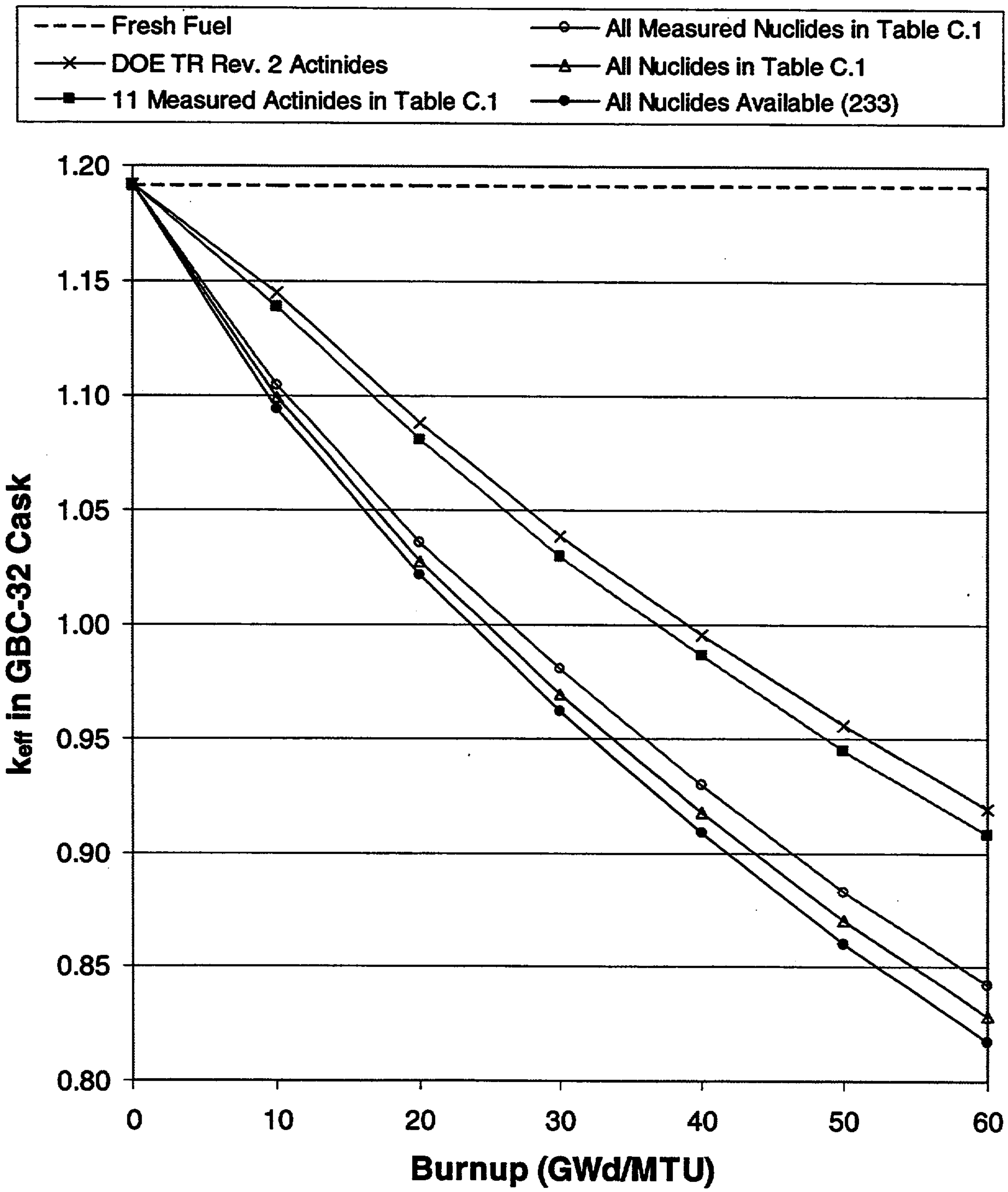

Figure C.8 Values of k_{eff} in the GBC-32 cask as a function of burnup using various nuclide sets and 20-year cooling time for fuel of 5 wt % ^{235}U initial enrichment

REFERENCES

C.1 C. V. Parks, M. D. DeHart and J. C. Wagner, *Review and Prioritization of Technical Issues Related to Burnup Credit for LWR Fuel*, NUREG/CR-6665 (ORNL/TM-1999/303), U.S. Nuclear Regulatory Commission, Oak Ridge National Laboratory, February 2000.

C.2 *Topical Report on Actinide-Only Burnup Credit for PWR Spent Nuclear Fuel Packages*, DOE/RW-0472, Rev. 2, U.S. Department of Energy (September 1998).

APPENDIX D

DISCUSSION OF REFERENCE RESULTS

APPENDIX D

DISCUSSION OF REFERENCE RESULTS

Although the intended scope of this report does not include analysis and interpretation of the results, some limited examination, discussion, and conclusions related to the reference results are offered in this Appendix.

To assist in the examination of the reference results, plots of a select set of the reference results are presented for a cooling time of 5 years, which corresponds to the cooling time addressed in ISG8. Figures D.1–D.4 plot the k_{eff} values in the GBC-32 cask for the two nuclide sets (refer to Tables D1 and D2 for specification of nuclide sets) as a function of burnup and 5-year cooling time for initial enrichments of 2, 3, 4, and 5 wt % ^{235}U, respectively. Although, for consistency, results were generated for burnups up to 60 GWd/MTU for each of the enrichments, it should be noted that typical discharge burnups for enrichments of 2 and 3 wt % ^{235}U are below 40 GWd/MTU. Similarly, for enrichments of 4 and 5 wt % ^{235}U, typical discharge burnups are greater than 30 GWd/MTU. Thus, one should be cognizant of this fact when examining the results for the various burnup and enrichment combinations. Limited data for actual initial enrichment and discharge burnup combinations for SNF discharged from U.S. reactors are available in Ref. D.1.

The reactivity reductions due to the major actinides (set 1 in Table D.1), additional nuclides (set 3 Table D.2), and all of the nuclides considered (set 2 in Table D.1) are plotted in Figures D.5–D.8 as a function of burnup and 5-year cooling time for each of the initial enrichments considered. Finally, bar charts showing the individual contributions from (a) the major actinides and (b) the additional nuclides to the total reactivity reduction for 5-year cooling as a function of burnup are plotted in Figures D.9–D.12. The relative reactivity reduction due to (a) the major actinides and (b) the additional nuclides are similar at low burnups, but quickly diverge for higher burnups. For typical enrichment and discharge burnup combinations, the figures show that approximately 70% of the reactivity reduction is due to the major actinides, with the remaining 30% being attributed to the additional nuclides (major fission products and minor actinides).

To examine the effect of initial enrichment, Figures D.13 and D.14 show the reactivity reductions (in terms of Δk values) as a function of burnup, for initial enrichments of 3, 4, and 5 wt % ^{235}U, for (a) the major actinides and (b) the additional nuclides, respectively. The effect of initial enrichment on these contributions to the reactivity reduction is shown to be relatively minor. However, these figures do reveal that, for a given burnup, an increase in the initial enrichment results in a decrease in the contribution from the major actinides and a simultaneous increase in the contribution from the additional nuclides. Consequently, the relative contribution from the additional nuclides to the total reactivity reduction increases with enrichment. The individual contributions to the total reactivity reduction from (a) the major actinides and (b) the additional nuclides, for the various initial enrichments are shown in Figures D.15 and D.16.

To examine the effect of cooling time, Figures D.17 and D.18 show the reactivity reductions (in terms of Δk values) as a function of burnup, for an initial enrichment 4 wt % ^{235}U, for (a) the major actinides and (b) the additional nuclides, respectively. During the time frame of interest to storage and transport, the reactivity reduction associated with the major actinides increases with cooling time, primarily due to the decay of the ^{241}Pu fissile nuclide ($t_{1/2}$ = 14.4 years) and the buildup of the neutron absorber ^{241}Am (from decay of ^{241}Pu). This behavior has been well documented.[D.2,D.3] For the fission products and minor actinides considered as the "additional nuclides" (see Table D.2), the associated reactivity reduction increases initially with cooling time due to the buildup of ^{155}Gd (from ^{155}Eu which decays with $t_{1/2}$ = 4.7 years), but then decreases somewhat due to the decay of ^{151}Sm. In general, however, the reactivity reduction due to the additional nuclides does not vary significantly in the 5-to-40 year time frame.

As there has been a great deal of interest in quantifying the minimum additional reactivity margin available from fission products and minor actinides, Figure D.19 plots the range of calculated reactivity margin (in terms of Δk values) for all of the burnup, initial enrichments, and cooling times considered in this report. Specifically, the range for burnups from 10 to 60 GWd/MTU, initial enrichments of 2, 3, 4, and 5 wt % ^{235}U, and cooling times of 0, 5, 10, 20, and 40 years. In all cases, except for the extremely unrealistic case at 2 wt % initial enrichment burned to 60 GWd/MTU, the minimum values correspond to zero cooling time.

Table D.1 Nuclide sets defined for the benchmark problem analysis

set 1: Major actinides (10 total)									
U-234	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	O†
set 2: Actinides and major fission products (29 total)									
U-234	U-235	U-236	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241
Am-243	Np-237	Mo-95	Tc-99	Ru-101	Rh-103	Ag-109	Cs-133	Sm-147	Sm-149
Sm-150	Sm-151	Sm-152	Nd-143	Nd-145	Eu-151	Eu-153	Gd-155	O†	

† Oxygen is neither an actinide nor a fission product, but is included in this list because it is included in the calculations.

Table D.2 Nuclides in "set 3," on which the additional reactivity margin available from fission products and minor actinides is based

set 3: Minor actinides and major fission products (19 total)									
U-236	Am-243	Np-237	Mo-95	Tc-99	Ru-101	Rh-103	Ag-109	Cs-133	Sm-147
Sm-149	Sm-150	Sm-151	Sm-152	Nd-143	Nd-145	Eu-151	Eu-153	Gd-155	

