RECOMMENDATIONS ON THE CREDIT FOR COOLING TIME IN PWR BURNUP CREDIT ANALYSES

Oak Ridge National Laboratory

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RECOMMENDATIONS ON THE CREDIT FOR COOLING TIME IN PWR BURNUP CREDIT ANALYSES

Prepared by:
J.C. Wagner and C.V. Parks

Oak Ridge National Laboratory
Managed by UT-Battelle, LLC
Oak Ridge, TN 37831-6370

R.Y. Lee, NRC Project Manager

ABSTRACT

The U.S. Nuclear Regulatory Commission's guidance on burnup credit for pressurized-water-reactor (PWR) spent nuclear fuel (SNF) recommends that analyses be based on a cooling time of five years. This recommendation eliminates assemblies with shorter cooling times from cask loading and limits the allowable credit for reactivity reduction associated with cooling time. This report examines reactivity behavior as a function of cooling time to assess the possibility of expanding the current cooling time recommendation for SNF storage and transportation. The effect of cooling time on reactivity for various initial enrichments, burnups, and selected nuclide sets is shown and discussed. Further, the benefits of additional credit for cooling time are quantified based on a realistic high-capacity rail-type cask designed for burnup credit. While this report is primarily focused on cask storage and transportation, analyses are extended out to 100,000 years to understand the relevant concerns associated with long-term disposal and their possible influence on storage and transportation practice. The report concludes with a discussion on the issues for consideration and recommendations for expanded allowance of credit for cooling time in criticality safety analyses using burnup credit for cask storage and transportation.

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FOREWORD

In 1999 the United States Nuclear Regulatory Commission (U.S. NRC) issued initial recommended guidance for using reactivity credit due to fuel irradiation (i.e., burnup credit) in the criticality safety analysis of spent pressurized-water-reactor (PWR) fuel in storage and transportation packages. This guidance was issued by the NRC Spent Fuel Project Office (SFPO) as Revision 1 to Interim Staff Guidance 8 (ISG8R1) and published in the *Standard Review Plan for Transportation Packages for Spent Nuclear Fuel*, NUREG-1617 (March 2000). With this initial guidance as a basis, the NRC Office of Nuclear Regulatory Research initiated a program to provide the SFPO with technical information that would:

- enable realistic estimates of the subcritical margin for systems with spent nuclear fuel (SNF) and an increased understanding of the phenomena and parameters that impact the margin, and
- support the development of technical bases and recommendations for effective implementation of burnup credit and provide realistic SNF acceptance criteria while maintaining an adequate margin of safety.

This report examines reactivity behavior as a function of cooling time to assess the possibility of expanding the current cooling time recommendation for SNF storage and transportation. The effect of cooling time on reactivity for various initial enrichments, burnups, and selected nuclide sets is shown and discussed. While this report is primarily focused on cask storage and transportation, analyses are extended out to 100,000 years to understand the relevant concerns associated with long-term disposal and their possible influence on storage and transportation practice. Based on this study and the related discussion, the report proposes recommendations for expanded allowance of credit for cooling time in criticality safety analyses using burnup credit for cask storage and transportation. The use of burnup credit results in fewer casks needing to be transported, thereby reducing regulatory burden on licensee while maintaining safety for transportation of SNF.

Farouk Eltawila, Director
Division of Systems Analysis and Regulatory Effectiveness

ACKNOWLEDGEMENTS

1 INTRODUCTION

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. After spent nuclear fuel (SNF) is discharged from a reactor, the reactivity continues to vary as a function of time due to the decay of unstable isotopes. The time period after discharge is referred to as the *cooling time* and taking credit for the reduction in reactivity due to cooling time is commonly referred to as *taking credit for cooling time*.

For casks designed without burnup credit allowance, the SNF is conservatively assumed to be unirradiated and cooling time is only important in consideration of the decay heat and radiation source terms. These source terms continuously decrease with cooling time. Thus, cooling time requirements for SNF to be loaded into a transportation or storage cask have typically been established to provide the minimum cooling time consistent with the maximum source terms that will enable the thermal and shielding requirements to be met.

Relative to reactivity, commercial SNF increases in reactivity for a short period after discharge from a reactor due to the decay of short-lived fission product absorbers. The peak occurs at approximately 100 hours after discharge. After this point, reactivity decreases continuously with time out to approximately 100 years, at which time it begins to increase again. The reactivity continues to increase until a second peak at around 30,000 years, after which time it begins decreasing out to approximately 100,000 years. With this knowledge of the SNF reactivity variation with cooling time, the U.S. Nuclear Regulatory Commission (NRC) guidance[1] for burnup credit use in spent fuel pools (SFPs) recommends burnup credit be evaluated at the initial peak (in practice, this condition basically corresponds to the discharge isotopics with ^{135}Xe removed). However, SFP licensees are allowed to take credit for as much cooling time as is available/appropriate (dictated by the cooling time accumulated by the resident SNF) and may assume multiple cooling times to establish separate storage criteria for fuel with different cooling times.

For transportation and dry storage casks, the NRC has recently issued guidance for pressurized-water-reactor (PWR) SNF burnup credit[2,3] that recommends the licensing-basis analysis assume an out-of-reactor cooling time of five years and, accordingly, only SNF cooled a minimum of five years should be loaded into a cask approved for burnup credit. This recommended restriction will allow cask loading of the vast majority of SNF assemblies currently in storage and simplifies the licensing and loading process by requiring only one burnup credit loading curve (required minimum burnup as a function of initial enrichment) for each fuel design classification. Also, this approach circumvents the need to consider the initial peak reactivity immediately after discharge. However, restricting the cooling time to a fixed value eliminates assemblies with shorter cooling times from cask loading and limits the allowable credit for reactivity reduction associated with longer cooling time. Preferential loading concepts, whereby the mixing of short-cooled assemblies and long-cooled assemblies is used to achieve optimum thermal and shielding performance, are also limited if assemblies with less than five years of cooling time are not allowed in burnup credit casks.

The objective of this report is to demonstrate the reactivity behavior of PWR SNF as a function of cooling time, discuss the issues associated with relaxing the current cooling time restriction for cask storage and transportation, and provide recommendations for revising the current regulatory guidance for cooling time. Although this report is focused on cask storage and transportation, analyses are extended far beyond the 200-year timeframe typically considered for such applications. Cooling times out to 100,000 years are included in the study to fully demonstrate the time-dependent behavior of the SNF reactivity and to enable consideration of issues related to the interface with permanent disposal[4] where such timeframes are relevant.

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2 EFFECT OF COOLING TIME ON REACTIVITY

Reference 5 provides a demonstration of the change in SNF reactivity as a function of out-of-reactor cooling time and provides a discussion on the principal nuclides responsible for the changes. As noted, SNF discharged from a reactor will increase in reactivity for approximately 100 hours after discharge due to the decrease in neutron absorption caused by the decay of very short-lived fission products. The decrease in reactivity from 100 hours to 100 years is driven by the decay of the ^{241}Pu fissile nuclide ($t_{1/2}$ = 14.4 years) and the buildup of the neutron absorbers ^{241}Am (from decay of ^{241}Pu) and ^{155}Gd (from ^{155}Eu which decays with $t_{1/2}$ = 4.7 years).[5] After about 50 years the ^{155}Gd buildup is complete and the ^{241}Pu has decayed out by approximately 100 years. After this time the reactivity begins to increase, governed primarily by the decay of two major neutron absorbers – ^{241}Am ($t_{1/2}$ = 432.7 years) and ^{240}Pu ($t_{1/2}$ = 6,560 years) – and mitigated somewhat by a decrease in the fissile inventory as ^{239}Pu ($t_{1/2}$ = 24,100 years) decays and causes an increase in ^{235}U. After approximately 30,000 years, the ^{240}Pu and ^{241}Am decay is complete and the reactivity again begins to decrease as the decay of ^{239}Pu dominates the process.

The cooling times corresponding to the SNF reactivity minimums and maximums and their values are dependent upon the nuclides included in the reactivity calculations. The time-dependent variation described above corresponds to actual SNF, and thus is based on all relevant nuclides. However, current NRC guidance[2,3] recommends limiting the amount of burnup credit to that available from actinide compositions, and any future plans to include credit for fission products are likely to include only a subset of fission product nuclides. Therefore, it is necessary to examine the effect of cooling time with consideration of the nuclides used in the analysis.

The use of just actinides in burnup credit calculations is referred to as "actinide-only" burnup credit. The nuclides used for actinide-only calculations in this report are consistent with those specified in a Department of Energy (DOE) Topical Report on burnup credit.[6] While not commonly defined in a consistent manner, the use of a subset of possible actinides and fission products will be referred to herein as "actinide + fission product" burnup credit. The fission product nuclides used here for actinide + fission product calculations are consistent with those identified in Table 2 of Ref. 7 as being the most important for criticality calculations. Finally, credit for all (or nearly all) nuclides will be referred to as "full" burnup credit. For the calculations presented in this report, Table 1 lists the nuclides included for each classification of burnup credit. These "classes" of burnup credit allowance and the nuclides included within each are defined here for the purposes of discussion; other terminology and specific sets of nuclides have been defined and used by others studying burnup credit phenomena.

Table 1 Nuclide sets associated with the various classifications of burnup credit

Set 1: Actinide-only burnup credit nuclides (10 total)*									
U-234	U-235	U-238	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Am-241	O†

Set 2: Actinide + fission product burnup credit nuclides (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†	

Set 3: All available nuclides‡ (236 total), full burnup credit									
Ge-72	Sr-89	Ru-101	Sn-114	Te-126	Ba-135	Pm-147	Gd-156	U-236	Bk-249
Ge-73	Y-89	Ru-102	Cd-115m	Xe-126	Xe-136	Sm-147	Eu-157	U-237	Cf-249
Ge-74	Sr-90	Ru-103	In-115	Te-127m	Cs-136	Nd-148	Gd-157	U-238	Cf-250
As-75	Y-90	Rh-103	Sn-115	I-127	Ba-136	Pm-148	Gd-158	Np-237	Cf-251
Ge-76	Zr-90	Ru-104	Cd-116	Te-128	Cs-137	Pm-148m	Tb-159	Pu-236	Cf-252
Se-76	Y-91	Pd-104	Sn-116	Xe-128	Ba-137	Sm-148	Gd-160	Pu-237	Es-253
Se-77	Zr-91	Ru-105	Sn-117	Te-129m	Ba-138	Pm-149	Tb-160	Pu-238	H-1
Se-78	Zr-92	Rh-105	Sn-118	I-129	La-139	Sm-149	Dy-160	Pu-239	H-2
Br-79	Zr-93	Pd-105	Sn-119	Xe-129	Ba-140	Nd-150	Dy-161	Pu-240	H-3
Se-80	Nb-93	Ru-106	Sn-120	Te-130	La-140	Sm-150	Dy-162	Pu-241	He-3
Kr-80	Zr-94	Pd-106	Sb-121	I-130	Ce-140	Pm-151	Dy-163	Pu-242	He-4
Br-81	Nb-94	Pd-107	Sn-122	Xe-130	Ce-141	Sm-151	Dy-164	Pu-243	Li-6
Se-82	Zr-95	Ag-107	Te-122	I-131	Pr-141	Eu-151	Ho-165	Pu-244	Li-7
Kr-82	Nb-95	Pd-108	Sn-123	Xe-131	Ce-142	Sm-152	Er-166	Am-241	Be-9
Kr-83	Mo-95	Cd-108	Sb-123	Te-132	Pr-142	Eu-152	Er-167	Am-242m	B-10
Kr-84	Zr-96	Ag-109	Te-123	Xe-132	Nd-142	Gd-152	Bi-209	Am-243	B-11
Kr-85	Mo-96	Pd-110	Sn-124	Xe-133	Ce-143	Sm-153	Th-230	Cm-241	N-14
Rb-85	Mo-97	Cd-110	Sb-124	Cs-133	Pr-143	Eu-153	Th-232	Cm-242	N-15
Kr-86	Mo-98	Ag-111	Te-124	Xe-134	Nd-143	Sm-154	Pa-231	Cm-243	O-16
Rb-86	Mo-99	Cd-111	Sn-125	Cs-134	Ce-144	Eu-154	Pa-233	Cm-244	O-17
Sr-86	Tc-99	Cd-112	Sb-125	Ba-134	Nd-144	Gd-154	U-232	Cm-245	
Rb-87	Ru-99	Cd-113	Te-125	I-135	Nd-145	Eu-155	U-233	Cm-246	
Sr-87	Mo-100	In-113	Sn-126	Xe-135	Nd-146	Gd-155	U-234	Cm-247	
Sr-88	Ru-100	Cd-114	Sb-126	Cs-135	Nd-147	Eu-156	U-235	Cm-248	

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* Consistent with the actinides considered in Ref. 6.

† Oxygen is neither an actinide nor a fission product, but is include in this list because it is an integral part of the fuel and is include in the calculations.

‡ All nuclides for which data are available in the SCALE 238-group cross-section library.

2.1 COMPUTATIONAL METHODS AND MODELS

The computational methods necessary for this analysis include codes for depletion and criticality simulation. A recently developed control module[8] designed to automate burnup-credit criticality safety analyses by coupling the depletion and criticality modules of SCALE (Ref. 9) was used for all of the analyses described in this report. This control module, referred to as STARBUCS, couples a number of SCALE code modules, including ARP, ORIGEN-S, CSASI, WAX, and KENO V.a, to achieve the 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 library. The depletion calculations were performed using operational parameters for fuel temperature (1100 K), clad temperature (620 K), moderator temperature (610 K), soluble boron concentration (1000 ppm), and specific power (continuous operation at 60 MW/MTU) that result in a conservative prediction of the effective neutron multiplication factor, k_{eff}, (i.e., k_{eff} is overestimated with respect to typical SNF parameters). The sensitivity of k_{eff} to variations in these parameters is discussed in Ref. 10. 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.

Using an ARP-generated cross-section library, ORIGEN-S performs the depletion calculations to generate fuel compositions for the burnup and decay time associated with each axial fuel region. ARP and ORIGEN-S calculations are performed for each axial fuel region. 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. Finally, the STARBUCS module executes the three-dimensional (3-D) KENO V.a Monte Carlo criticality code using the generated axially-varying macroscopic cross-section library. 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. The criticality calculations utilized the SCALE 238-group cross-section library, which is primarily based on ENDF/B-V data.