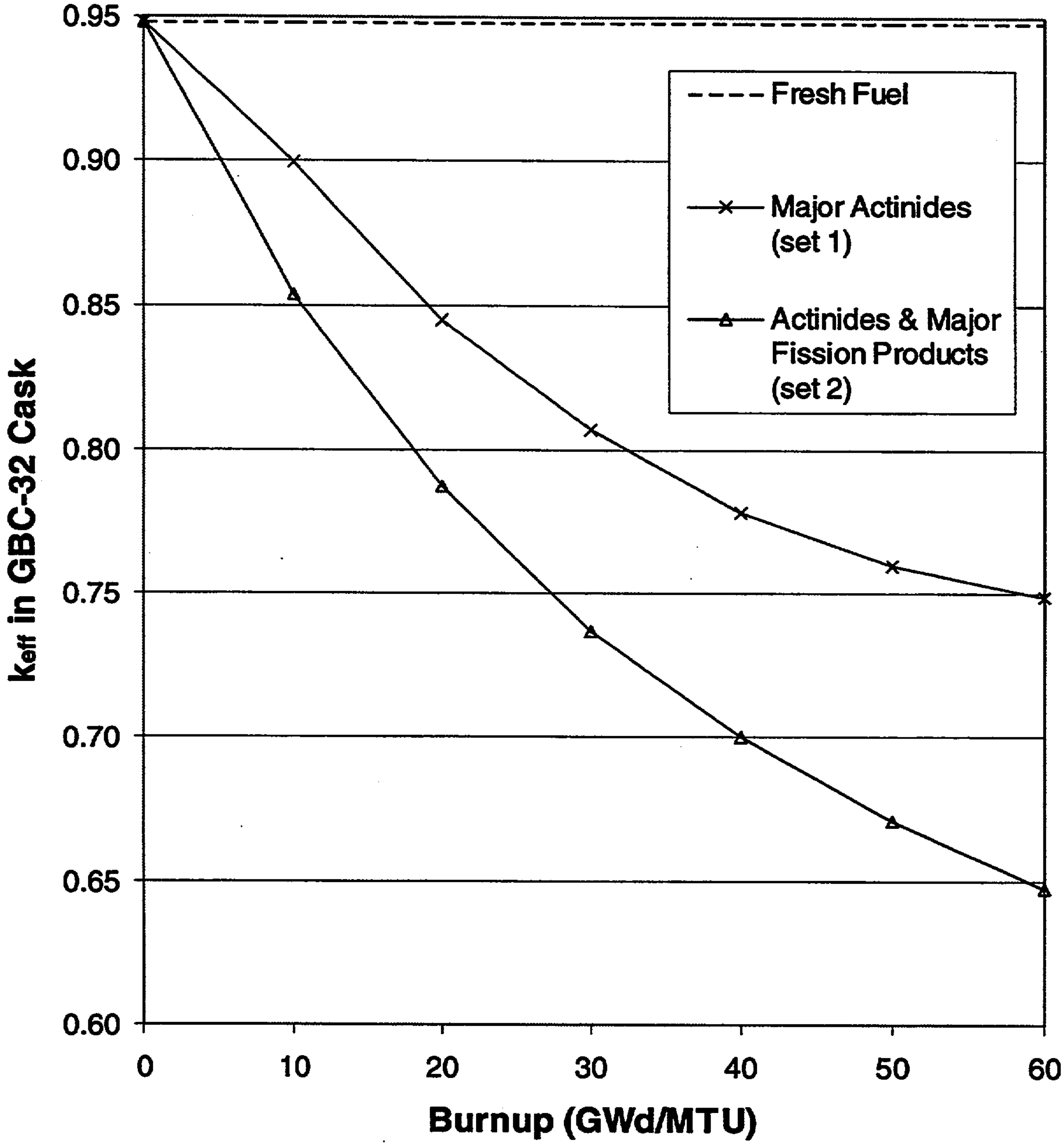

Figure D.1 Values of k_{eff} in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 2 wt % ^{235}U initial enrichment

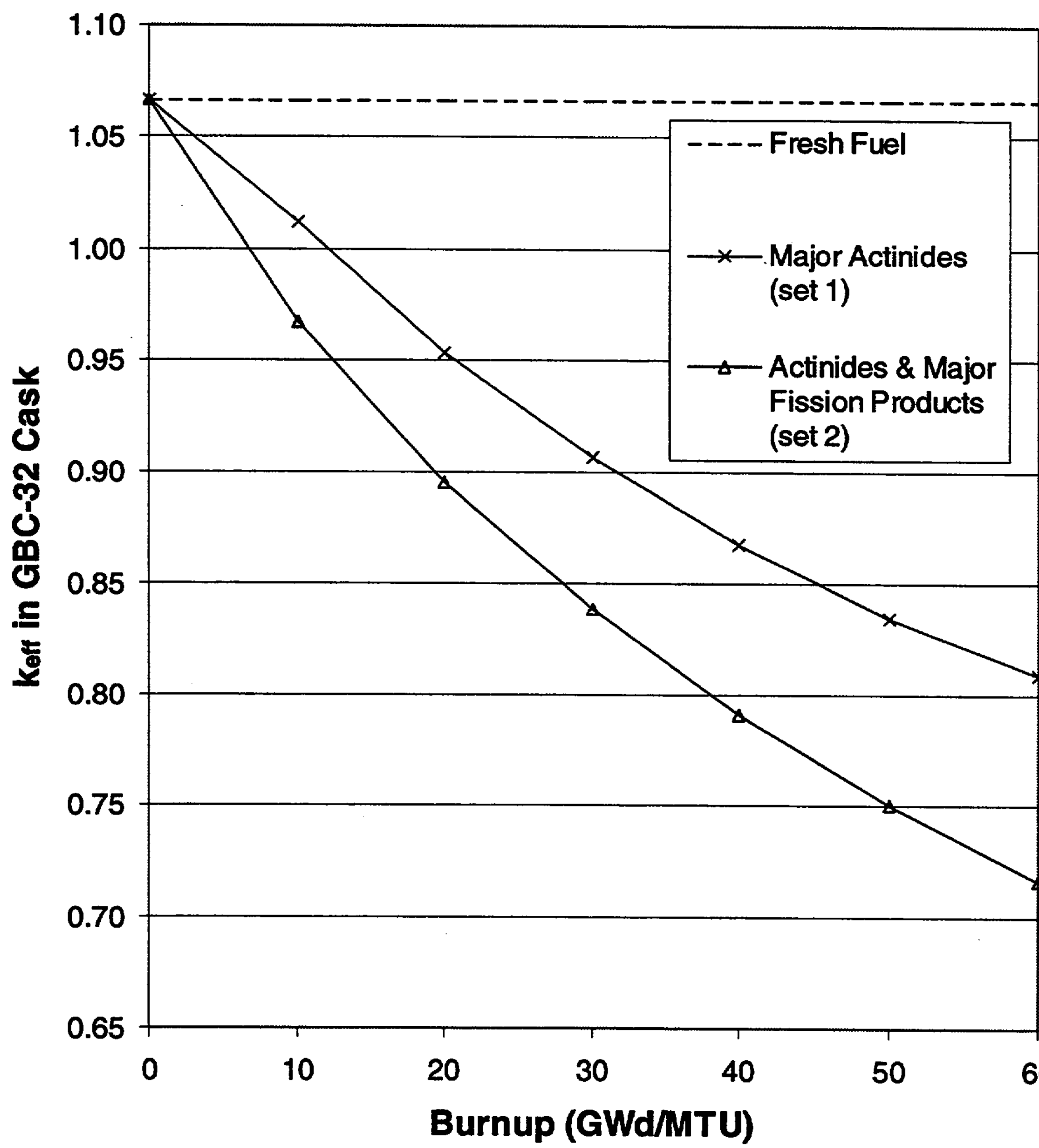

Figure D.2 Values of k_{eff} in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 3 wt % ^{235}U initial enrichment

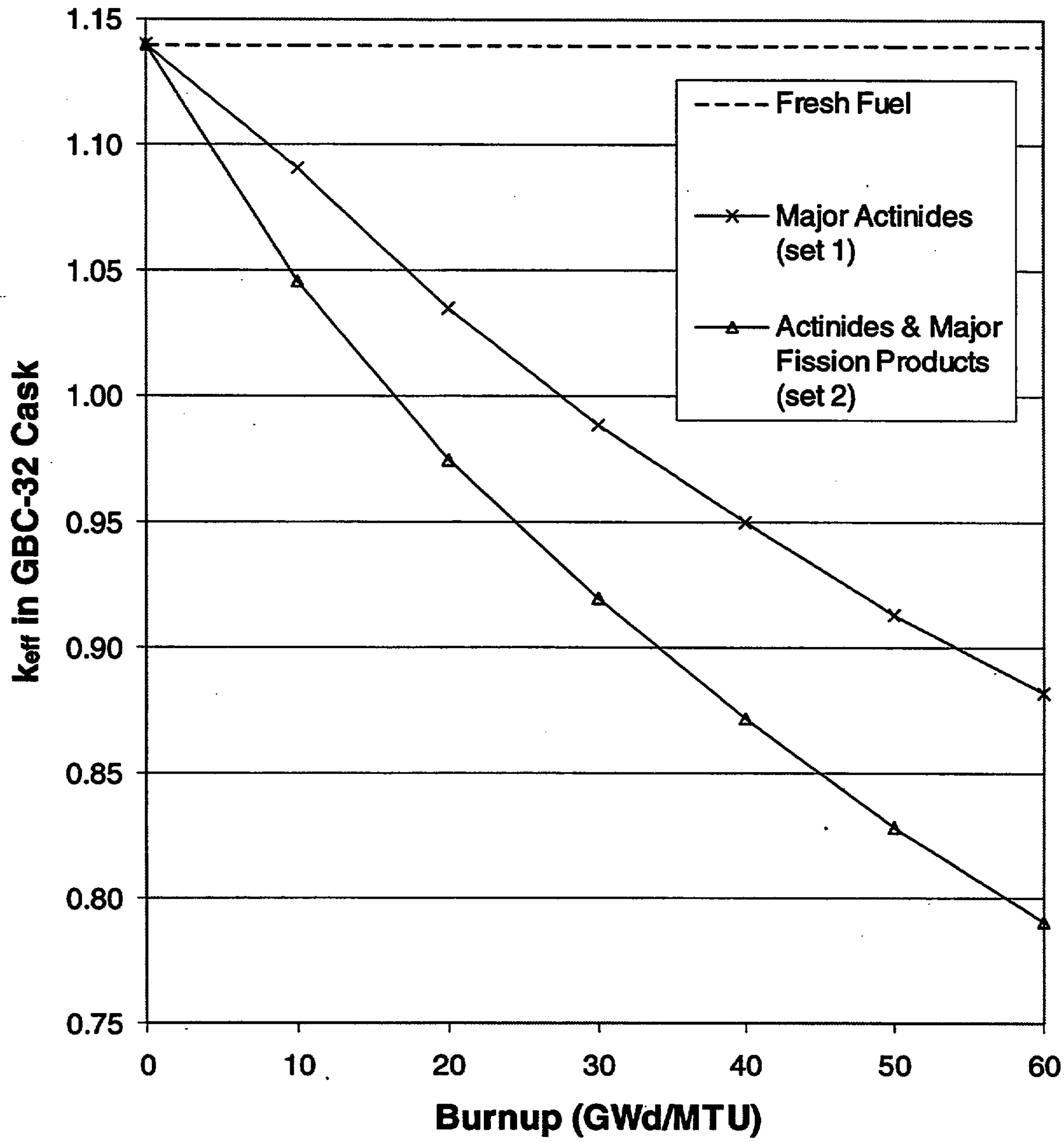

Figure D.3 Values of k_{eff} in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 4 wt % ^{235}U initial enrichment