2.1.1 Rail-Type Cask

The generic 32 PWR-assembly burnup credit (GBC-32) cask[11] was used for the calculations to quantify the reactivity effect of cooling time within a realistic high-capacity rail-type cask. The GBC-32 design was previously developed[11] to provide a reference cask configuration that is representative of typical high-capacity rail casks being considered by industry, and thus is considered to be a relevant and appropriate configuration for the analyses presented in this report. The boron loading in the Boral panels in the GBC-32 cask is 0.0225 g ^{10}B/cm^2, and detailed specifications for the GBC-32 cask are provided in Ref. 11. The reference fuel design used in the GBC-32 cask is the Westinghouse (WE) 17 × 17 fuel assembly; dimensional specifications are available in Ref. 11. In all cases, all of the assemblies in the cask model are the same (i.e., the same initial enrichment, burnup, and cooling time). Cross-sectional views of the computational model, as generated by KENO V.a, are shown in Figures 1 and 2. Consistent with the specification in Ref. 11, the model represents the active fuel length as 18 equally-spaced axial regions to enable simulation of the variation in axial composition due to axial burnup. Although the axial burnup profile is known to be dependent on accumulated burnup, a single axial burnup profile was used throughout this analysis. The axial burnup profile used in the computational model corresponds to the bounding profile suggested in Ref. 6 for PWR fuel with assembly-averaged discharge burnup greater than 30 GWd/MTU.
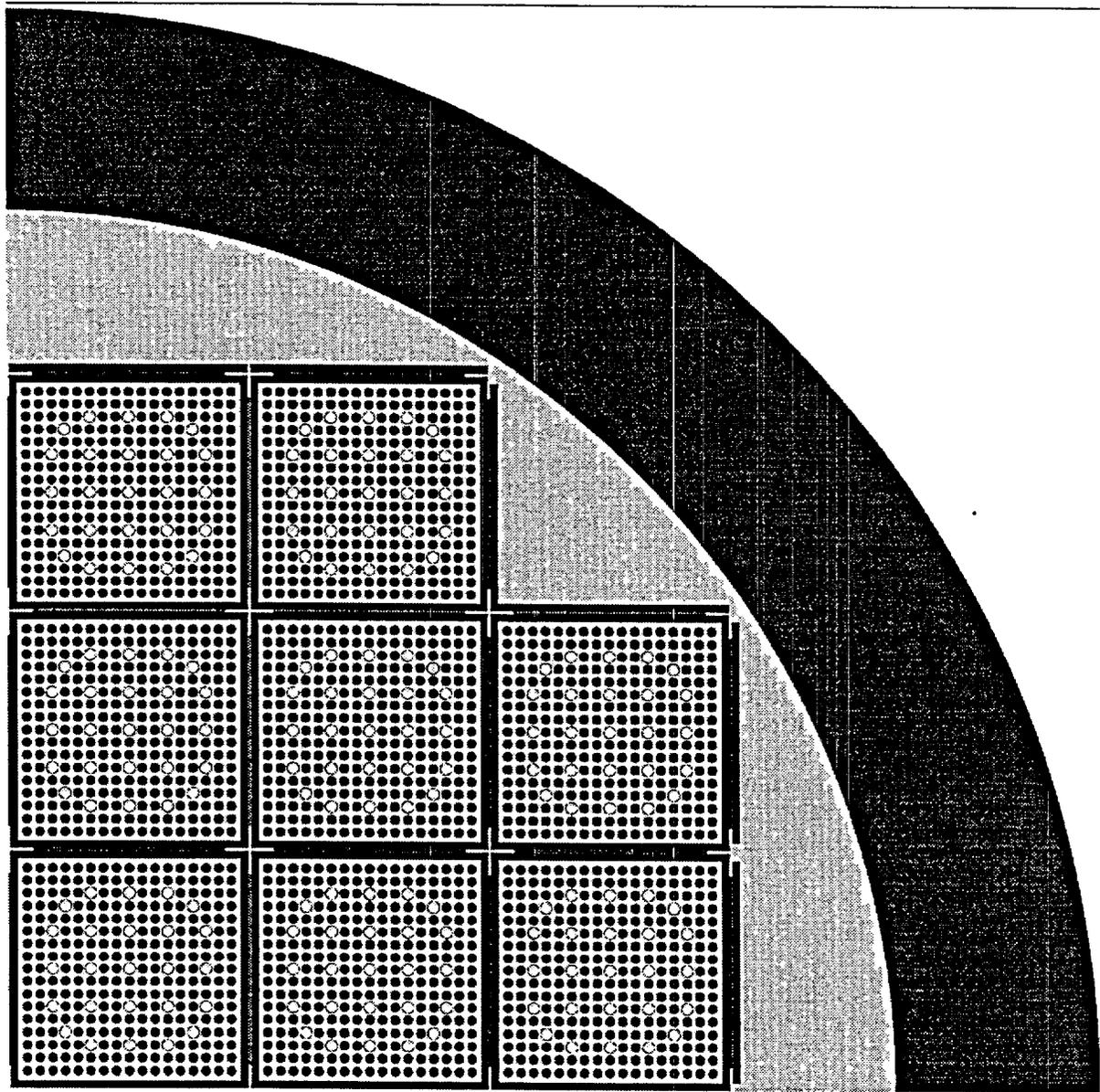
Figure 1 Radial cross section of one quarter of the KENO V.a model of the GBC-32 cask
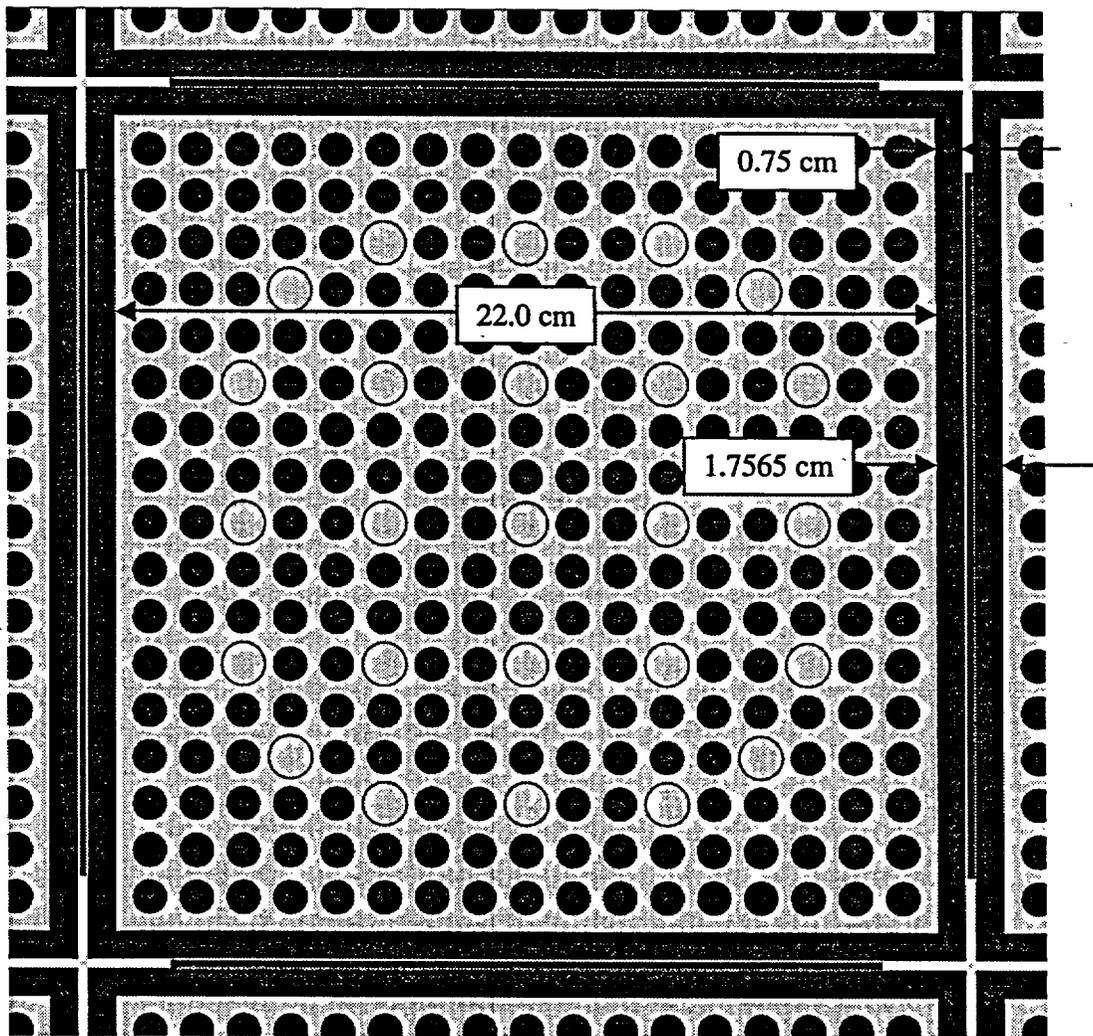
Figure 2 Cross-sectional view of assembly cell in KENO V.a model of the GBC-32 cask

2.1.2 Truck-Type Cask

The General Atomics 4-PWR assembly (GA-4) cask[12,13] was used for the calculations to quantify the reactivity effect of cooling time within an actual truck-type cask. The GA-4 cask design uses a fixed stainless steel fuel support structure, which contains solid pellets of enriched boron carbide (B_4C) in radial holes, to separate the fuel assemblies. A detailed description of the GA-4 cask is provided in Refs. 12 and 13. The GA-4 cask model is loaded with WE 17 × 17 OFA assemblies and includes an axial burnup distribution as described above for the GBC-32 cask model.

2.2 ANALYSES WITH A RAIL-TYPE CASK

Based on current regulatory guidance for burnup credit, loading criteria for SNF assemblies will be based on their burnup and initial enrichment, for a single cooling time of five years. Including cooling time as an additional variable must be supported by a complete understanding of reactivity behavior as a function of cooling time, in conjunction with variations in initial enrichment and accumulated burnup. Hence, the following sections present analyses to demonstrate the reactivity behavior in the GBC-32 cask as a function of cooling time for variations in enrichment, burnup, and nuclides included, quantify the reactivity change associated with cooling time, and establish the potential benefit of additional credit for cooling time for SNF storage and transportation.

The effective neutron multiplication factor, k_{eff}, as a function of cooling time for the three classifications of burnup credit (i.e., actinide-only, actinide + fission product, and full) defined in Table 1, is shown in Figure 3. The results correspond to fuel with an initial enrichment and discharge burnup combination of 4.0 wt % ^{235}U and 40 GWd/MTU, which is a fairly representative enrichment and burnup combination for typical discharged SNF.[14] Error bars representing 1-σ statistical uncertainties from the criticality calculations are smaller than the data symbols, and thus are not explicitly shown. As stated previously, the reactivity of SNF, which is most accurately represented by the "full" burnup credit case, peaks at approximately 100 hours after discharge and then decreases until approximately 100 years. After 100 years, k_{eff} increases continuously with time until approximately 30,000 years, at which time it again begins to decrease. The peaking behavior at approximately 100 hours is due to the decay of very short-lived fission product absorbers, which are not present in the actinide-only and actinide + fission product cases. Beyond approximately 100 hours, the actinide-only and actinide + fission product cases exhibit similar behavior to the "full" burnup credit case (i.e., maximums and minimums occur at approximately the same times). Figure 4 provides a focused view of 1–200 year timeframe, which is most relevant to storage and transportation.

The effect of cooling time on k_{eff} values for various burnup and initial enrichment combinations is shown for each of the three classifications of burnup credit (i.e., actinide-only, actinide + fission product, and full) in Figures 5–7. The k_{eff} values vary as a function of cooling time due to the decay of unstable isotopes and subsequent buildup of others. The concentration of unstable isotopes is dependent upon the discharge burnup. The effect of cooling time is shown to increase with burnup. The "dip" that occurs at around 100 years is due to the decay of ^{241}Pu and the buildup of ^{241}Am and becomes less pronounced as the burnup decreases for a constant initial enrichment. It is interesting to note from Figures 5–7 that while the full and actinide + fission product cases reach their peak reactivity within the first 100 hours, actinide-only cases for SNF that is highly under-burned (e.g., 5.0 wt %, 20 GWd/MTU) reach their peak reactivity at approximately 30,000 years. However, one must remember that the actinide-only case corresponds to a calculational assumption and does not accurately represent the reactivity of the actual SNF because the effects of the fission products are excluded. Relative to initial enrichment, Figures 5–7 demonstrate no variation in the shape of the curves until at least 10,000 years when the relative importance of the ^{235}U generated from ^{239}Pu decay becomes slightly noticeable.

Figure 8 shows Δk values, relative to the suggested cooling time of five-years,[23] as a function of cooling time for the three classifications of burnup credit for the initial enrichment and discharge burnup combination of 4.0 wt % ^{235}U and 40 GWd/MTU. Finally, to highlight the differences in k_{eff} values associated with the different nuclides sets, Figure 9 shows Δk values corresponding to the different nuclide sets considered (defined in Table 1) as a function of cooling time.

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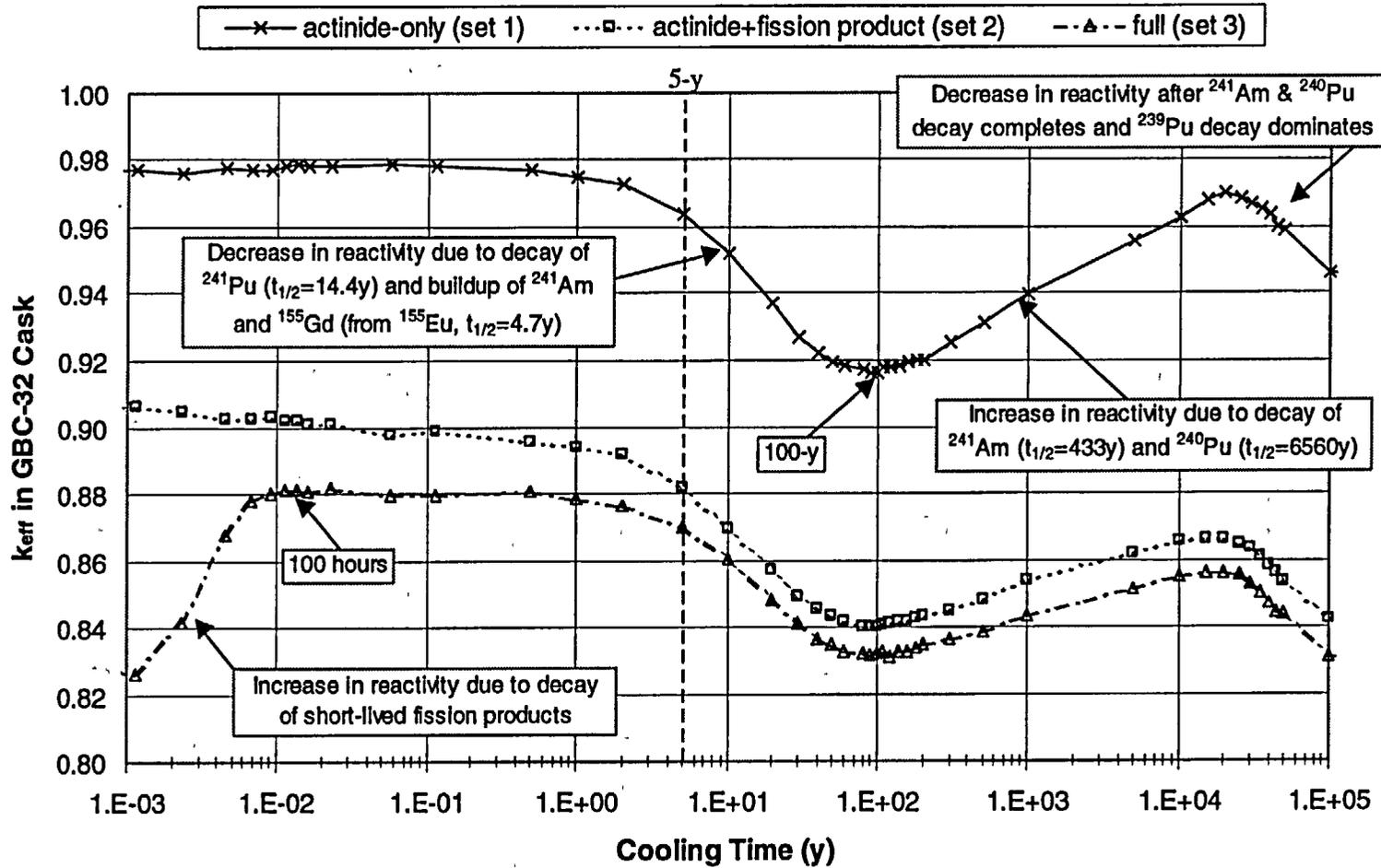
Figure 3 Reactivity behavior in the GBC-32 cask as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.

Figure 4 Reactivity behavior in the GBC-32 cask during the 1–200 year timeframe for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.

Figure 5 Reactivity behavior in the GBC-32 cask for actinide-only burnup credit as a function of cooling time for various initial enrichment and burnup combinations. The calculations include an axial burnup distribution as described in Section 2.1.
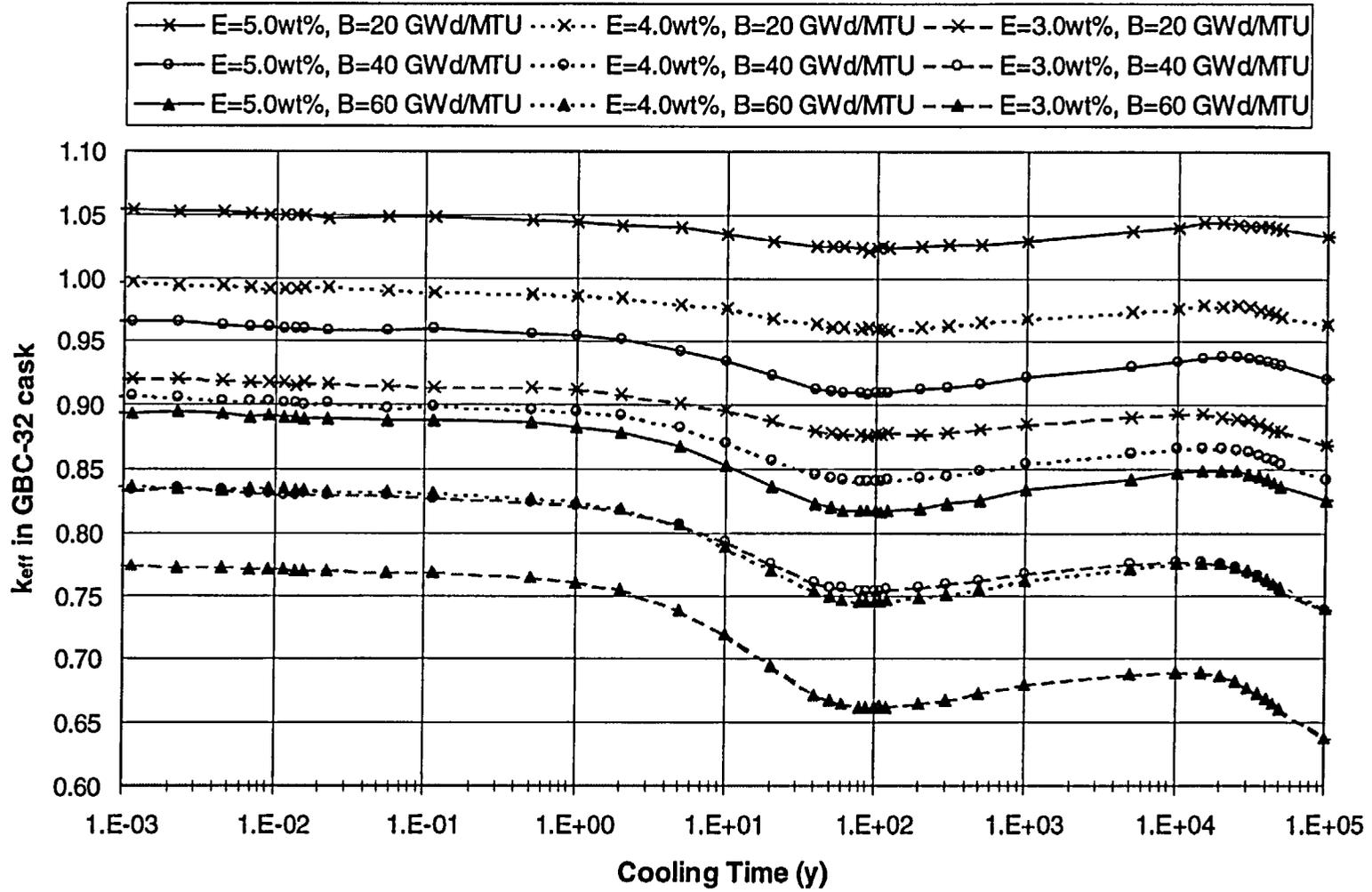
Figure 6 Reactivity behavior in the GBC-32 cask for actinide + fission product burnup credit as a function of cooling time for various initial enrichment and burnup combinations. The calculations include an axial burnup distribution as described in Section 2.1.
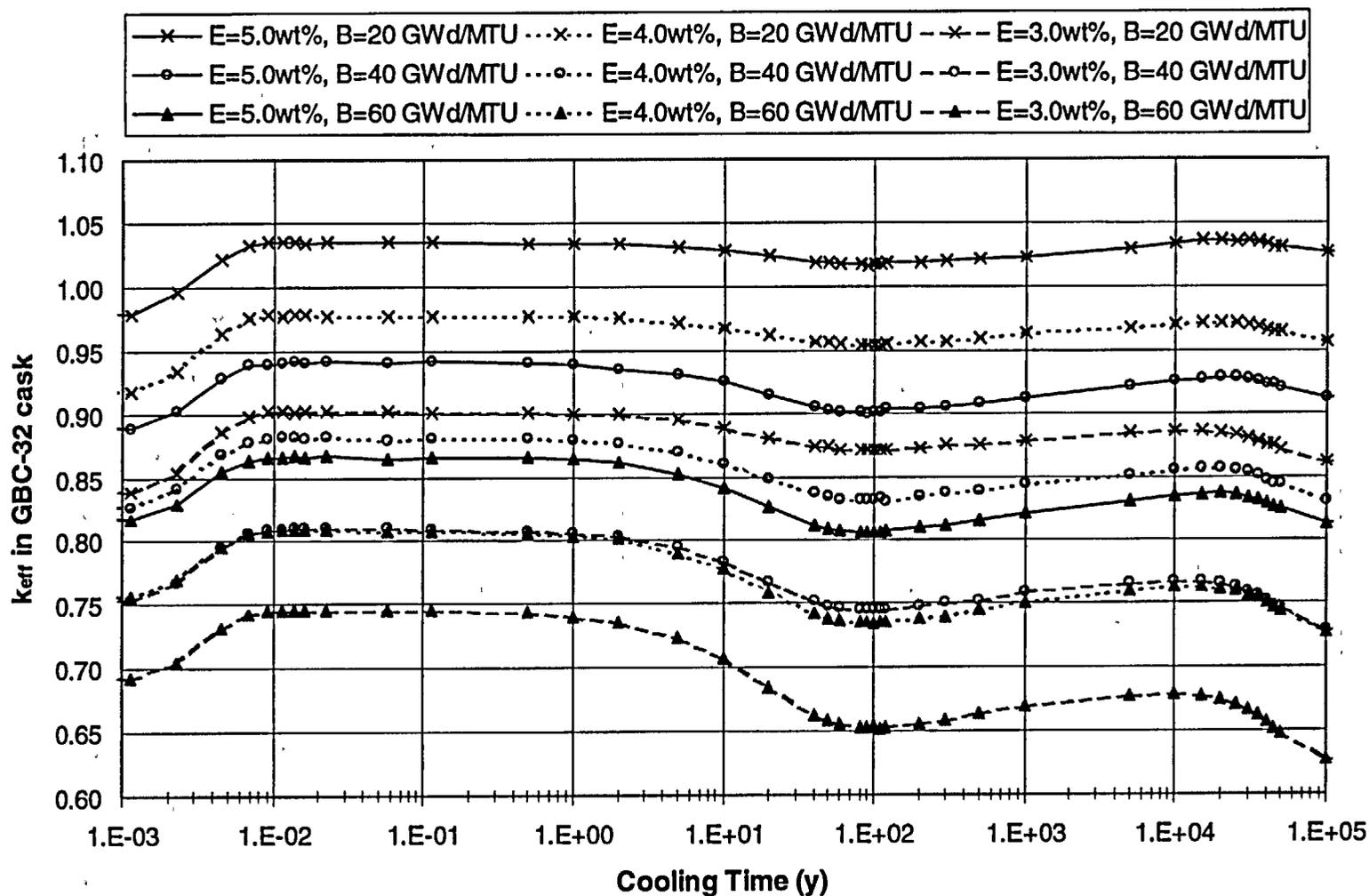
Figure 7 Reactivity behavior in the GBC-32 cask for full burnup credit as a function of cooling time for various initial enrichment and burnup combinations. The calculations include an axial burnup distribution as described in Section 2.1.

Figure 8 Δk values in the GBC-32 cask relative to the suggested five-year cooling time, as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % [235]U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.
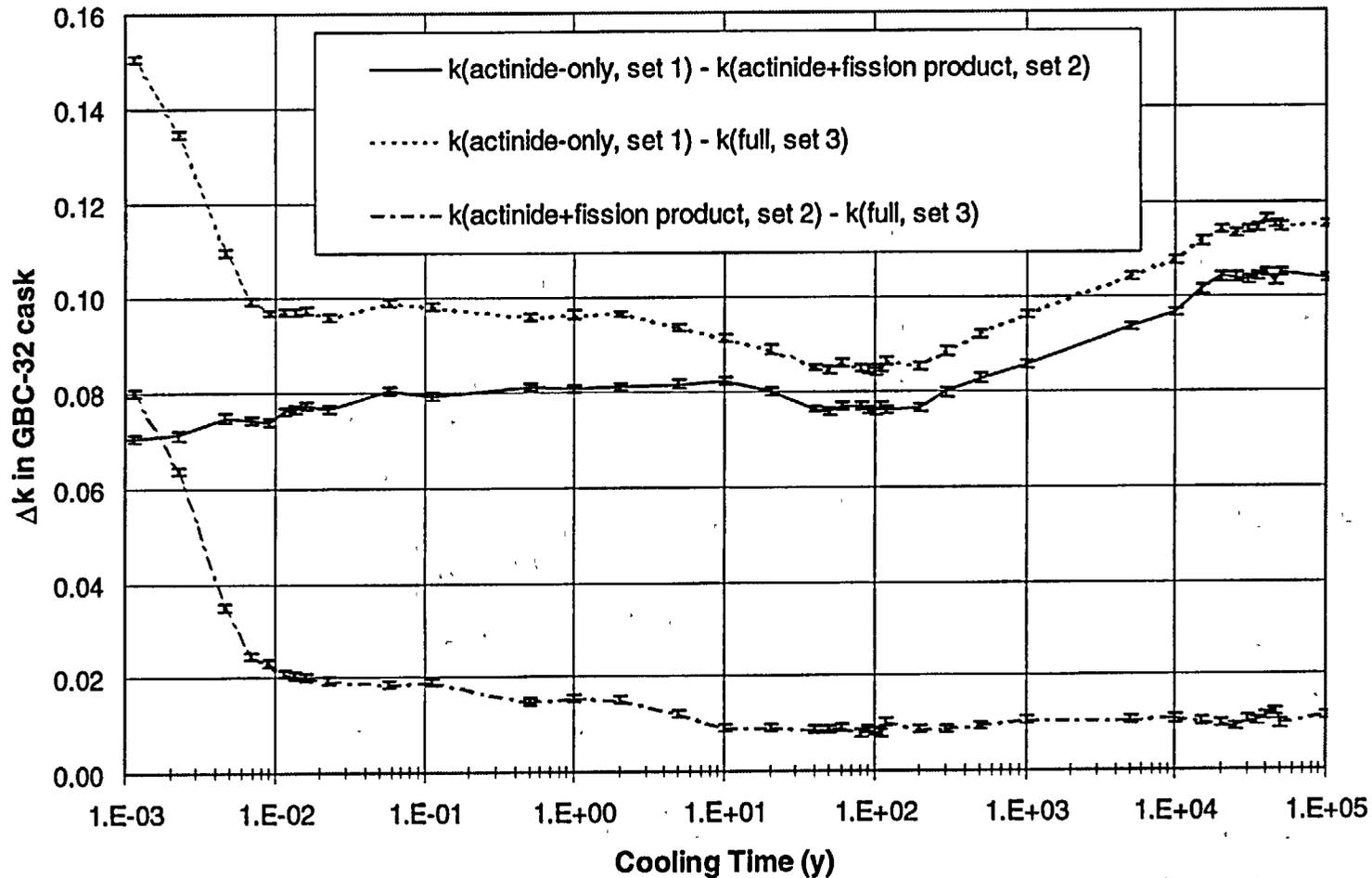
Figure 9 Δk values in the GBC-32 cask corresponding to differences in the various nuclide sets (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.