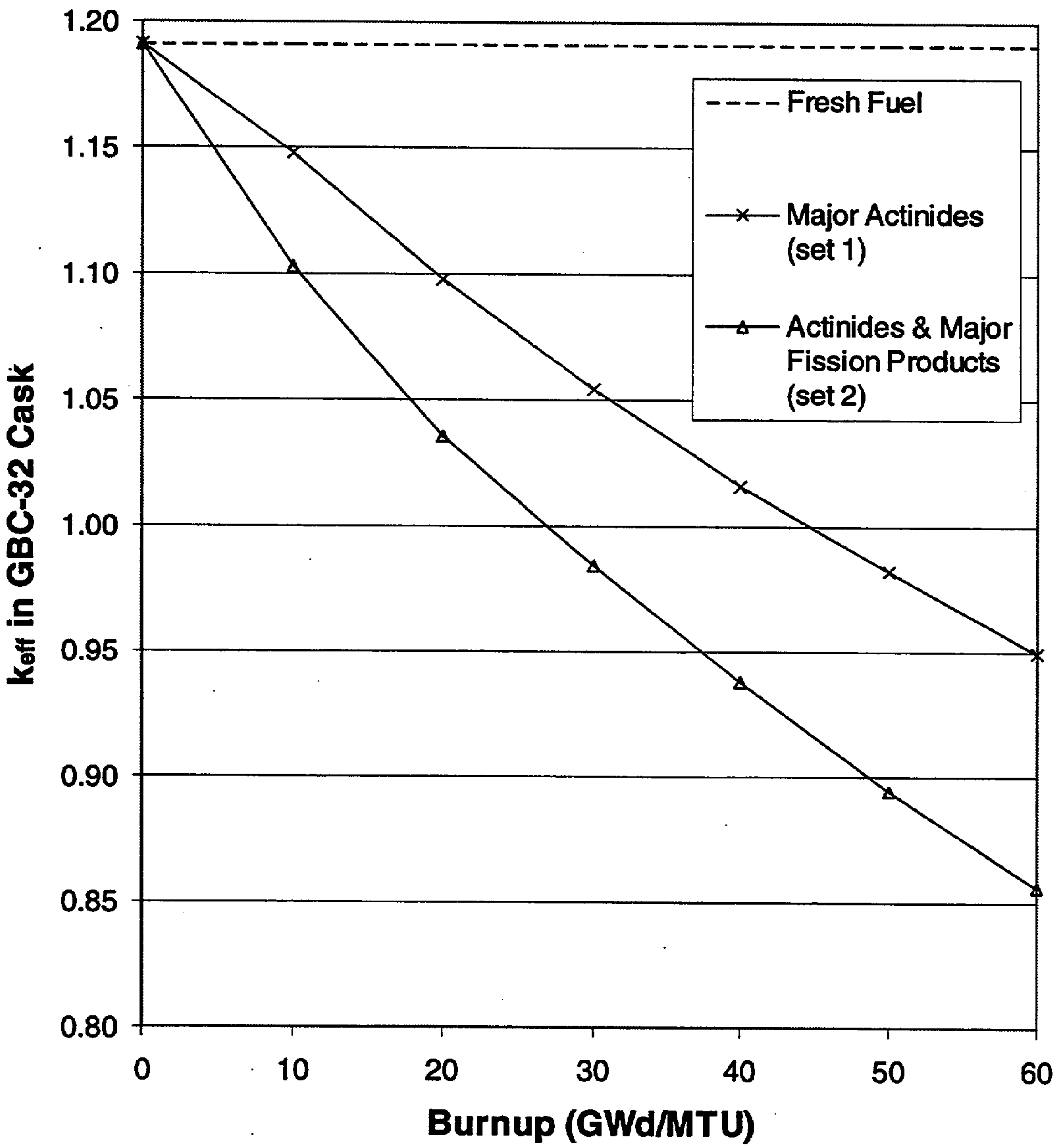

Figure D.4 Values of k_{eff} in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 5 wt % ^{235}U initial enrichment

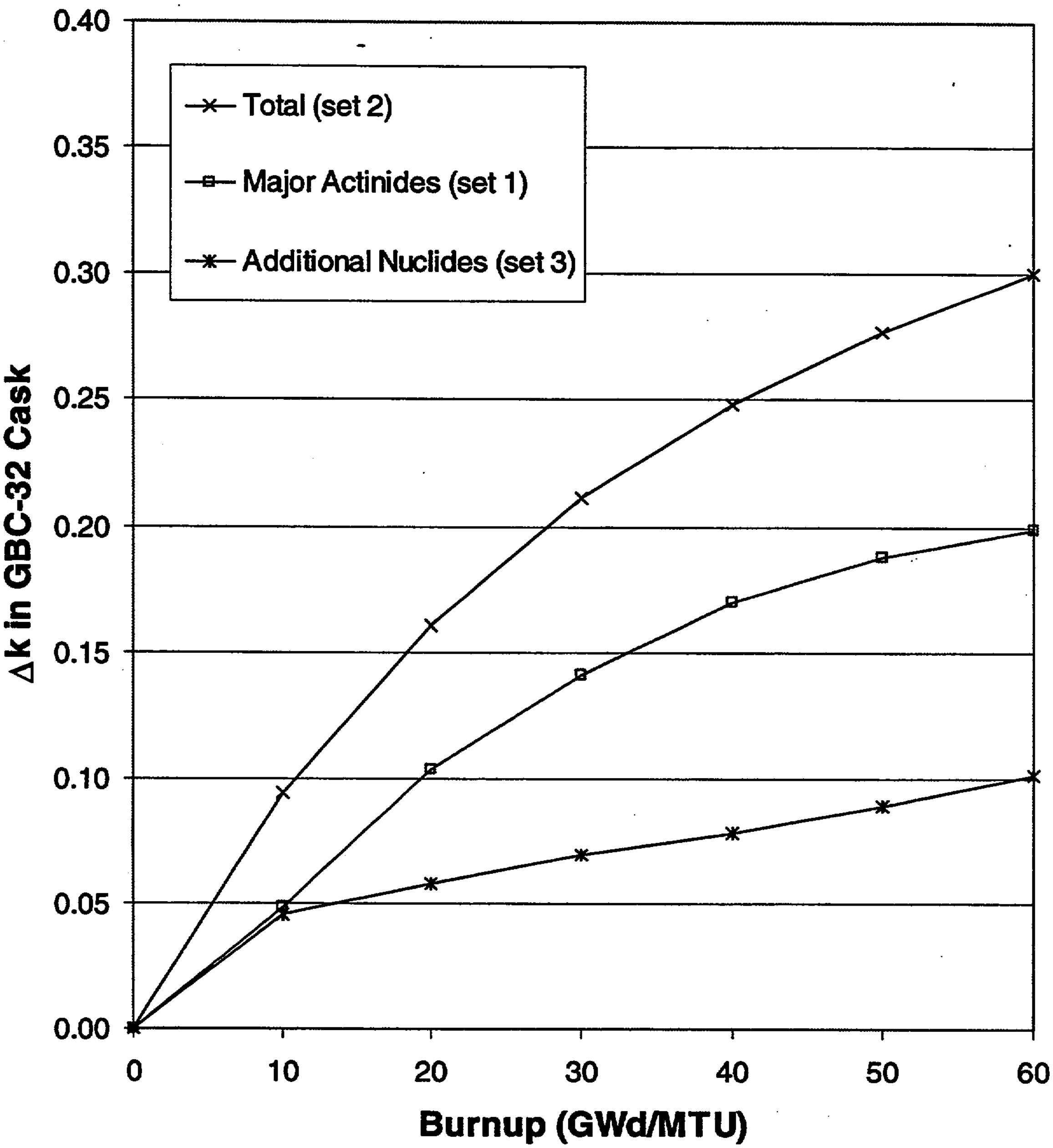

Figure D.5 **Δk values (relative to fresh fuel) in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 2 wt % ^{235}U initial enrichment**

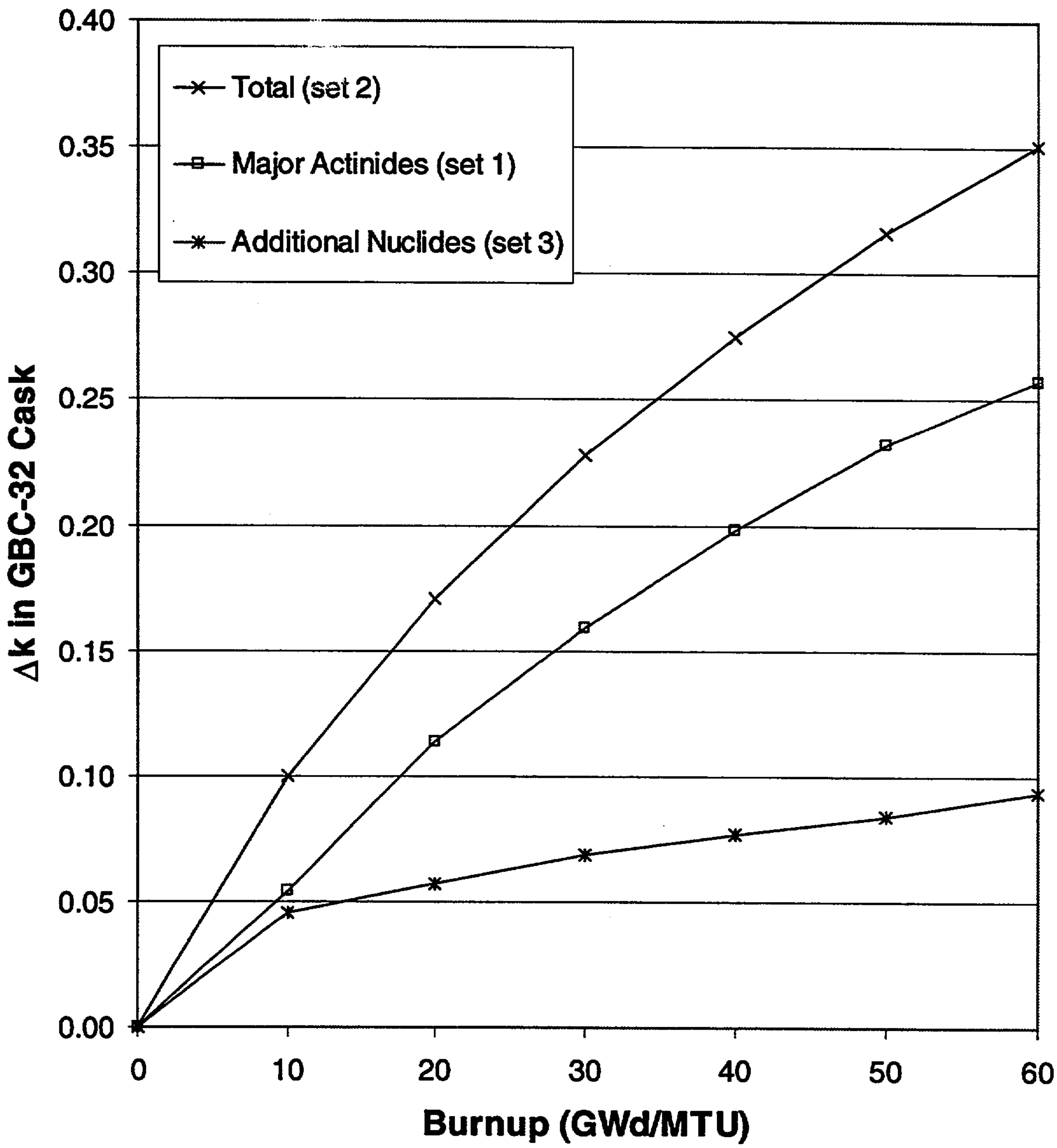

Figure D.6 **Δk values (relative to fresh fuel) in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 3 wt % ^{235}U initial enrichment**