2.2.1 Effect Without the Axial Burnup Distribution Included

Axial variations in flux in a reactor core, which are mainly due to leakage at the fuel ends, result in a non-uniform burnup distribution along the axial length of the fuel. The axial burnup distribution is characterized by end regions that are significantly under-burned with respect to the assembly-averaged burnup. The shape of the axial burnup distribution is dependent upon the accumulated burnup, as well as other characteristics of the assembly operating history. For fuels of moderate-to-high burnup (i.e., burnups beyond ~20-30 GWd/MTU), the under-burned regions at the ends of the fuel are dominant in terms of reactivity.[15] Therefore, when the axial burnup distribution is included in the calculational model, the reactivity tends to be controlled by the lower burnup in the end regions. The difference in k_{eff} values between a calculation with explicit representation of the axial burnup distribution and a calculation that assumes uniform axial burnup has become known as the "*end effect*" (Ref. 16). Although the assumption of uniform axial burnup has no physical validity for SNF, it has proven useful as a reference for comparison of the effect of the axial burnup distribution.

Since the reactivity reduction associated with cooling time increases with fuel burnup, the lower burnup end-regions of the SNF are less sensitive to cooling time than the higher burnup center region. Hence, relative to the center region, the reactivity worth of the ends increases with increasing cooling time. As a result, the reactivity reduction associated with cooling time is overestimated when uniform axial burnup is assumed in the calculational model. It is for this reason that the reference computational model includes an axial burnup distribution.

To demonstrate the impact of neglecting the axial burnup distribution (i.e., assuming uniform axial burnup), Figures 10 and 11 show the reactivity behavior as a function of cooling time with and without the axial burnup distribution included for the three classifications of burnup credit (i.e., actinide-only, actinide + fission product, and full). The results in Figures 10 and 11 correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated discharge burnups of 40 and 60 GWd/MTU, respectively. As mentioned in Section 2.1, the axial burnup distribution that is used in the reference calculational model corresponds to the bounding profile suggested in Ref. 6 for PWR fuel with assembly-averaged burnup greater than 30 GWd/MTU. The relative behavior is not significantly affected by the axial burnup distribution (i.e., the points in time at which the maximum and minimum k_{eff} values occur remain essentially the same). However, during the regime of prime importance to transportation and storage (e.g., 1 to 200 years), the reduction in reactivity with cooling time is significantly less when the axial burnup distribution is included. As mentioned above, this reduced reactivity change as a function of cooling time is due to the fact that the end-region of the fuel, that controls the reactivity when the axial burnup distribution is included in the model, has an accumulated burnup that is significantly less than the assembly-averaged burnup.
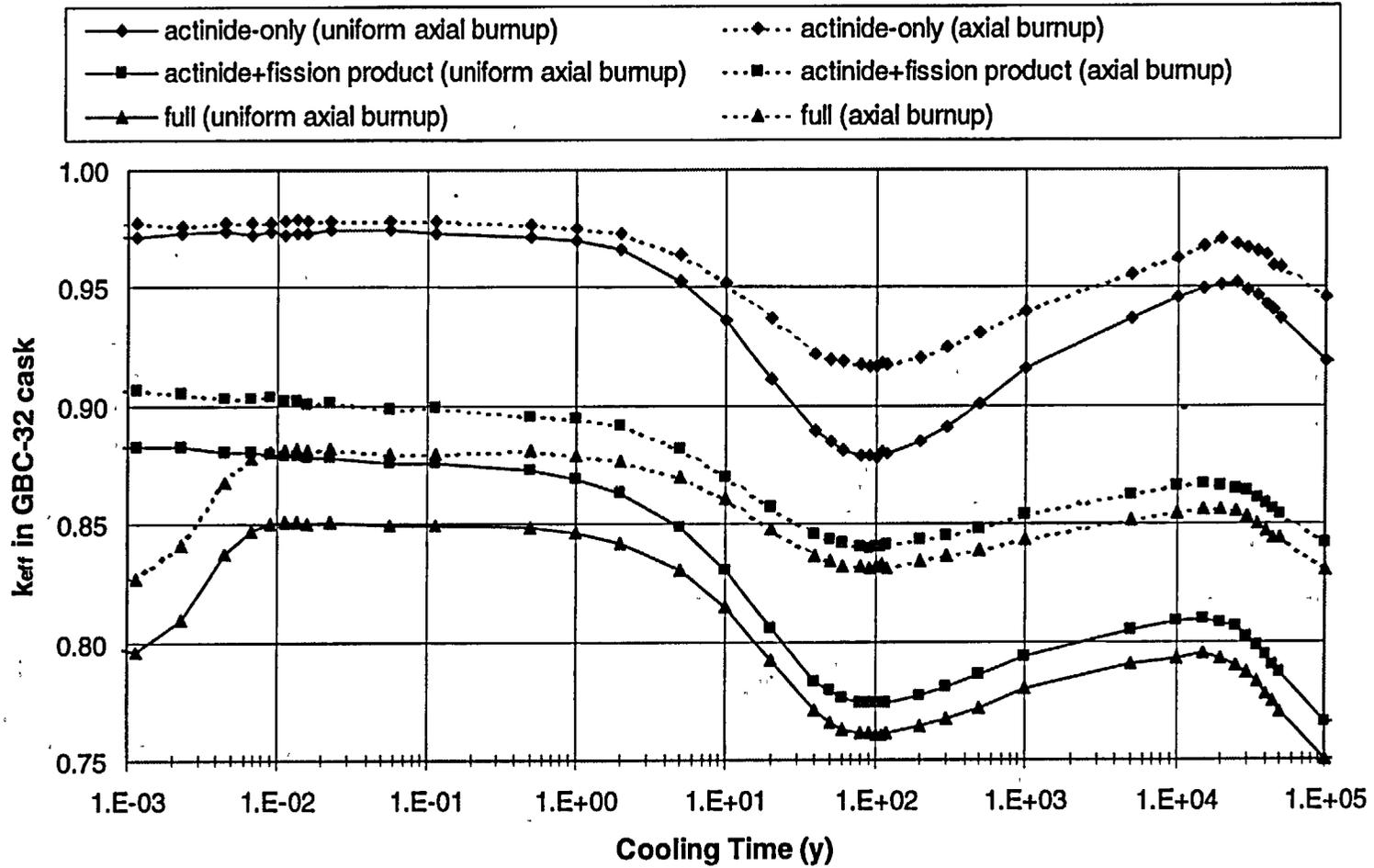
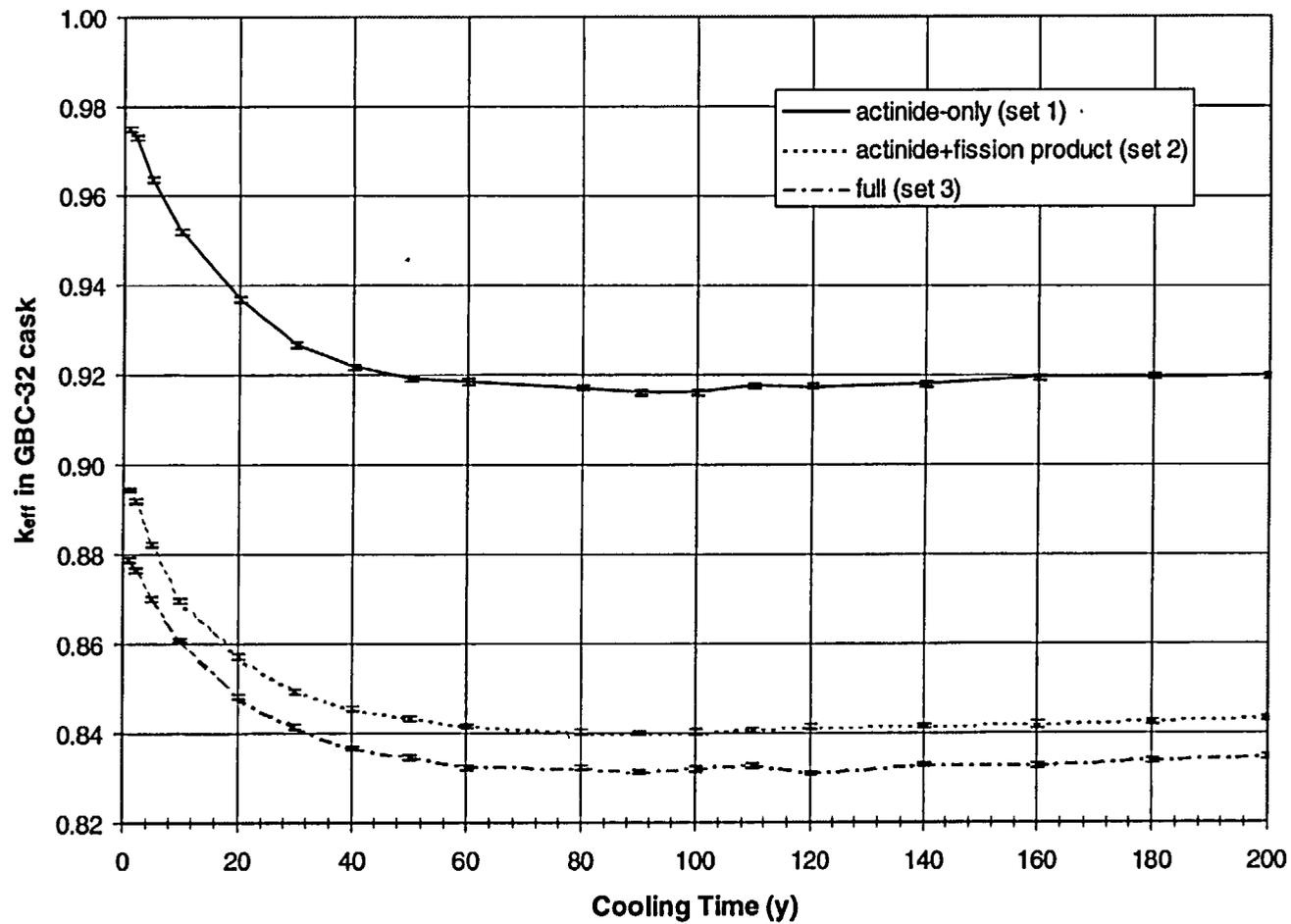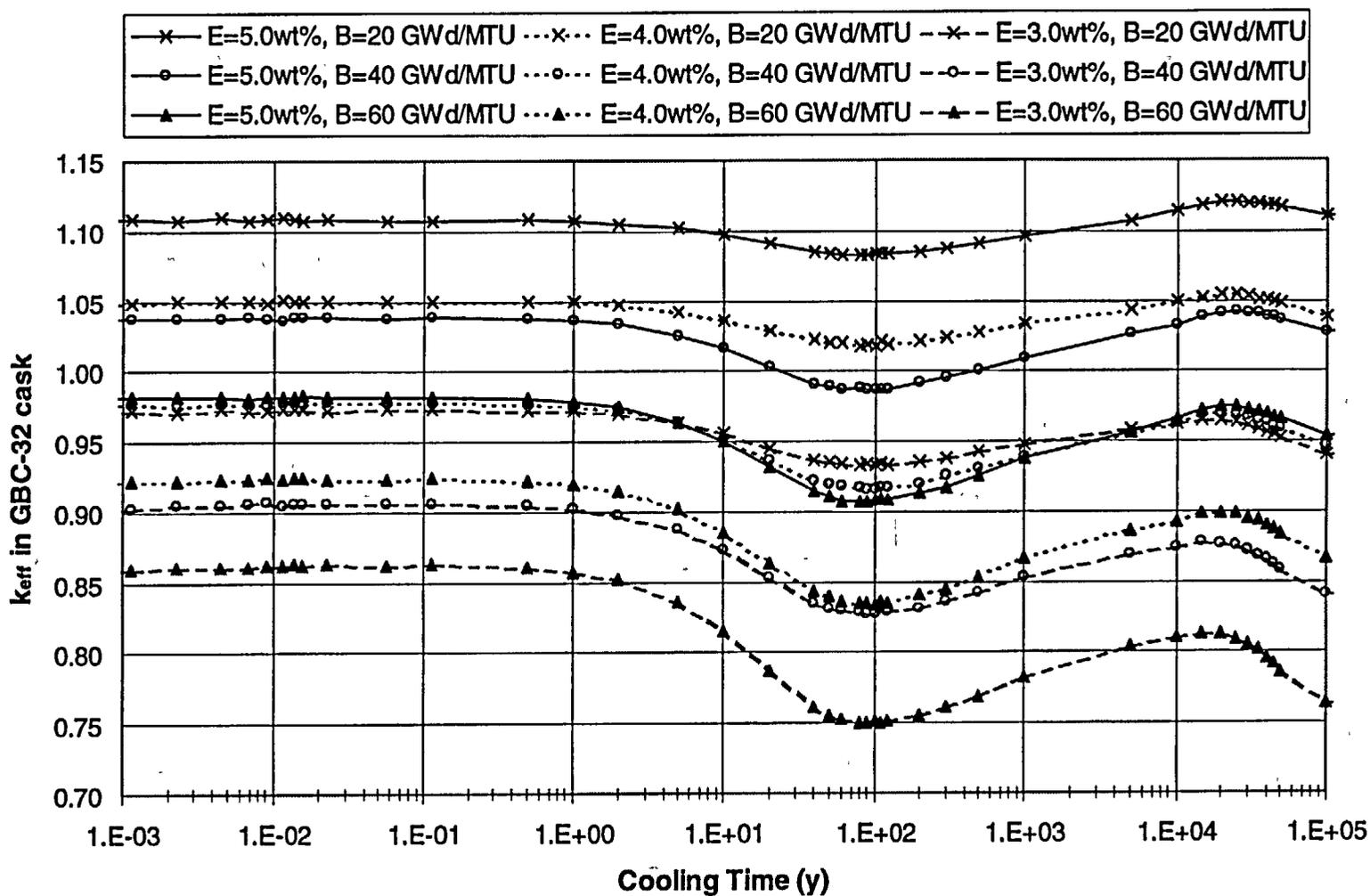Figure 10 Reactivity behavior in the GBC-32 cask with and without the axial burnup distribution as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup.