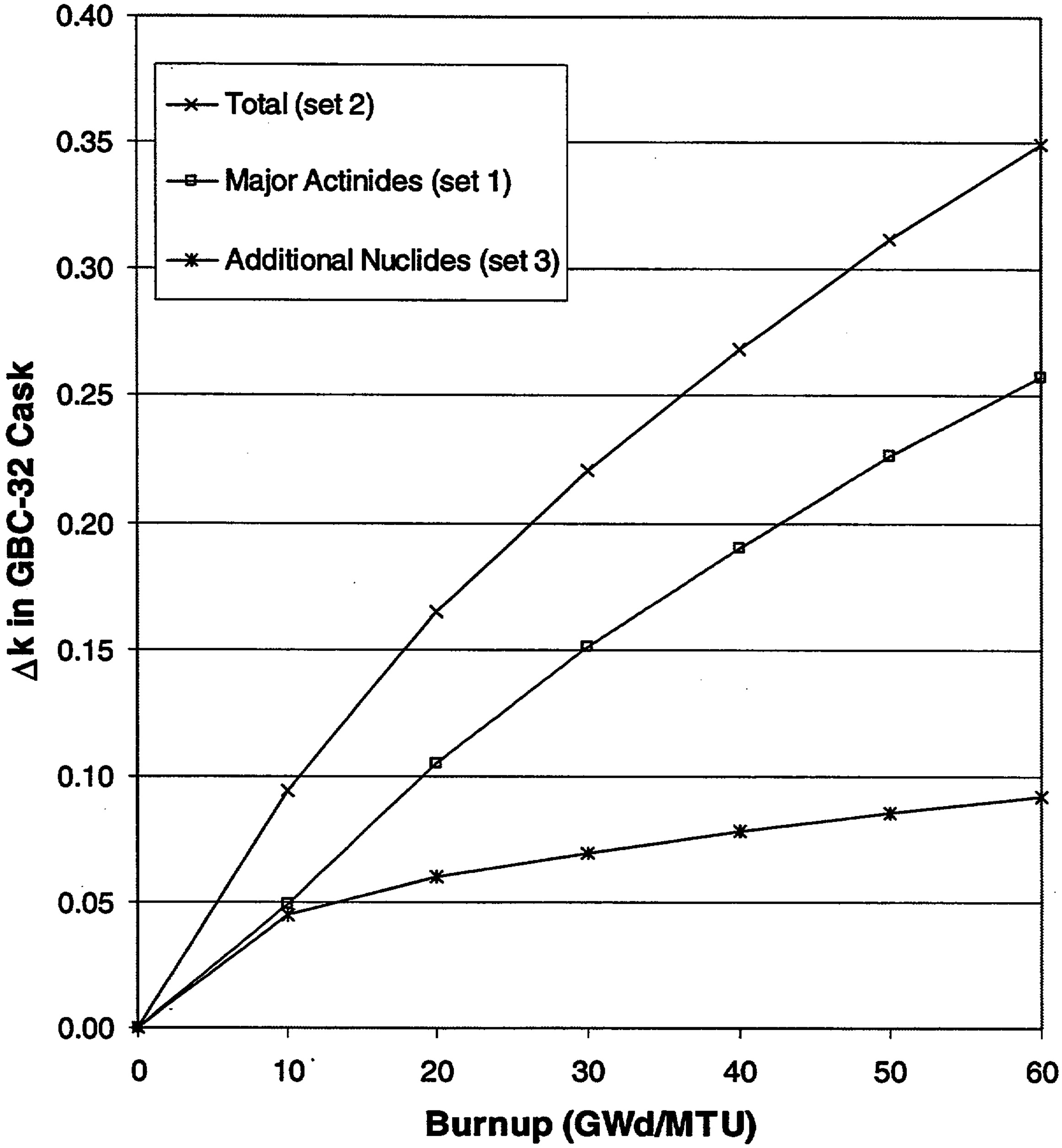

Figure D.7 Δk **values (relative to fresh fuel) in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 4 wt % ^{235}U initial enrichment**

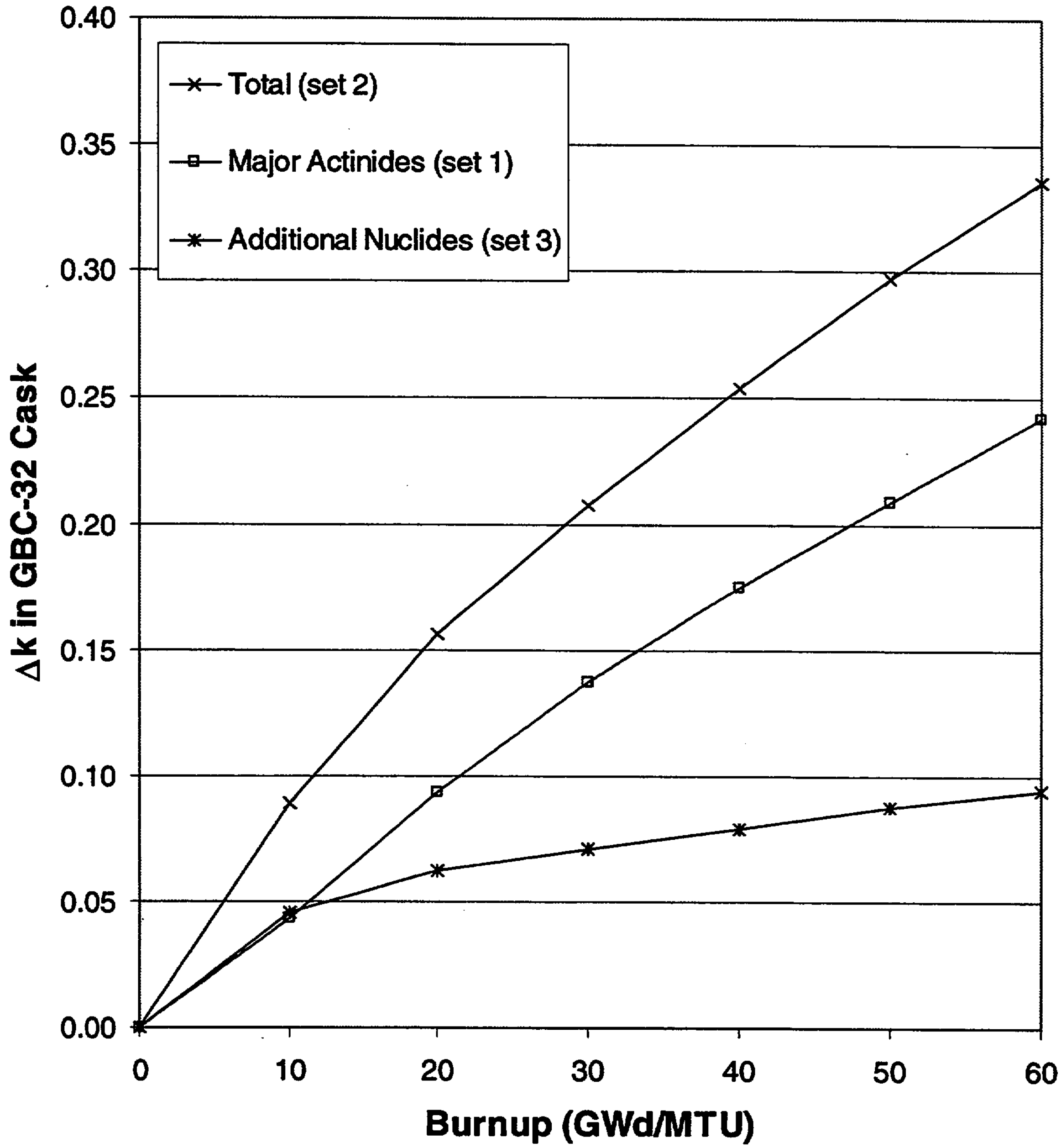

Figure D.8 **Δk values (relative to fresh fuel) in the GBC-32 cask as a function of burnup using the different nuclide sets and 5-year cooling time for fuel of 5 wt % ^{235}U initial enrichment**

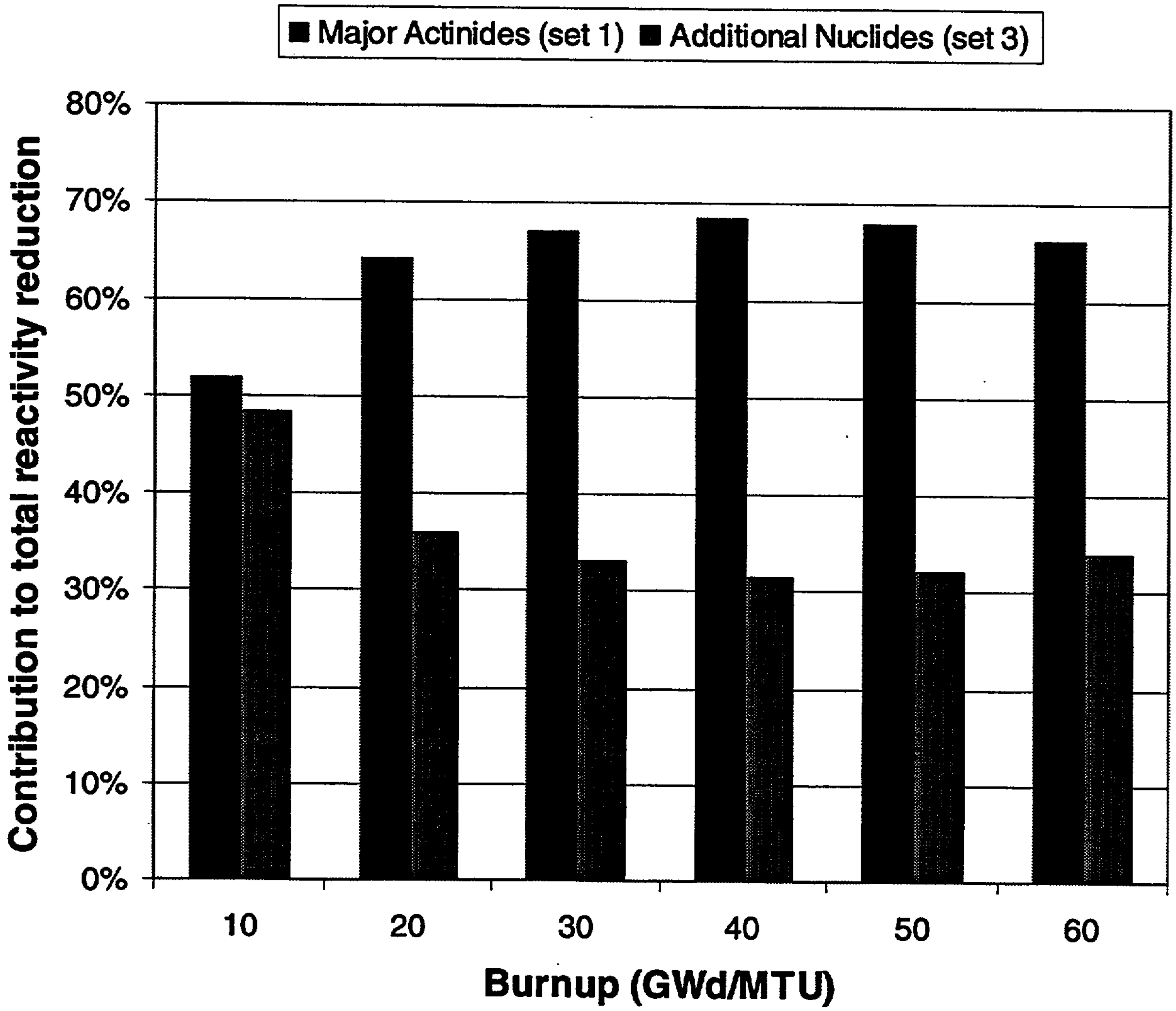

Figure D.9 Individual contributions to the total reduction in k_{eff} for the different nuclide sets as a function of burnup and 5-year cooling time for fuel of 2 wt % ^{235}U initial enrichment