Figure 11 Reactivity behavior in the GBC-32 cask with and without the axial burnup distribution as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 60 GWd/MTU burnup.
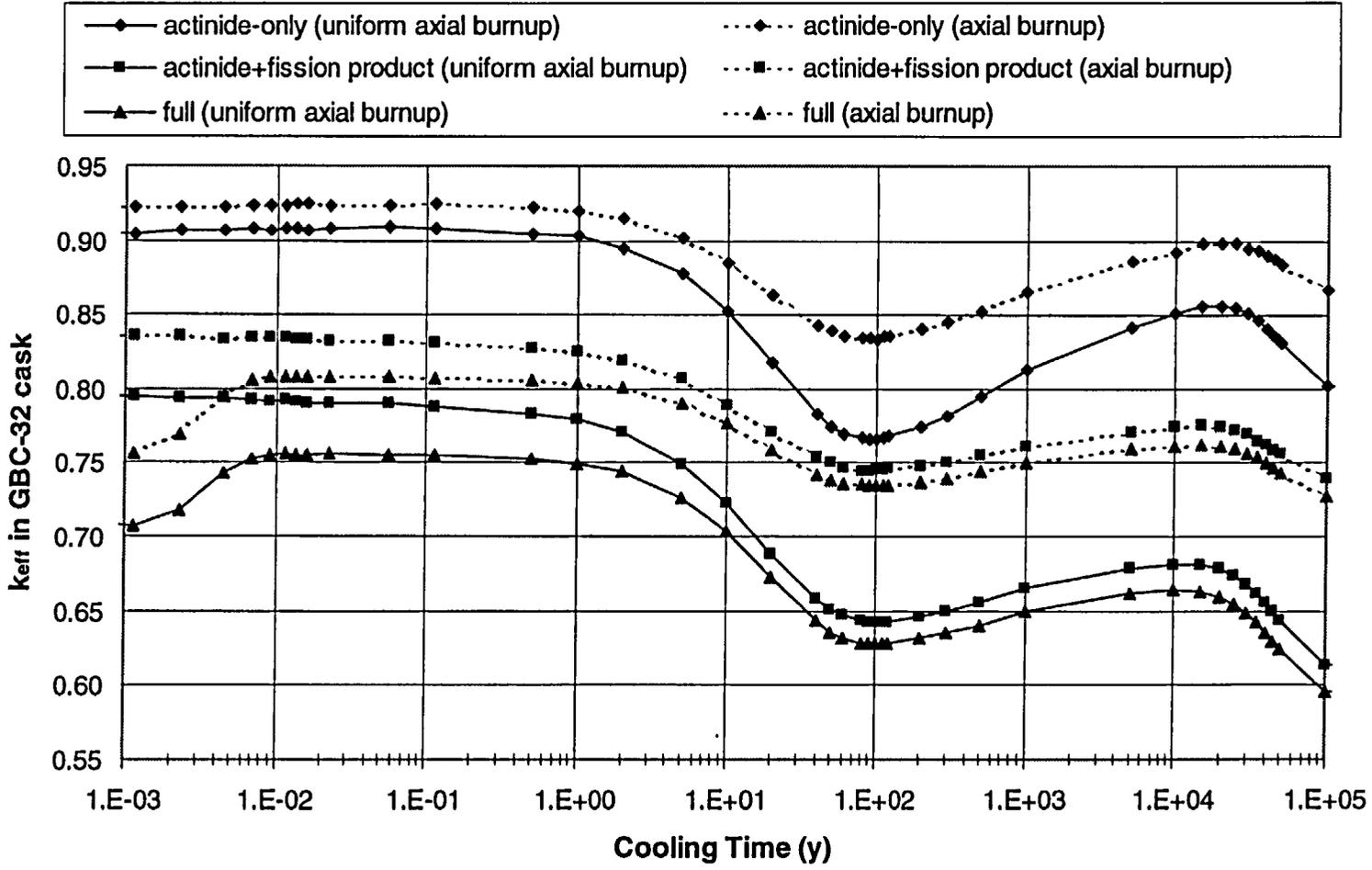
The magnitude of the reactivity decrease with cooling time from 1 to 100 years is significantly reduced by the inclusion of the axial burnup distribution. In other words, the *end effect* increases with cooling time. To demonstrate this behavior, the actinide-only *end effect* as a function of burnup for several cooling times is plotted in Figure 12 for fuel with initial enrichment of 4.0 wt % ^{235}U. The behavior is similar for other initial enrichments. The results correspond to the GBC-32 cask and 1-σ statistical uncertainties are < 0.001. Similarly, Figure 13 shows the *end effect* when fission products are included (i.e., actinide + fission product burnup credit). Finally, Figure 14 shows the *end effect* as a function of cooling time over the entire timeframe considered (i.e., 0–100,000 y) for each of the three classifications of burnup credit (i.e., actinide-only, actinide + fission product, and full). These figures illustrate the increase in the *end effect* with cooling time and that the *end effect* is greater when fission products are included. This behavior is shown here to emphasize the connection between the axial burnup distribution and cooling time and demonstrate the importance of proper representation of the axial burnup distribution when taking credit for cooling time. For simplicity, some analysts may choose to account for the *end effect* by calculating and applying a single reactivity penalty to analyses performed with uniform assembly-averaged burnup. If credit is taken for cooling time, the end effect reactivity penalty must be calculated with proper consideration of cooling time.

2.2.2 Quantification of Reactivity Reduction Due to Cooling Time

In this section, the total reduction in reactivity associated with cooling time in the GBC-32 cask is quantified for several different initial enrichment and burnup combinations with an axial burnup distribution included. The actinide-only reactivity reduction as a function of cooling time for several burnups is plotted in Figure 15 for fuel with initial enrichment of 4.0 wt % ^{235}U. Once again, the behavior is similar for other enrichments. All results correspond to the GBC-32 cask and 1-σ statistical uncertainties are < 0.001. Similarly, Figure 16 shows the reactivity reduction when fission products are included (i.e., actinide + fission product burnup credit). Although the reactivity reduction with cooling time is expected to vary somewhat with variations in cask design, these figures quantify in detail the reactivity reduction associated with cooling time in the GBC-32 cask. Figures 17 and 18 quantify the reduction in reactivity for actinide-only and actinide + fission product burnup credit for some typical initial enrichment and discharge burnup combinations. Because the decrease in reactivity during the first 100 years is primarily driven by the buildup of ^{241}Am (from decay of ^{241}Pu), the reduction in reactivity associated with cooling time in this timeframe is very similar for both the actinide-only and actinide + fission product cases. Expansion of the allowed cooling time for actinide-only burnup credit from 5 years to 40 years would allow approximately 4.0% Δk additional credit for cooling time, which can be significant in terms of increased cask capacity and/or range of fuels allowed. Expanded utilization of credit for cooling time from 5 years to 20 years will yield approximately 2.5% Δk. Since the reactivity reduction associated with cooling time decreases with decreasing fuel burnup (see Figures 15 and 16), the benefits of additional cooling time also decrease with decreasing burnup. The overall effect on loading curves (which is the most appropriate representation of the potential benefits) is illustrated for both actinide-only and actinide + fission product burnup credit in Figure 19, which contains some illustrative cooling-time dependent loading curves for the reference computational model of the GBC-32 cask described in Section 2.1. These curves are based on a k_{eff} value of 0.94 ± 0.002 and do not include: (1) criticality calculational bias and uncertainty, (2) the effect of a horizontal burnup distribution, or (3) isotopic correction factors (used to "correct" predicted isotopic compositions to that determined from comparisons with measured assay data). These curves are intended to demonstrate the potential benefits of expanding the current limitations on cooling time. For 4.0 wt % ^{235}U fuel, the actinide-only loading curves in Figure 19 show a potential reduction in required burnup of ~8 GWd/MTU with expansion of credit for cooling time from 5 years to 20 years and a reduction of 11 GWd/MTU with expansion from 5 years to 40 years. Further, the benefits increase with burnup.
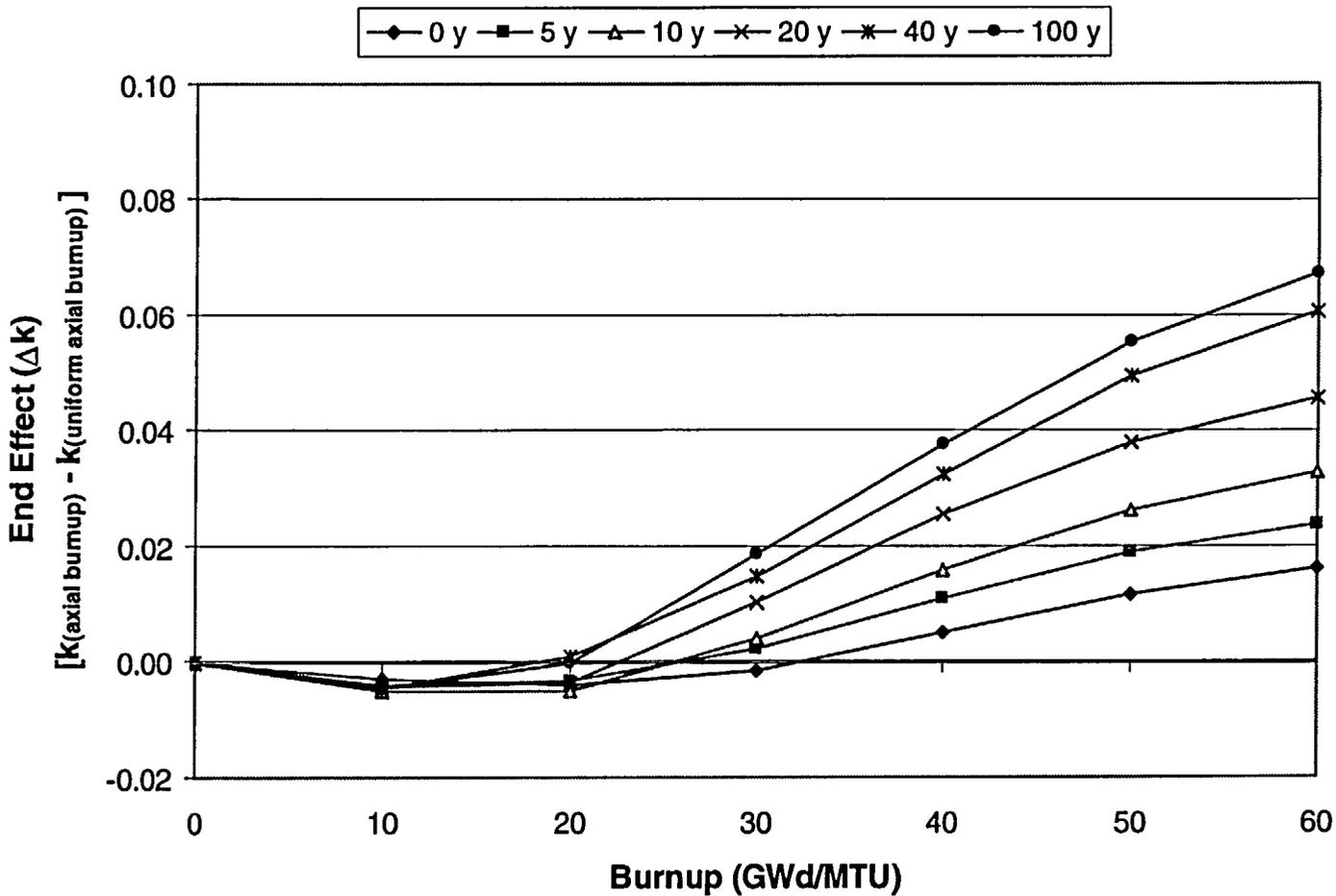
Figure 12 End effect in GBC-32 cask for actinide-only burnup credit as a function of burnup for various cooling times and an initial enrichment of 4.0 wt % [235]U. The axial burnup distribution used in the calculational model corresponds to the bounding profile suggested in Ref. 6 for PWR fuel with assembly-averaged burnup greater than 30 GWd/MTU.
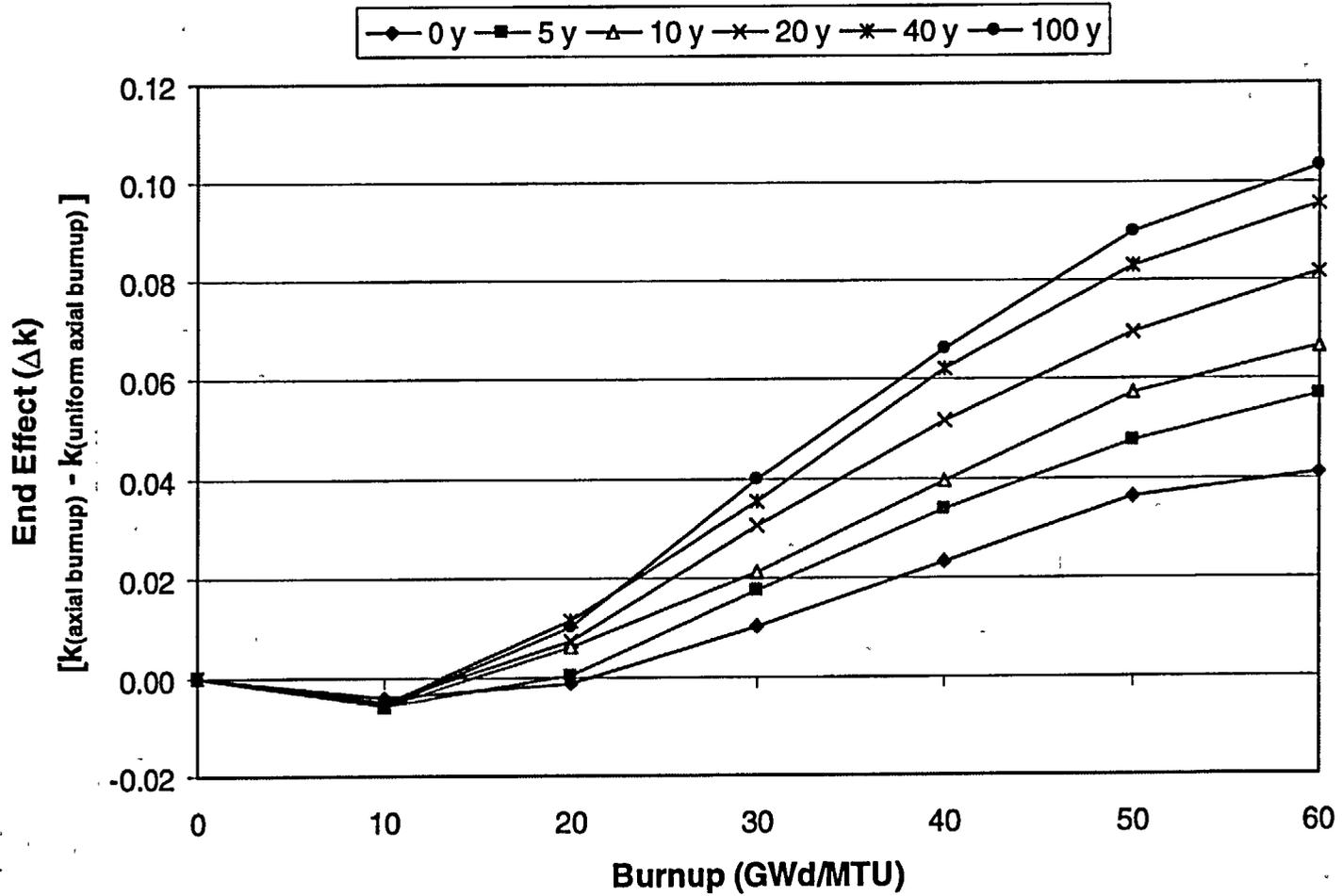
Figure 13 End effect in the GBC-32 cask for actinide + fission product burnup credit as a function of burnup for various cooling times and an initial enrichment of 4.0 wt % ^{235}U. The axial burnup distribution used in the calculational model corresponds to the bounding profile suggested in Ref. 6 for PWR fuel with assembly-averaged burnup greater than 30 GWd/MTU.
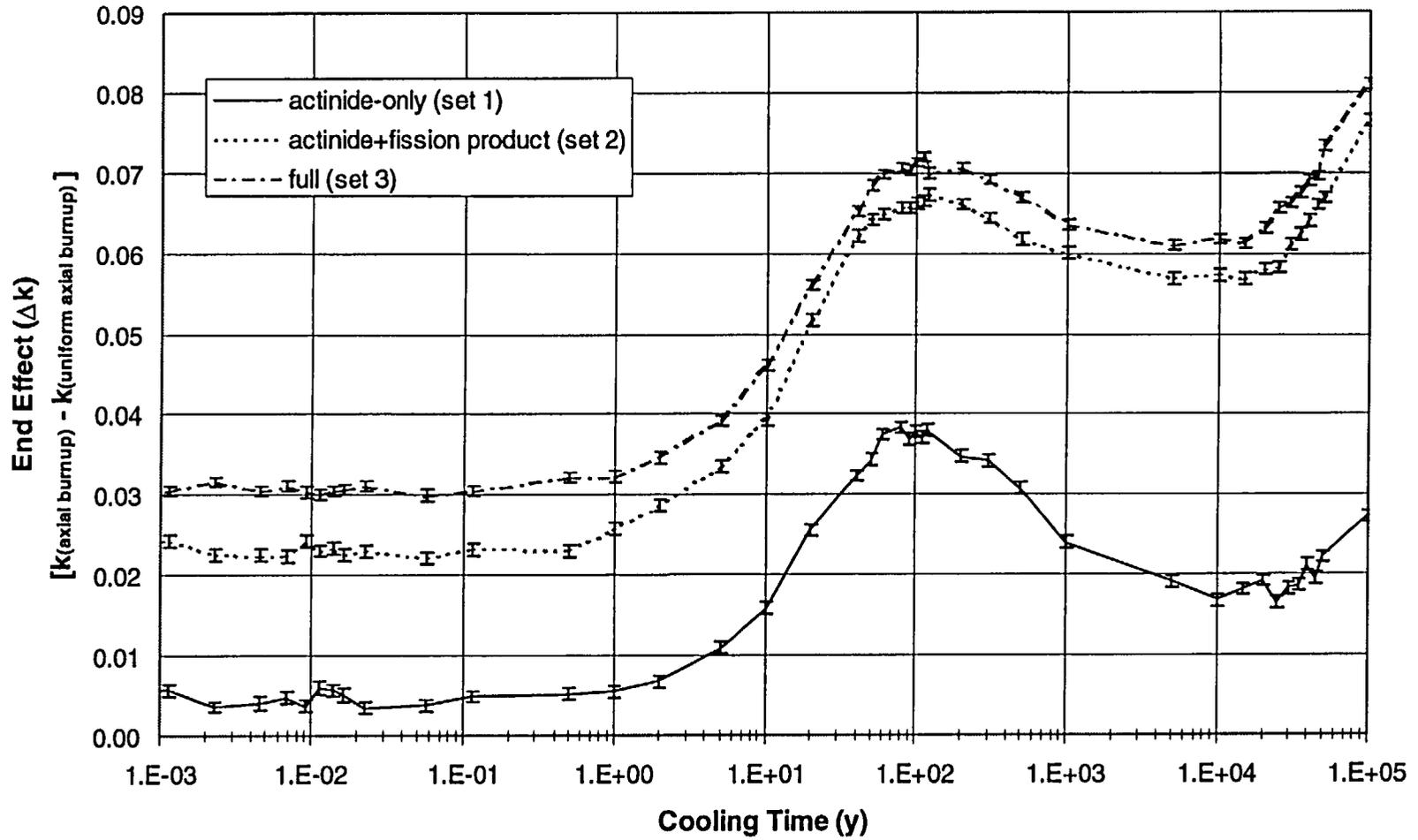
Figure 14 End effect in the GBC-32 cask as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.
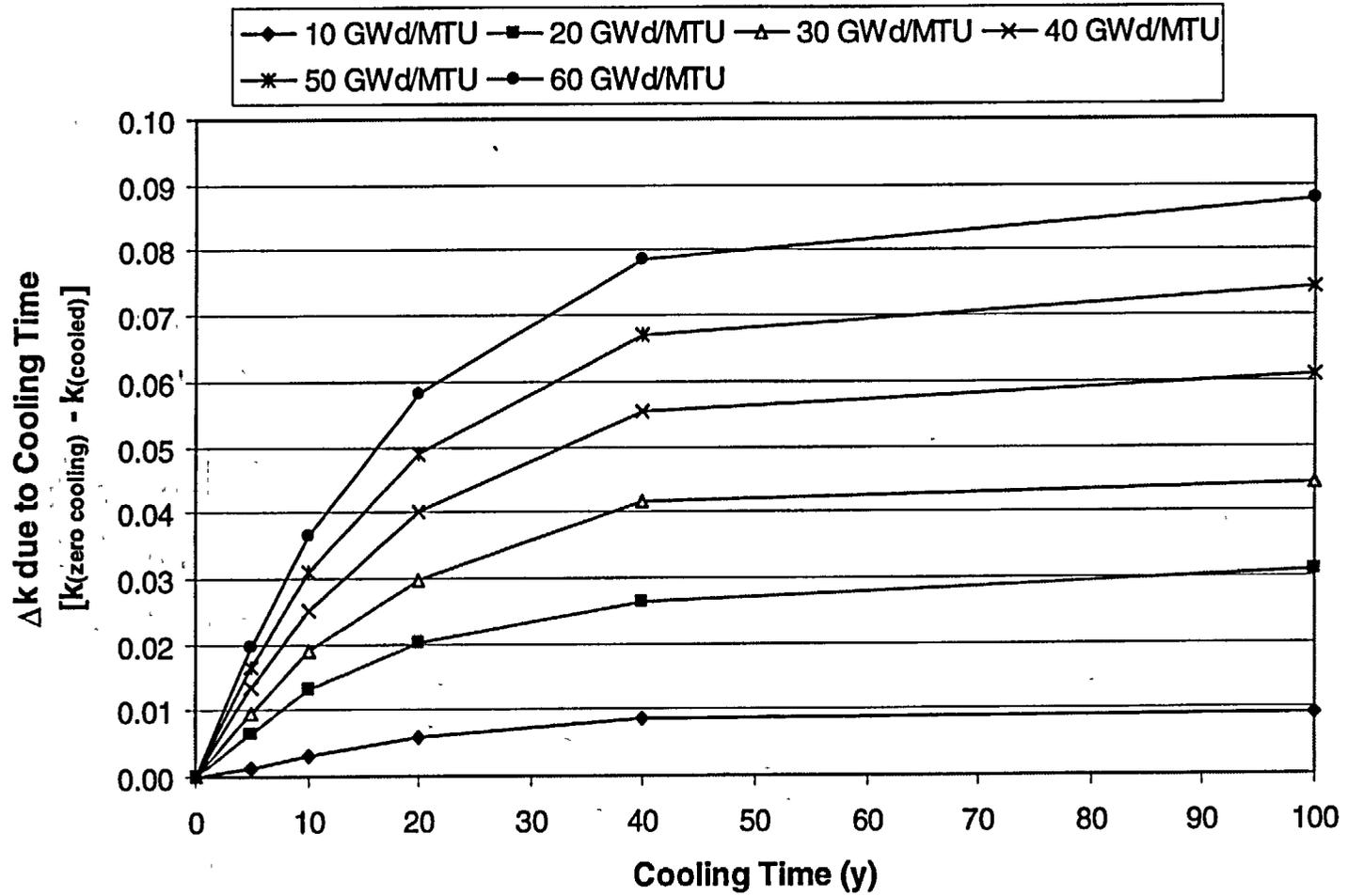
Figure 15 Reactivity reduction as a function of cooling time in the GBC-32 cask for actinide-only burnup credit, various burnups, and an initial enrichment of 4.0 wt % ^{235}U. The calculations include an axial burnup distribution as described in Section 2.1.
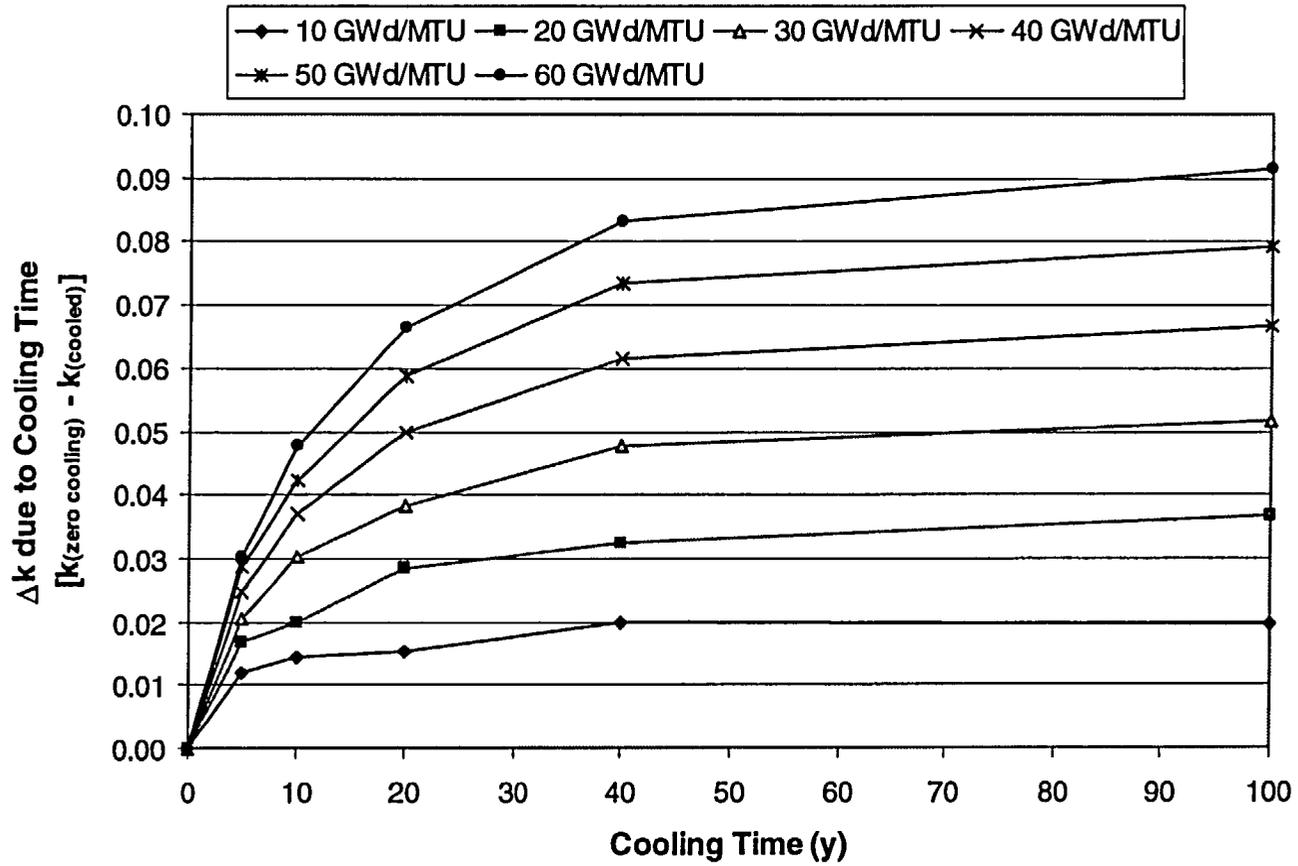
Figure 16 Reactivity reduction as a function of cooling time in the GBC-32 cask for actinide + fission product burnup credit, various burnups, and an initial enrichment of 4.0 wt % ^{235}U. The calculations include an axial burnup distribution as described in Section 2.1.
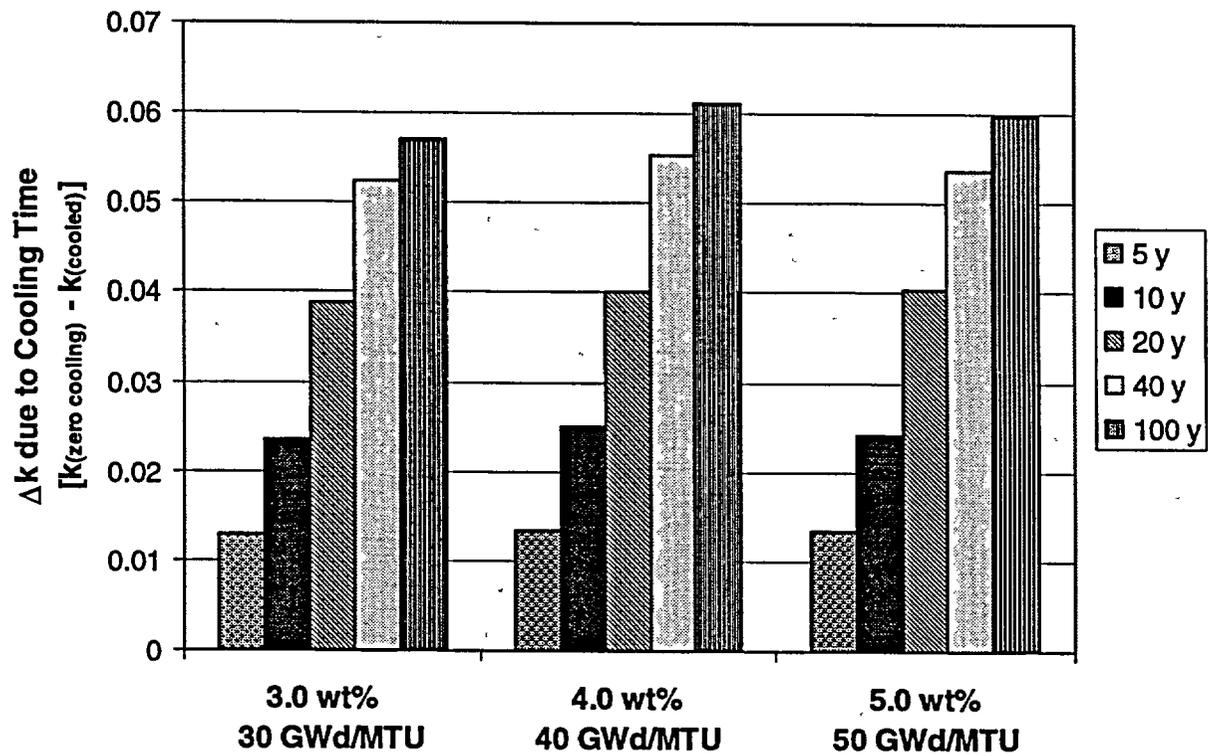
Figure 17 Reactivity reduction as a function of cooling time in the GBC-32 cask for some typical initial enrichment and discharge burnup combinations with actinide-only burnup credit. The calculations include an axial burnup distribution as described in Section 2.1.
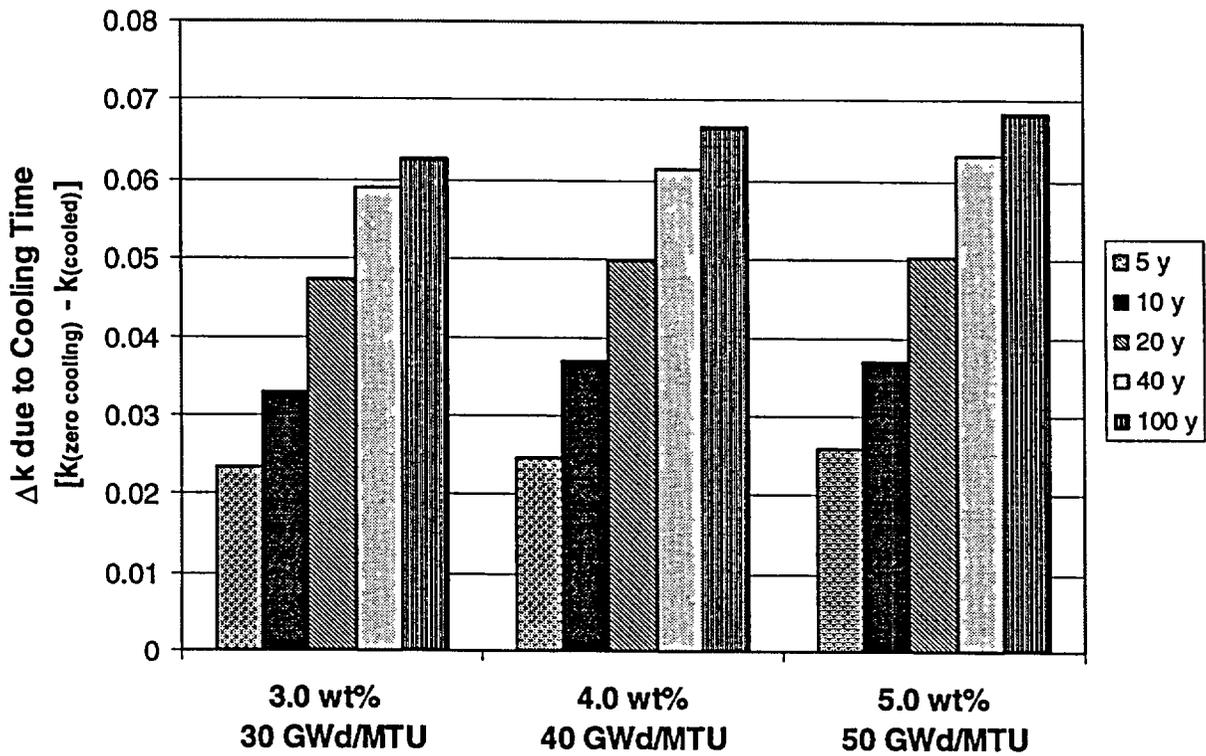
Figure 18 Reactivity reduction as a function of cooling time in the GBC-32 cask for some typical initial enrichment and discharge burnup combinations with actinide + fission product burnup credit. The calculations include an axial burnup distribution as described in Section 2.1.
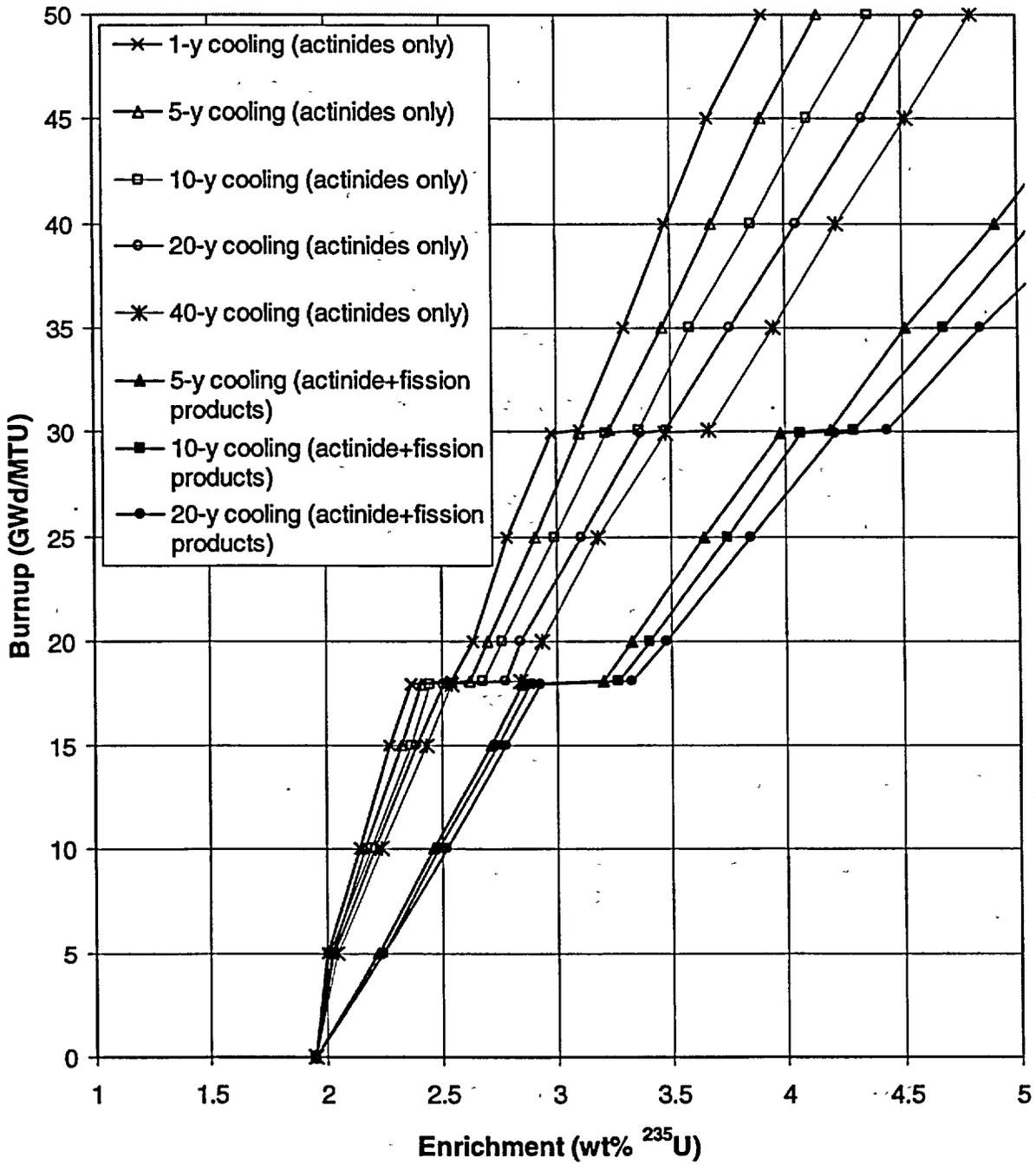
Figure 19   Illustrative cooling-time dependent loading curves for the GBC-32 cask and
actinide-only burnup credit. (These curves are based on a k_{eff} value of 0.94 and do not include:
(1) criticality calculational bias and uncertainty, (2) the effect of the horizontal burnup distribution,
or (3) isotopic correction factors. Consequently, these curves are for illustrative purposes only.)