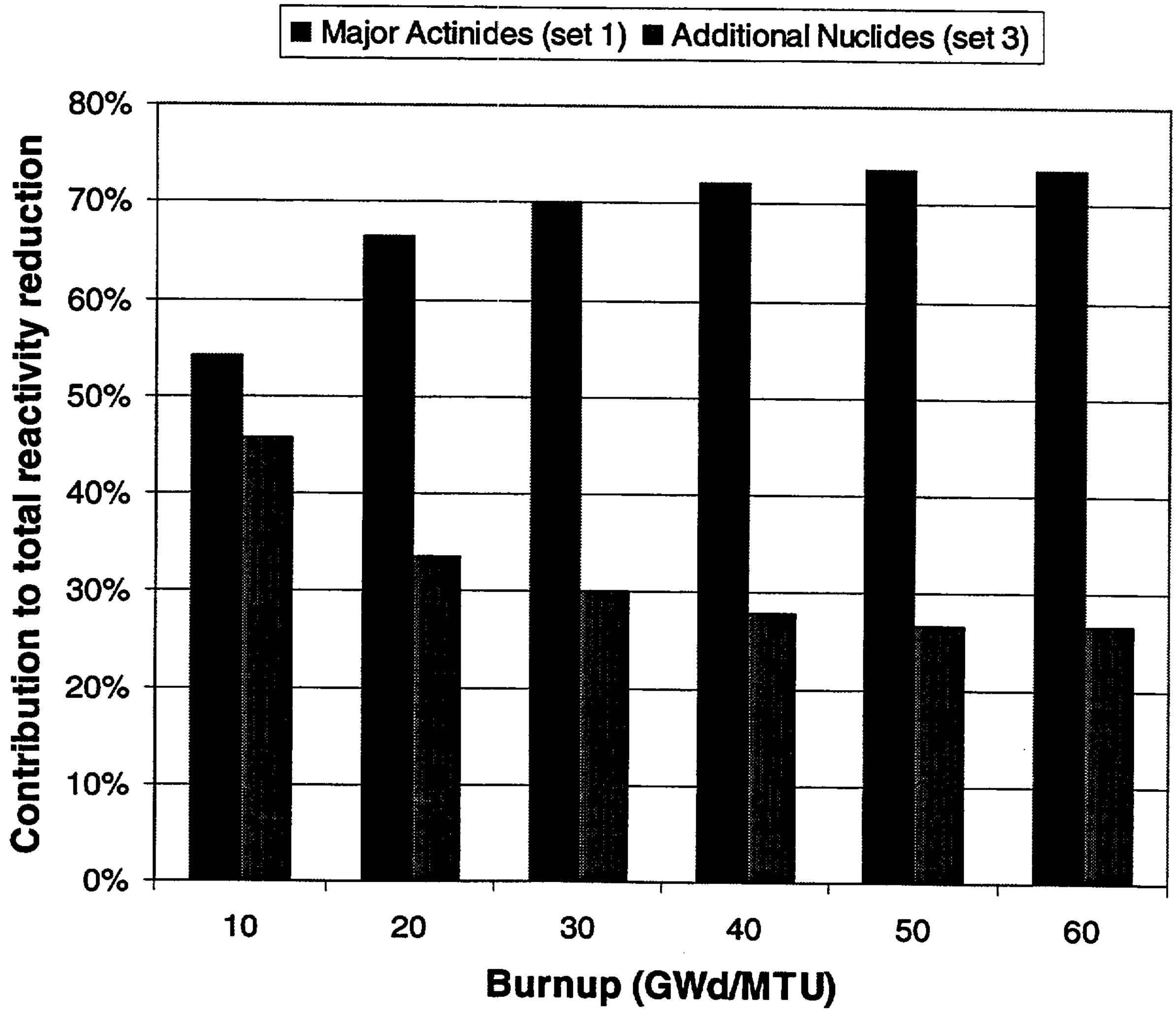

Figure D.10 Individual contributions to the total reduction in k_{eff} for the different nuclide sets as a function of burnup and 5-year cooling time for fuel of 3 wt % ^{235}U initial enrichment

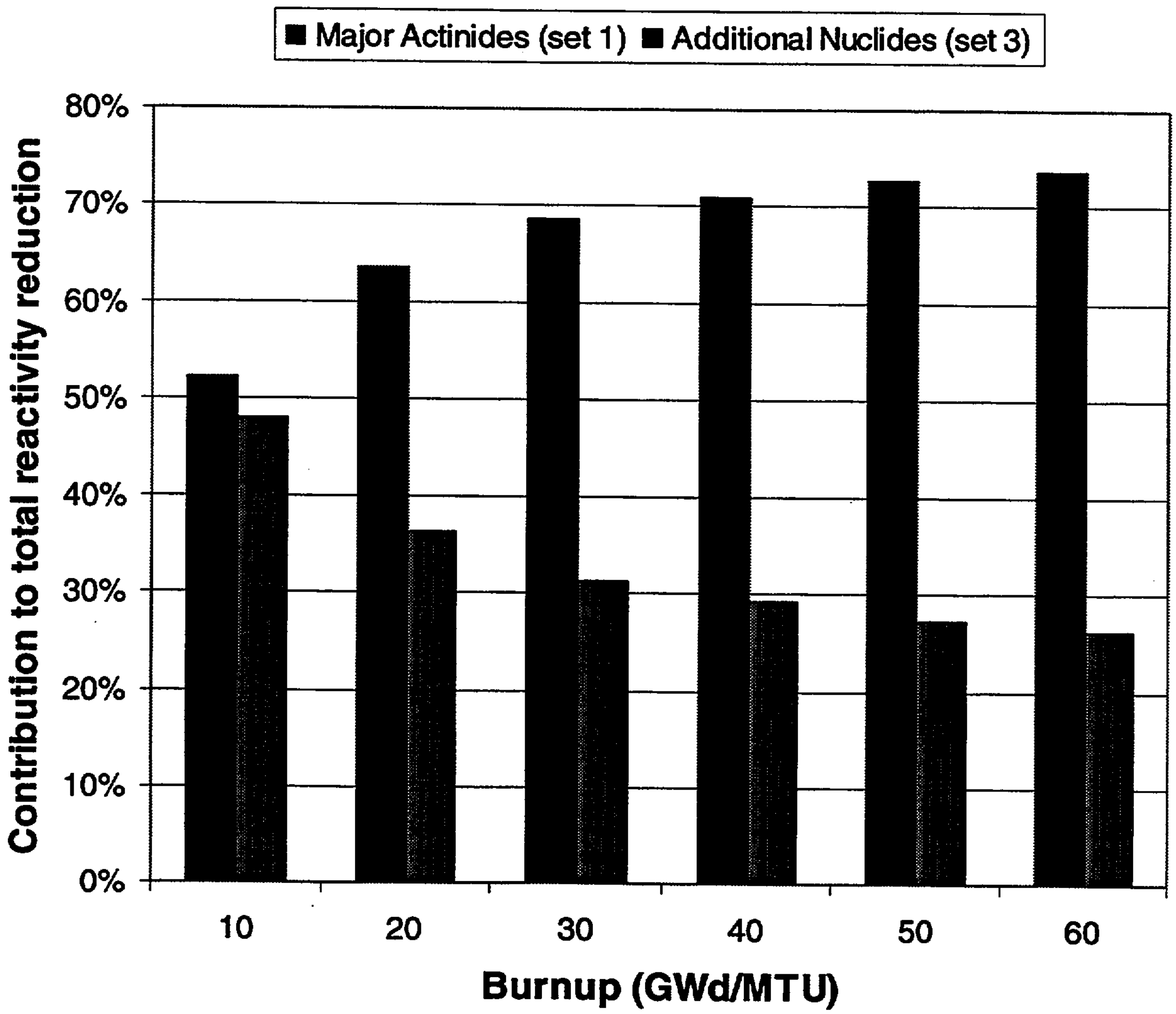

Figure D.11 Individual contributions to the total reduction in k_{eff} for the different nuclide sets as a function of burnup and 5-year cooling time for fuel of 4 wt % ^{235}U initial enrichment

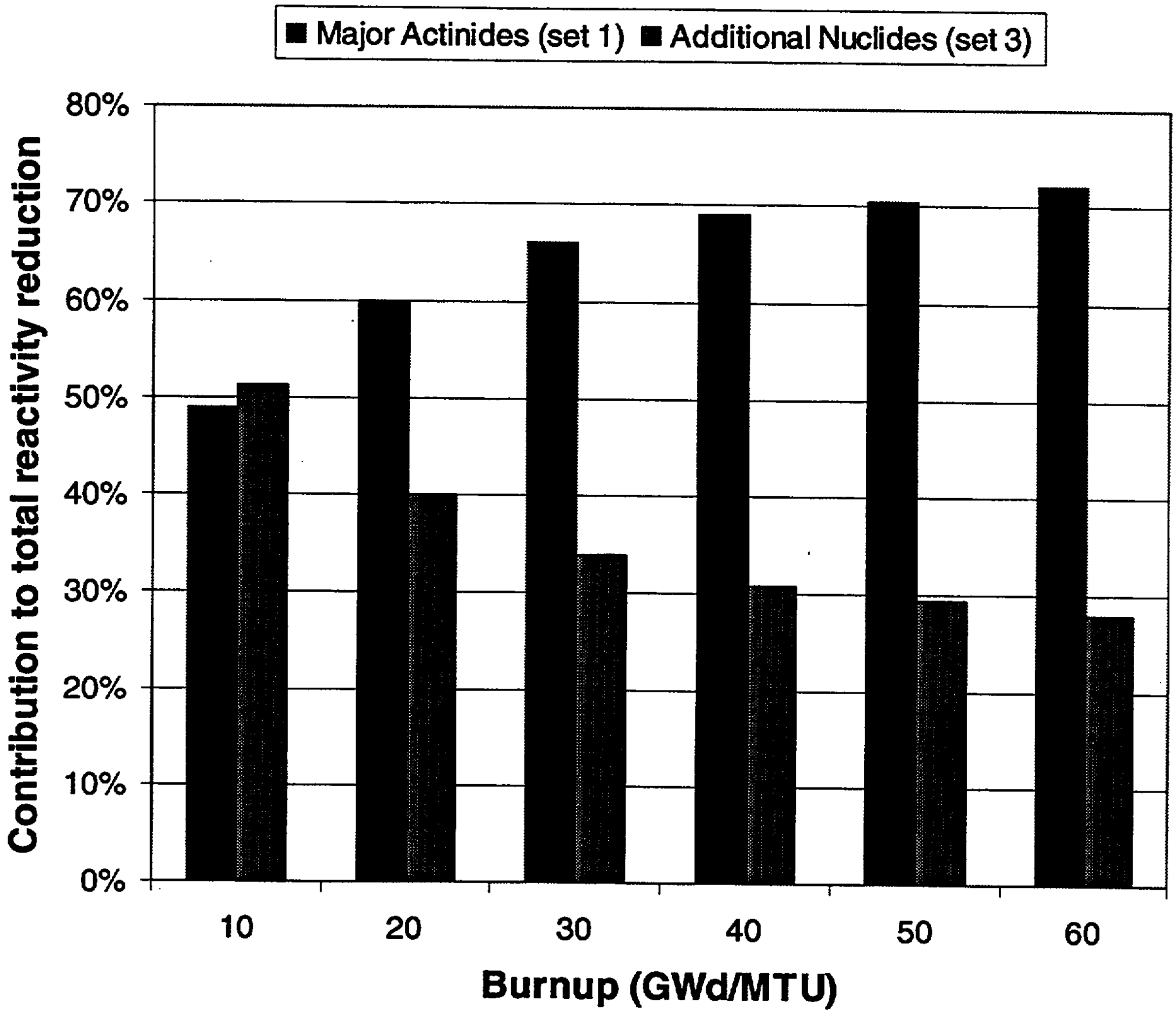

Figure D.12 Individual contributions to the total reduction in k_{eff} for the different nuclide sets as a function of burnup and 5-year cooling time for fuel of 5 wt % ^{235}U initial enrichment

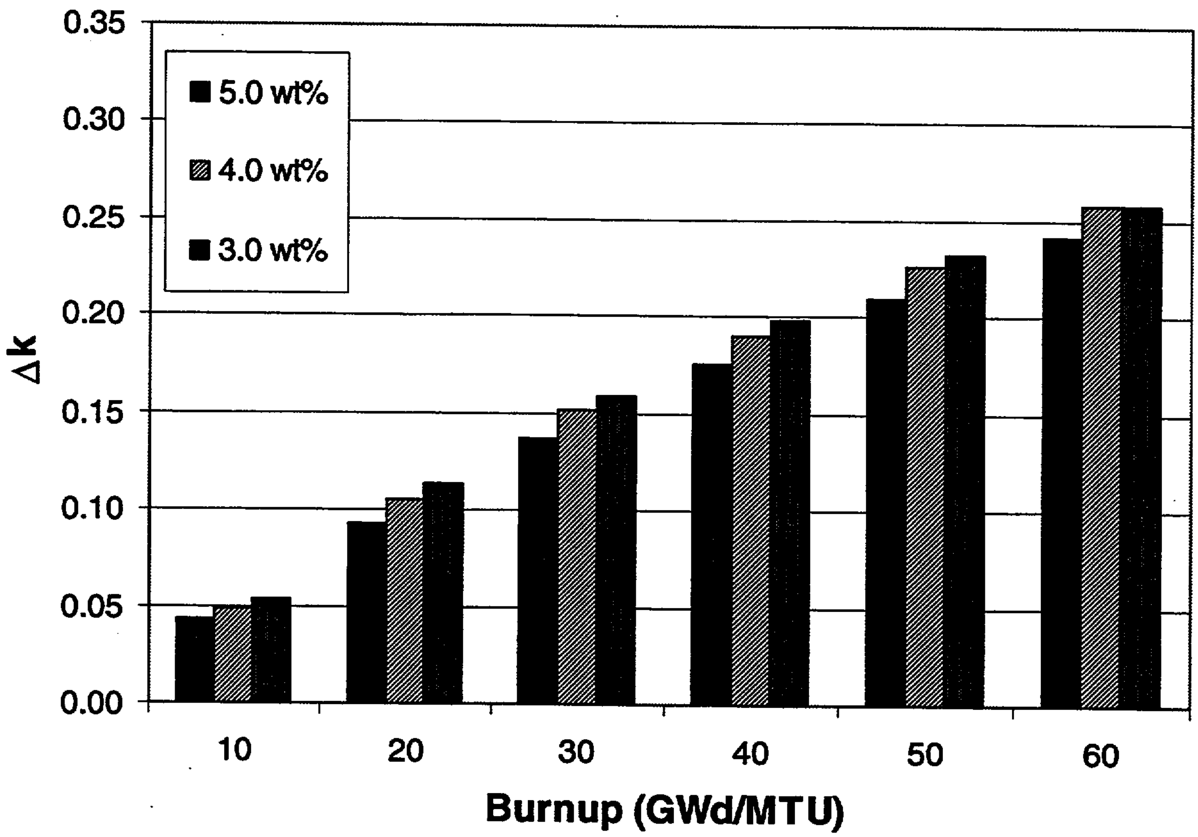

Figure D.13 Δk **(relative to fresh fuel) in GBC-32 cask due to the major actinides (set 1) as a function of burnup for various initial enrichments and 5-year cooling time**