2.2.3 Effect of Variations in Cask Design

The previous subsection quantified the reactivity reduction associated with cooling time for the GBC-32 cask. Although the reactivity behavior is not expected to vary significantly with minor variations in cask design, calculations were performed for variations in the fixed neutron poison (Boral) loading in the GBC-32 cask to verify this assertion. The ^{10}B loading was arbitrarily increased and decreased by one third. The reactivity behavior as a function of cooling time with the variations in poison loading for actinide-only burnup credit is shown in Figure 20 and the Δk values from the reference poison loading are plotted in Figure 21. The results correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and the error bars on the figure correspond to 1-σ statistical uncertainties. The reactivity reduction with cooling time is clearly insensitive to these variations in the poison loading, which represents an important cask design parameter with respect to reactivity.

2.3 ANALYSES WITH A TRUCK-TYPE CASK

In this section, the effect of out-of-reactor cooling time on reactivity for SNF loaded in a truck-type cask is briefly examined. For this analysis, the General Atomics 4-PWR assembly (GA-4) cask was used. A physical description of the cask is provided in Refs. 12 and 13. The GA-4 cask model is loaded with WE 17 × 17 OFA assemblies.

The k_{eff} values as a function of cooling time for the three classifications of burnup credit (i.e., actinide-only, actinide + fission product, and full), defined in Table 1, are shown in Figure 22. The results correspond to fuel with an initial enrichment and discharge burnup combination of 4.0 wt % ^{235}U and 40 GWd/MTU, which is a fairly representative enrichment and burnup combination for typical discharged SNF.[14] The effect of cooling time on k_{eff} values for various burnup values is shown for actinide-only burnup credit in Figure 23. The relative behavior is consistent with that exhibited in the previous sections for the GBC-32 cask. Also, the actual reactivity reduction is very similar to, but slightly less than, that shown for the GBC-32 cask.

Relative to the suggested cooling time of five-years,[23] Figure 24 shows Δk values as a function of cooling time for the three classifications of burnup credit for the initial enrichment and discharge burnup combination of 4.0 wt % ^{235}U and 40 GWd/MTU. Finally, to highlight the differences in k_{eff} values associated with the different nuclides sets, Figure 25 shows Δk values corresponding to different nuclide sets considered (defined in Table 1) as a function of cooling time. The results in Figures 24 and 25 may be directly compared to the results for the GBC-32 cask in Figures 8 and 9.