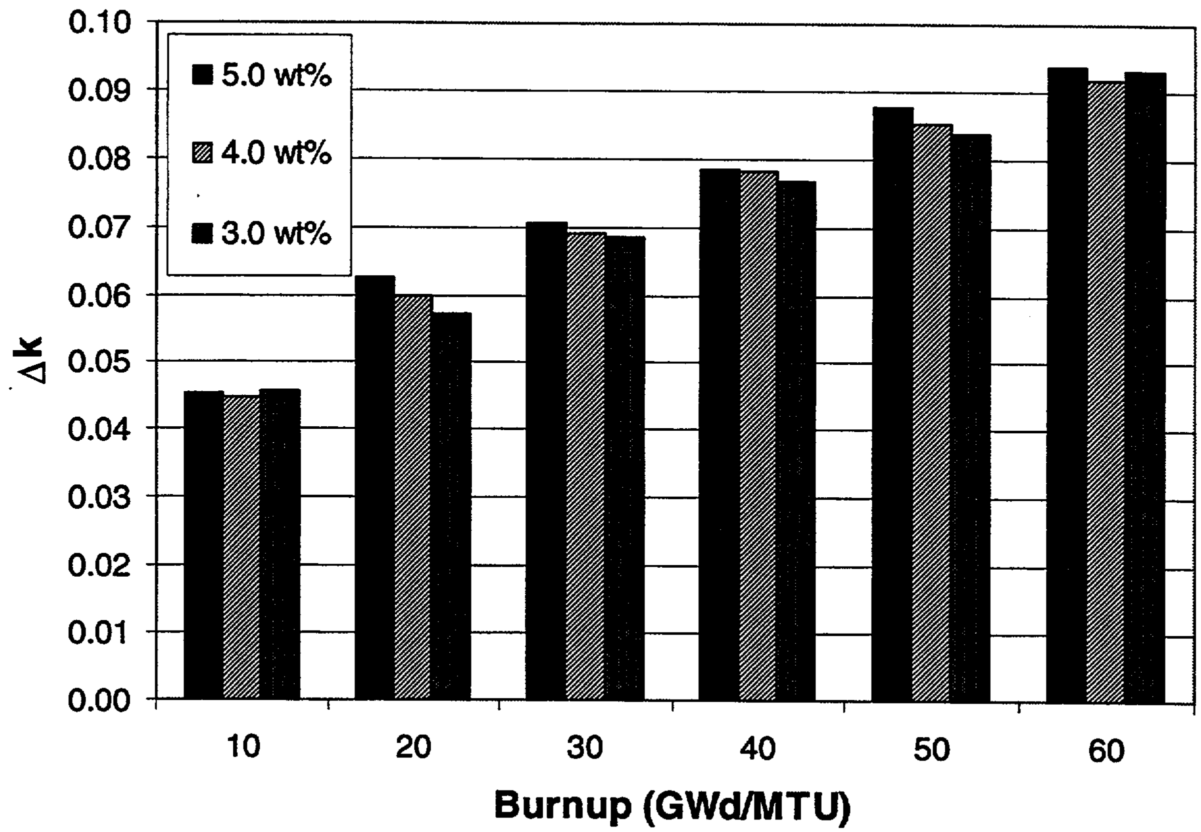

Figure D.14 Δk in GBC-32 cask due to the additional nuclides (set 3) as a function of burnup for various initial enrichments and 5-year cooling time

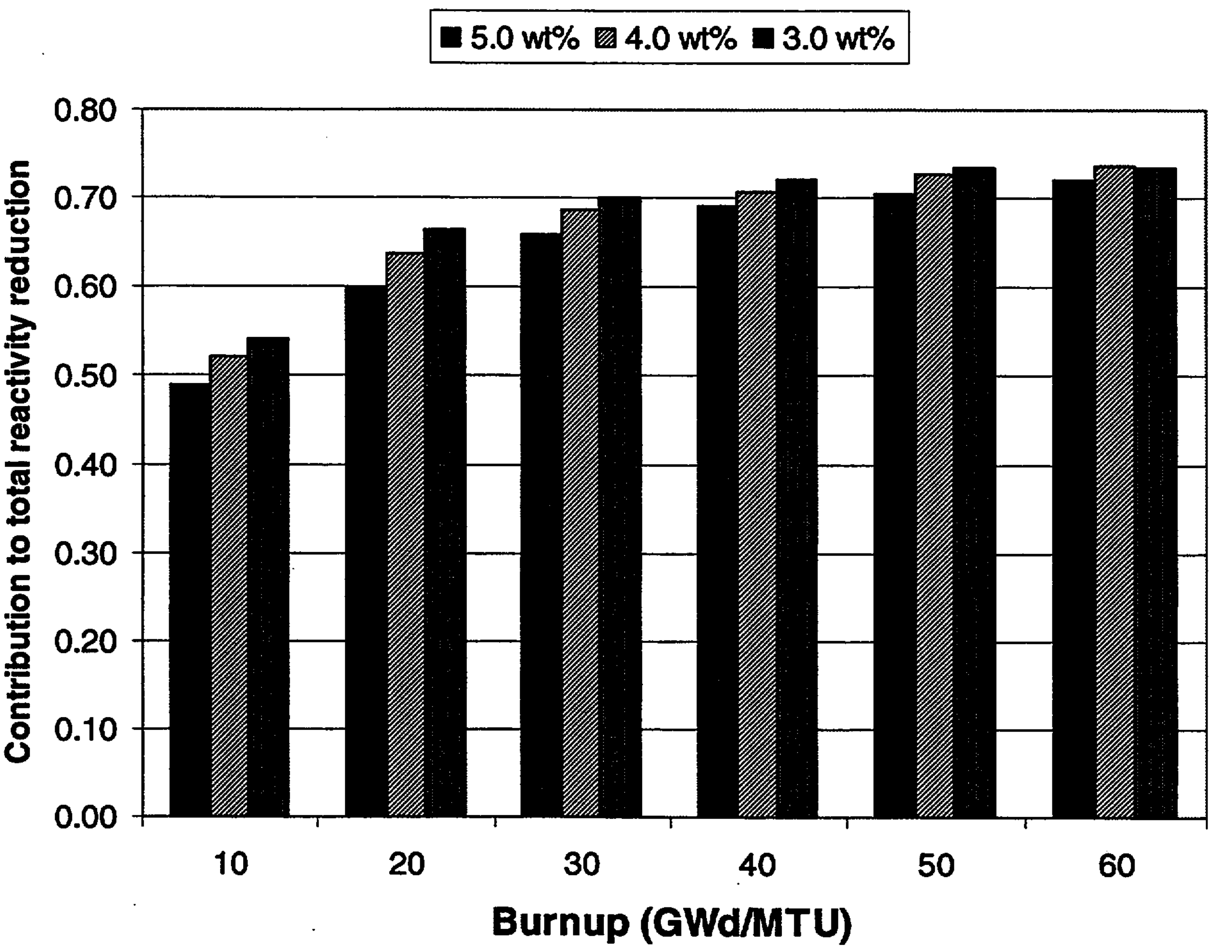

Figure D.15 Effect of initial enrichment on the contribution to total reduction in k_{eff} due to the major actinides (set 1) as a function of burnup for 5-year cooling time

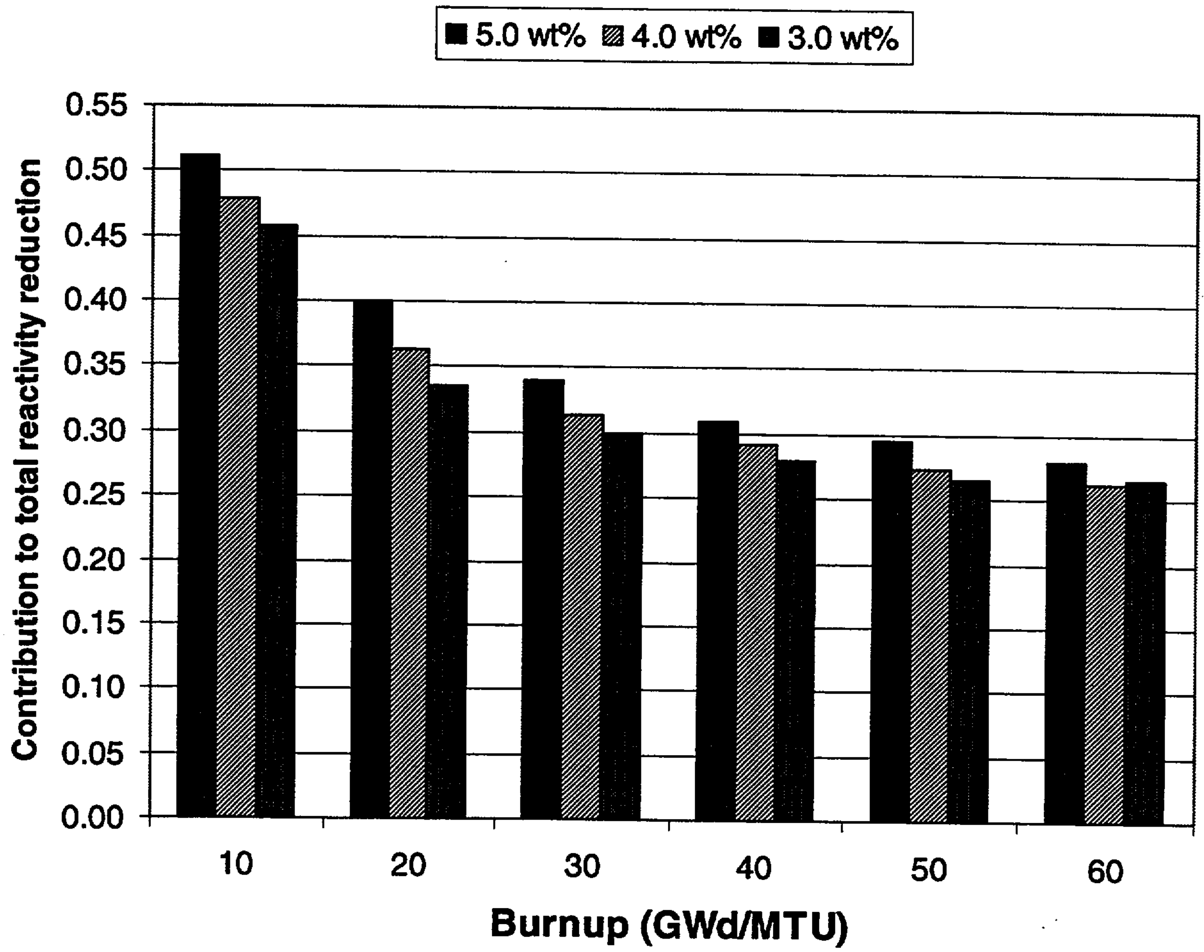

Figure D.16 Effect of initial enrichment on the contribution to total reduction in k_{eff} due to the additional nuclides (set 3) as a function of burnup for 5-year cooling time

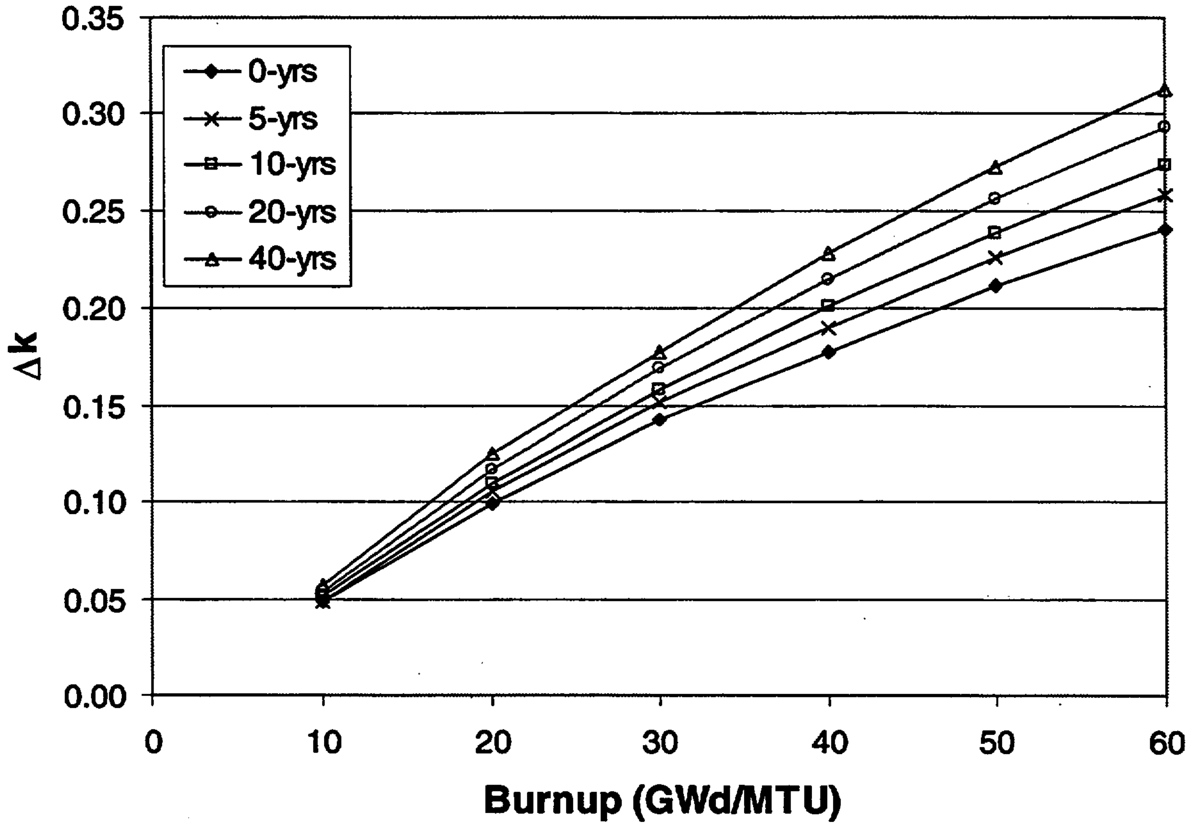

Figure D.17 Δk (relative to fresh fuel) in the GBC-32 cask due to the major actinides (set 1) as a function of burnup for various cooling times and 4 wt % ^{235}U initial enrichment

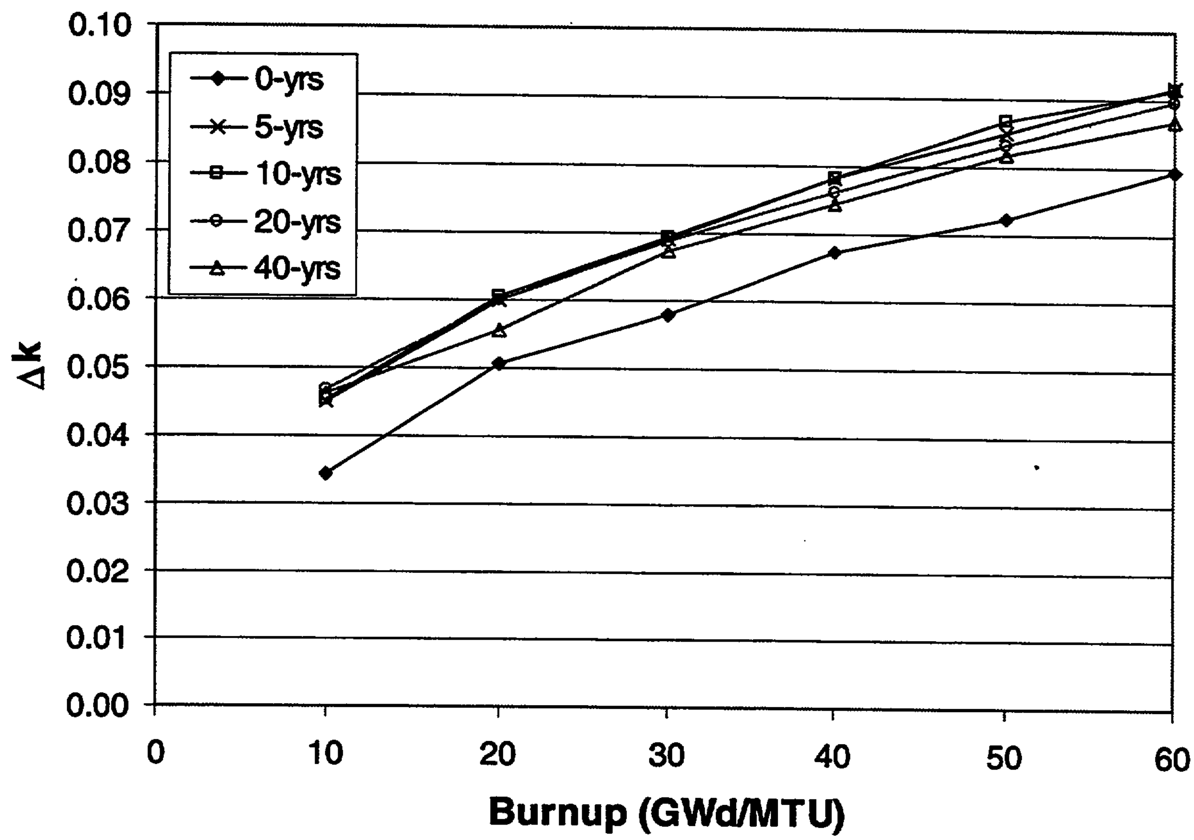

Figure D.18 **Δk in the GBC-32 cask due to the additional nuclides (set 3) as a function of burnup for various cooling times and 4 wt % ^{235}U initial enrichment**

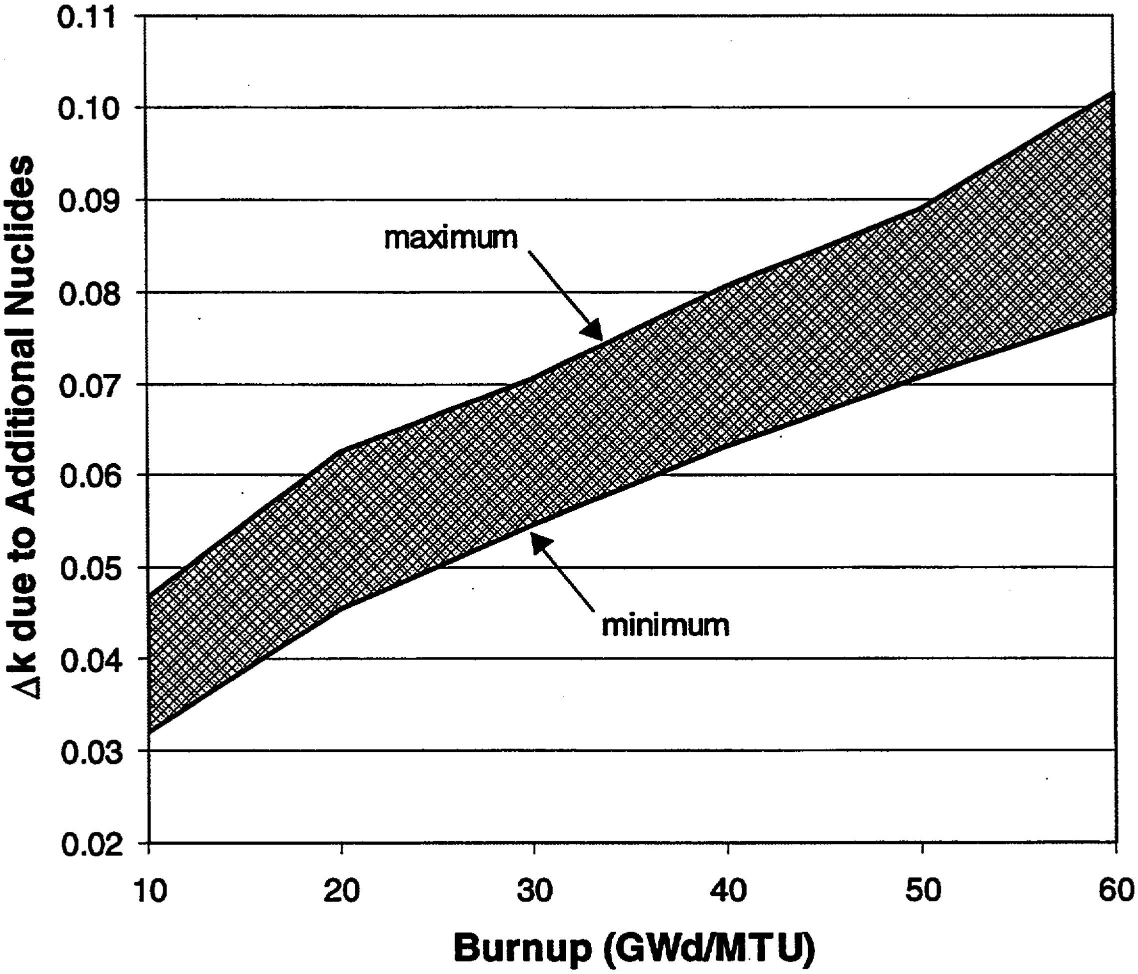

Figure D.19 Range of Δk values in the GBC-32 cask due to the additional nuclides (set 3) as a function of burnup for all cooling times and initial enrichments considered

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APPENDIX E

LIMITED NUCLIDE COMPOSITION DATA

Table E.1 Nuclide atom densities (atoms/b-cm) for fuel with initial enrichment of 4 wt % ^{235}U, zero cooling time, and various burnups

Nuclide	10 GWd/MTU	20 GWd/MTU	30 GWd/MTU	40 GWd/MTU	50 GWd/MTU	60 GWd/MTU
U-234	7.25E-06	6.30E-06	5.41E-06	4.61E-06	3.88E-06	3.24E-06
U-235	6.99E-04	5.05E-04	3.55E-04	2.41E-04	1.58E-04	9.97E-05
U-236	5.07E-05	8.42E-05	1.08E-04	1.23E-04	1.32E-04	1.35E-04
U-238	2.24E-02	2.22E-02	2.20E-02	2.18E-02	2.16E-02	2.14E-02
Np-237	1.81E-06	5.14E-06	9.13E-06	1.32E-05	1.69E-05	2.01E-05
Pu-238	1.42E-07	8.27E-07	2.26E-06	4.48E-06	7.33E-06	1.05E-05
Pu-239	8.03E-05	1.17E-04	1.34E-04	1.40E-04	1.41E-04	1.41E-04
Pu-240	1.15E-05	2.89E-05	4.51E-05	5.85E-05	6.86E-05	7.58E-05
Pu-241	4.34E-06	1.56E-05	2.70E-05	3.59E-05	4.19E-05	4.55E-05
Pu-242	3.13E-07	2.55E-06	7.32E-06	1.42E-05	2.23E-05	3.10E-05
Am-241	2.47E-08	1.76E-07	4.27E-07	6.80E-07	8.70E-07	9.82E-07
Am-243	1.53E-08	2.77E-07	1.24E-06	3.19E-06	6.11E-06	9.75E-06
Mo-95	5.16E-06	1.76E-05	3.09E-05	4.33E-05	5.46E-05	6.48E-05
Tc-99	1.49E-05	2.92E-05	4.23E-05	5.44E-05	6.53E-05	7.52E-05
Ru-101	1.30E-05	2.59E-05	3.86E-05	5.10E-05	6.32E-05	7.49E-05
Rh-103	5.58E-06	1.34E-05	2.07E-05	2.68E-05	3.18E-05	3.57E-05
Ag-109	6.27E-07	1.89E-06	3.47E-06	5.22E-06	7.01E-06	8.77E-06
Cs-133	1.53E-05	3.03E-05	4.40E-05	5.64E-05	6.73E-05	7.70E-05
Nd-143	1.16E-05	2.23E-05	3.07E-05	3.68E-05	4.09E-05	4.33E-05
Nd-145	9.21E-06	1.74E-05	2.47E-05	3.12E-05	3.68E-05	4.17E-05
Sm-147	2.28E-07	7.98E-07	1.47E-06	2.09E-06	2.60E-06	2.95E-06
Sm-149	1.02E-07	1.16E-07	1.19E-07	1.16E-07	1.12E-07	1.07E-07
Sm-150	2.90E-06	6.51E-06	1.04E-05	1.42E-05	1.78E-05	2.12E-05
Sm-151	4.13E-07	5.39E-07	6.37E-07	7.20E-07	7.91E-07	8.55E-07
Eu-151	3.12E-10	4.27E-10	4.76E-10	4.98E-10	5.06E-10	5.11E-10
Sm-152	1.41E-06	2.95E-06	4.33E-06	5.55E-06	6.63E-06	7.59E-06
Eu-153	6.80E-07	1.89E-06	3.44E-06	5.13E-06	6.81E-06	8.38E-06
Gd-155	1.77E-10	4.27E-10	8.17E-10	1.29E-09	1.81E-09	2.33E-09
O-16	4.70E-02	4.69E-02	4.69E-02	4.69E-02	4.69E-02	4.69E-02

Table E.2 Nuclide atom densities (atoms/b-cm) for fuel with initial enrichment of 4 wt % ^{235}U, 5-year cooling time, and various burnups

Nuclide	10 GWd/MTU	20 GWd/MTU	30 GWd/MTU	40 GWd/MTU	50 GWd/MTU	60 GWd/MTU
U-234	7.26E-06	6.33E-06	5.51E-06	4.79E-06	4.18E-06	3.67E-06
U-235	6.99E-04	5.05E-04	3.55E-04	2.41E-04	1.58E-04	9.97E-05
U-236	5.07E-05	8.43E-05	1.08E-04	1.23E-04	1.32E-04	1.35E-04
U-238	2.24E-02	2.22E-02	2.20E-02	2.18E-02	2.16E-02	2.14E-02
Np-237	1.99E-06	5.45E-06	9.54E-06	1.37E-05	1.75E-05	2.06E-05
Pu-238	1.45E-07	8.49E-07	2.34E-06	4.64E-06	7.58E-06	1.08E-05
Pu-239	8.31E-05	1.20E-04	1.37E-04	1.43E-04	1.45E-04	1.45E-04
Pu-240	1.15E-05	2.89E-05	4.51E-05	5.86E-05	6.90E-05	7.67E-05
Pu-241	3.41E-06	1.23E-05	2.12E-05	2.82E-05	3.29E-05	3.58E-05
Pu-242	3.13E-07	2.55E-06	7.32E-06	1.42E-05	2.23E-05	3.10E-05
Am-241	9.52E-07	3.51E-06	6.20E-06	8.34E-06	9.81E-06	1.07E-05
Am-243	1.54E-08	2.78E-07	1.24E-06	3.20E-06	6.12E-06	9.76E-06
Mo-95	1.55E-05	2.97E-05	4.27E-05	5.46E-05	6.53E-05	7.51E-05
Tc-99	1.53E-05	2.96E-05	4.27E-05	5.48E-05	6.57E-05	7.55E-05
Ru-101	1.30E-05	2.59E-05	3.86E-05	5.10E-05	6.32E-05	7.49E-05
Rh-103	8.68E-06	1.72E-05	2.48E-05	3.12E-05	3.64E-05	4.05E-05
Ag-109	6.33E-07	1.90E-06	3.49E-06	5.23E-06	7.03E-06	8.79E-06
Cs-133	1.62E-05	3.12E-05	4.49E-05	5.72E-05	6.82E-05	7.78E-05
Nd-143	1.33E-05	2.40E-05	3.23E-05	3.84E-05	4.24E-05	4.47E-05
Nd-145	9.23E-06	1.74E-05	2.47E-05	3.12E-05	3.69E-05	4.18E-05
Sm-147	3.56E-06	6.01E-06	7.64E-06	8.64E-06	9.18E-06	9.39E-06
Sm-149	1.72E-07	2.00E-07	2.14E-07	2.19E-07	2.20E-07	2.19E-07
Sm-150	2.90E-06	6.51E-06	1.04E-05	1.42E-05	1.78E-05	2.12E-05
Sm-151	4.10E-07	5.33E-07	6.28E-07	7.09E-07	7.79E-07	8.41E-07
Eu-151	1.64E-08	2.13E-08	2.51E-08	2.83E-08	3.11E-08	3.35E-08
Sm-152	1.41E-06	2.95E-06	4.33E-06	5.55E-06	6.63E-06	7.59E-06
Eu-153	7.00E-07	1.93E-06	3.49E-06	5.19E-06	6.89E-06	8.48E-06
Gd-155	1.74E-08	4.15E-08	7.96E-08	1.27E-07	1.79E-07	2.29E-07
O-16	4.70E-02	4.69E-02	4.69E-02	4.69E-02	4.69E-02	4.69E-02

Table E.3 Nuclide atom densities (atoms/b-cm) for fuel with initial enrichment of 4 wt % ^{235}U, 20-year cooling time, and various burnups

Nuclide	10 GWd/MTU	20 GWd/MTU	30 GWd/MTU	40 GWd/MTU	50 GWd/MTU	60 GWd/MTU
U-234	7.28E-06	6.43E-06	5.77E-06	5.31E-06	5.03E-06	4.89E-06
U-235	6.99E-04	5.05E-04	3.55E-04	2.41E-04	1.58E-04	9.98E-05
U-236	5.07E-05	8.43E-05	1.08E-04	1.24E-04	1.32E-04	1.35E-04
U-238	2.24E-02	2.22E-02	2.20E-02	2.18E-02	2.16E-02	2.14E-02
Np-237	2.04E-06	5.62E-06	9.83E-06	1.41E-05	1.79E-05	2.11E-05
Pu-238	1.29E-07	7.54E-07	2.08E-06	4.12E-06	6.73E-06	9.63E-06
Pu-239	8.30E-05	1.20E-04	1.37E-04	1.43E-04	1.45E-04	1.45E-04
Pu-240	1.15E-05	2.89E-05	4.52E-05	5.89E-05	6.98E-05	7.84E-05
Pu-241	1.65E-06	5.94E-06	1.03E-05	1.37E-05	1.59E-05	1.73E-05
Pu-242	3.13E-07	2.55E-06	7.32E-06	1.42E-05	2.23E-05	3.10E-05
Am-241	2.66E-06	9.66E-06	1.68E-05	2.25E-05	2.63E-05	2.86E-05
Am-243	1.54E-08	2.78E-07	1.24E-06	3.19E-06	6.11E-06	9.75E-06
Mo-95	1.55E-05	2.97E-05	4.27E-05	5.46E-05	6.53E-05	7.51E-05
Tc-99	1.53E-05	2.96E-05	4.27E-05	5.48E-05	6.57E-05	7.55E-05
Ru-101	1.30E-05	2.59E-05	3.86E-05	5.10E-05	6.32E-05	7.49E-05
Rh-103	8.68E-06	1.72E-05	2.48E-05	3.12E-05	3.64E-05	4.05E-05
Ag-109	6.33E-07	1.90E-06	3.49E-06	5.23E-06	7.03E-06	8.79E-06
Cs-133	1.62E-05	3.12E-05	4.49E-05	5.72E-05	6.82E-05	7.78E-05
Nd-143	1.33E-05	2.40E-05	3.23E-05	3.84E-05	4.24E-05	4.47E-05
Nd-145	9.23E-06	1.74E-05	2.47E-05	3.12E-05	3.69E-05	4.18E-05
Sm-147	4.75E-06	7.87E-06	9.84E-06	1.10E-05	1.15E-05	1.17E-05
Sm-149	1.72E-07	2.00E-07	2.14E-07	2.19E-07	2.20E-07	2.19E-07
Sm-150	2.90E-06	6.51E-06	1.04E-05	1.42E-05	1.78E-05	2.12E-05
Sm-151	3.66E-07	4.75E-07	5.60E-07	6.32E-07	6.94E-07	7.49E-07
Eu-151	6.12E-08	7.95E-08	9.37E-08	1.06E-07	1.16E-07	1.25E-07
Sm-152	1.41E-06	2.95E-06	4.33E-06	5.55E-06	6.63E-06	7.59E-06
Eu-153	7.00E-07	1.93E-06	3.49E-06	5.19E-06	6.89E-06	8.48E-06
Gd-155	3.14E-08	7.49E-08	1.44E-07	2.30E-07	3.23E-07	4.14E-07
O-16	4.70E-02	4.69E-02	4.69E-02	4.69E-02	4.69E-02	4.69E-02

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10. SUPPLEMENTARY NOTES

R. Y. Lee, NRC Project Manager

11. ABSTRACT *(200 words or less)*

This report proposes and documents a computational benchmark problem for the estimation of the additional reactivity margin available in spent nuclear fuel (SNF) from fission products and minor actinides in a burnup-credit storage/transport environment, relative to SNF compositions containing only the major actinides. The benchmark problem/configuration is a generic burnup credit cask designed to hold 32 pressurized-water-reactor (PWR) assemblies. The purpose of this computational benchmark is to provide a reference configuration for the estimation of the additional reactivity margin, which is encouraged in the U.S. Nuclear Regulatory Commission (NRC) guidance for partial burnup credit (ISG8), and document reference estimations of the additional reactivity margin as a function of initial enrichment, burnup, and cooling time. Consequently, the geometry and material specifications are provided in sufficient detail to enable independent evaluations. The reference solutions were generated with the SAS2H-depletion and CSAS25-criticality sequences of the SCALE 4.4a package. Although the SAS2H and CSAS25 sequences have been extensively validated elsewhere, the reference solutions are not directly or indirectly based on experimental results. Consequently, this computational benchmark cannot be used to satisfy the ANS 8.1 requirements for validation of calculational methods and is not intended to be used to establish biases for burnup credit analyses.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

burnup credit, criticality safety, spent fuel, storage, transportation

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