Truck-type casks generally have significantly greater leakage than high-capacity rail-type casks like the GBC-32, and thus may accommodate more reactive fuel assemblies. Therefore, for a given initial enrichment, the minimum burnup required for loading in a truck-type cask is expected to be less than that required for loading in a high-capacity rail-type cask. Consequently, credit for cooling time will have slightly less benefit for truck-type casks than for high-capacity rail-type casks.
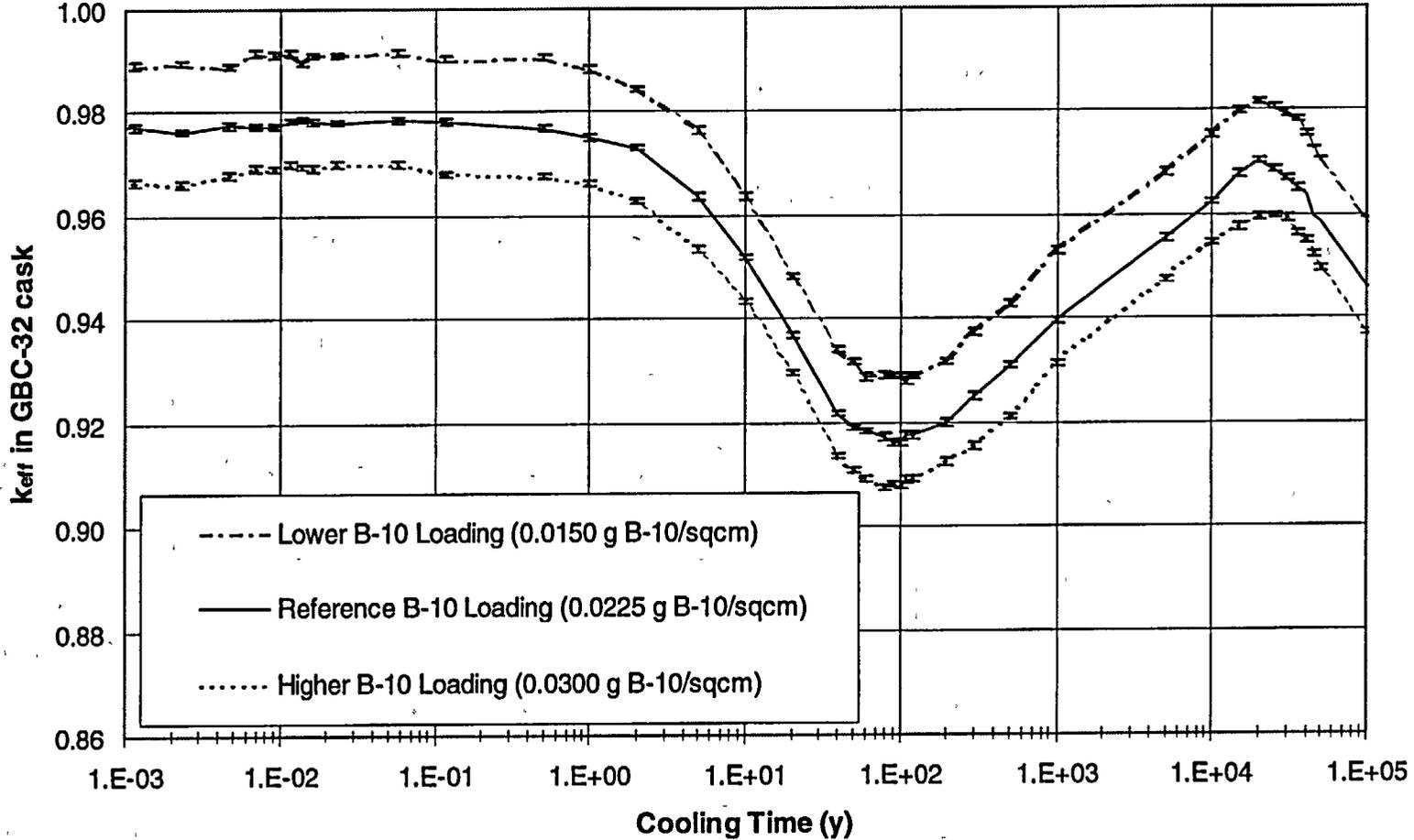
Figure 20 Reactivity behavior for actinide-only burnup credit as a function of cooling time for variations in the neutron poison loading in the GBC-32 cask. The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.
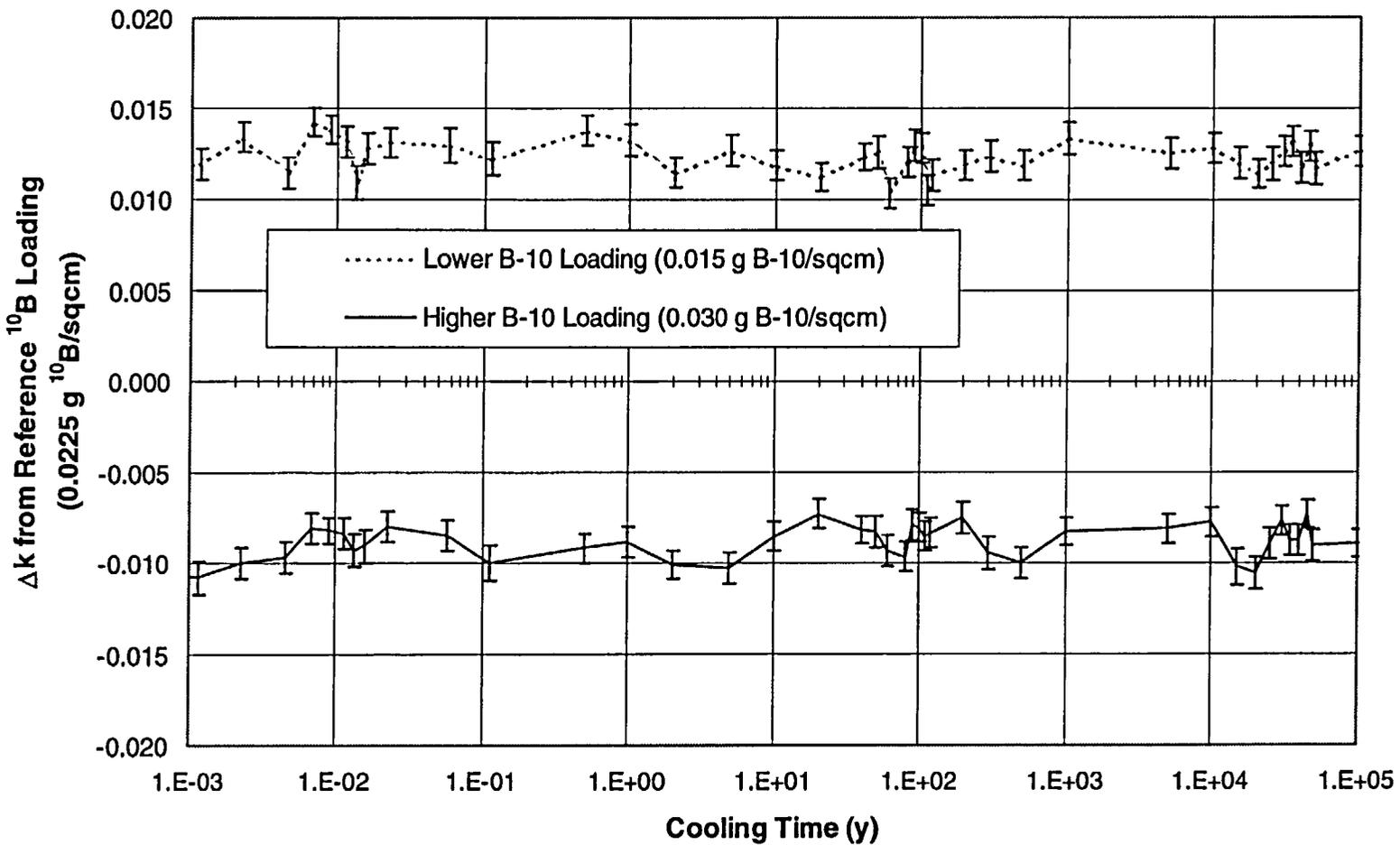
Figure 21 Δk values in the GBC-32 cask corresponding to differences in the poison loading as a function of cooling time. The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.
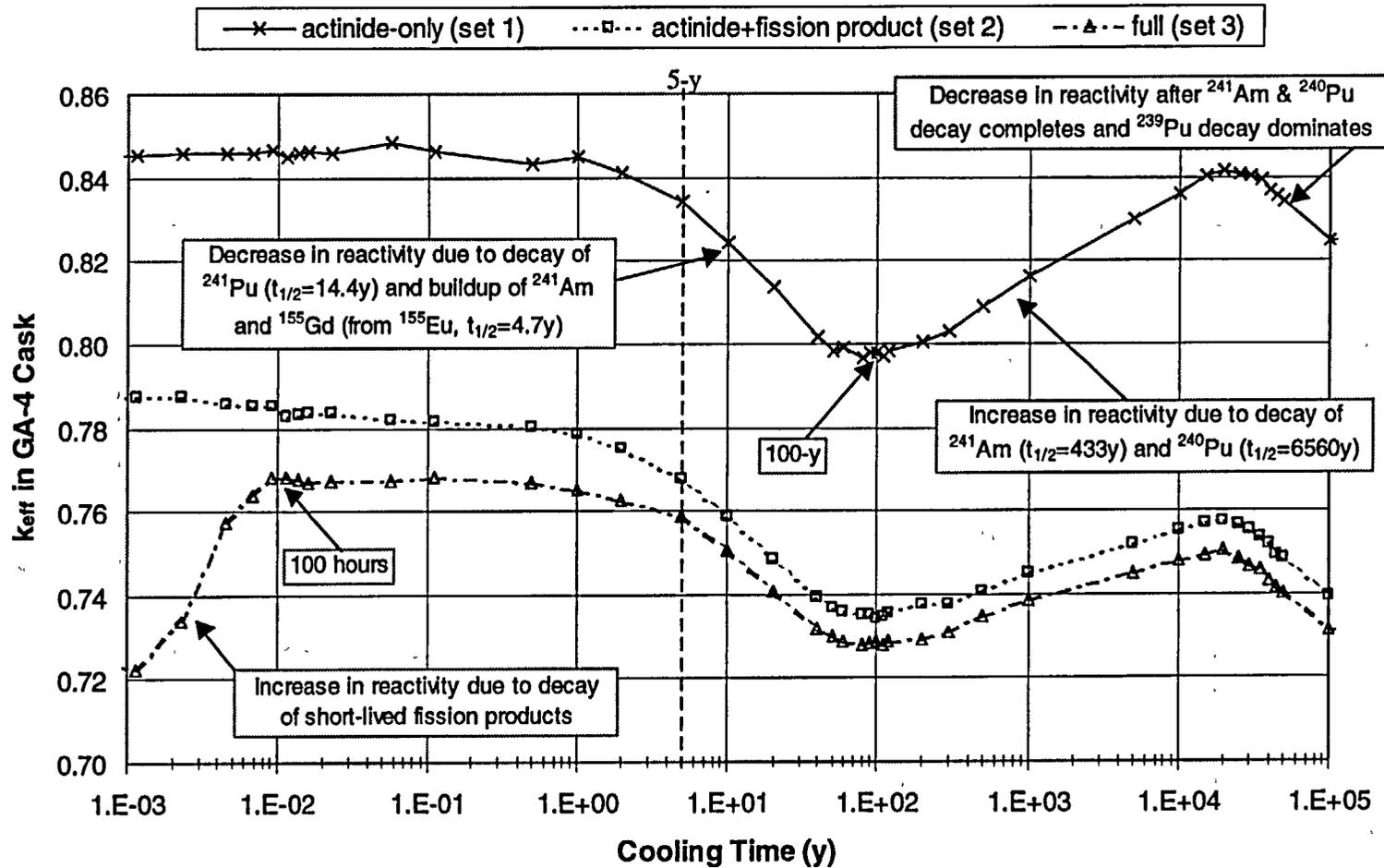
Figure 22 Reactivity behavior in the GA-4 cask as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.
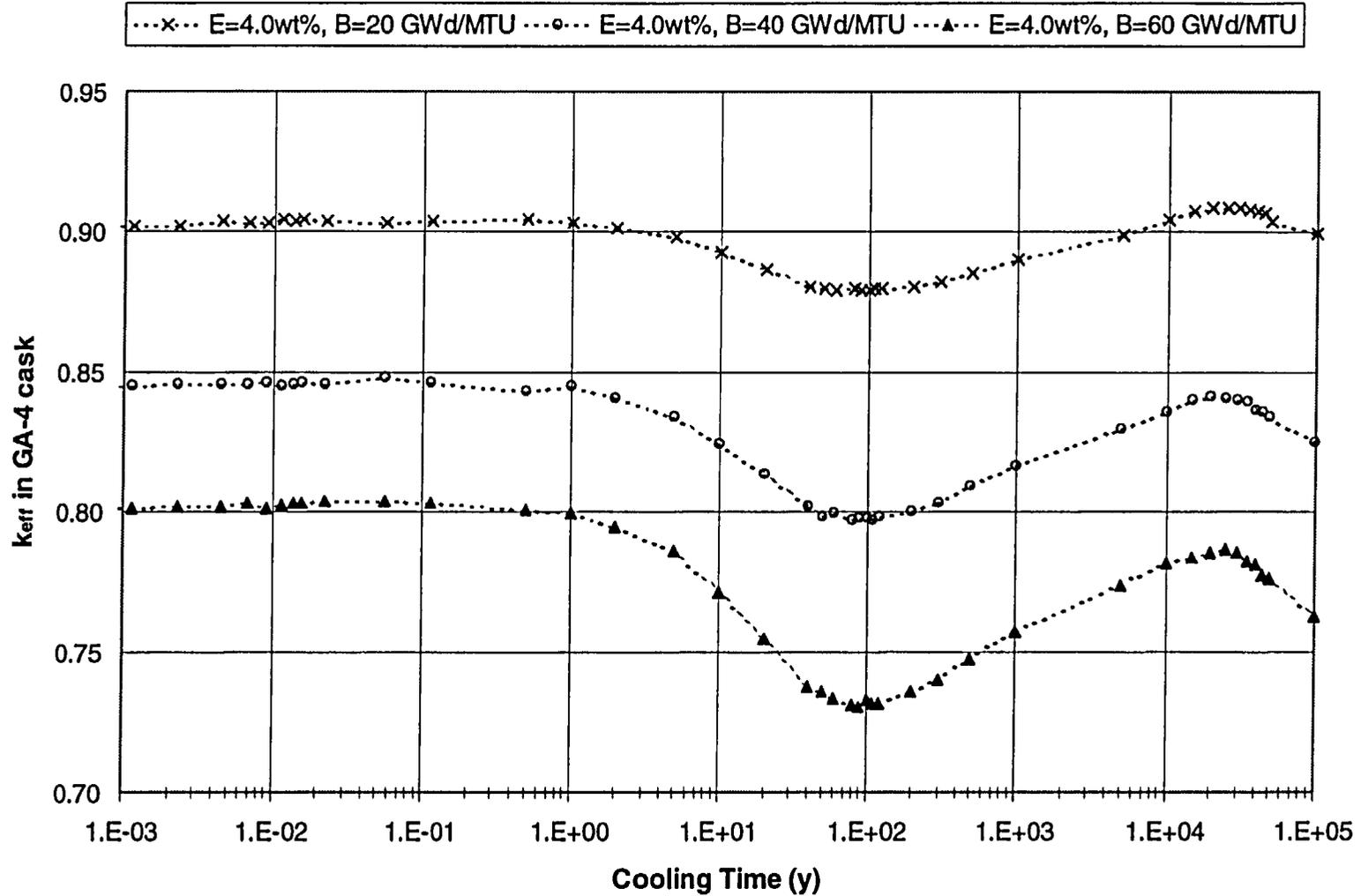
Figure 23 Reactivity behavior in the GA-4 cask as a function of cooling time for actinide-only burnup credit. The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment and include an axial burnup distribution as described in Section 2.1.
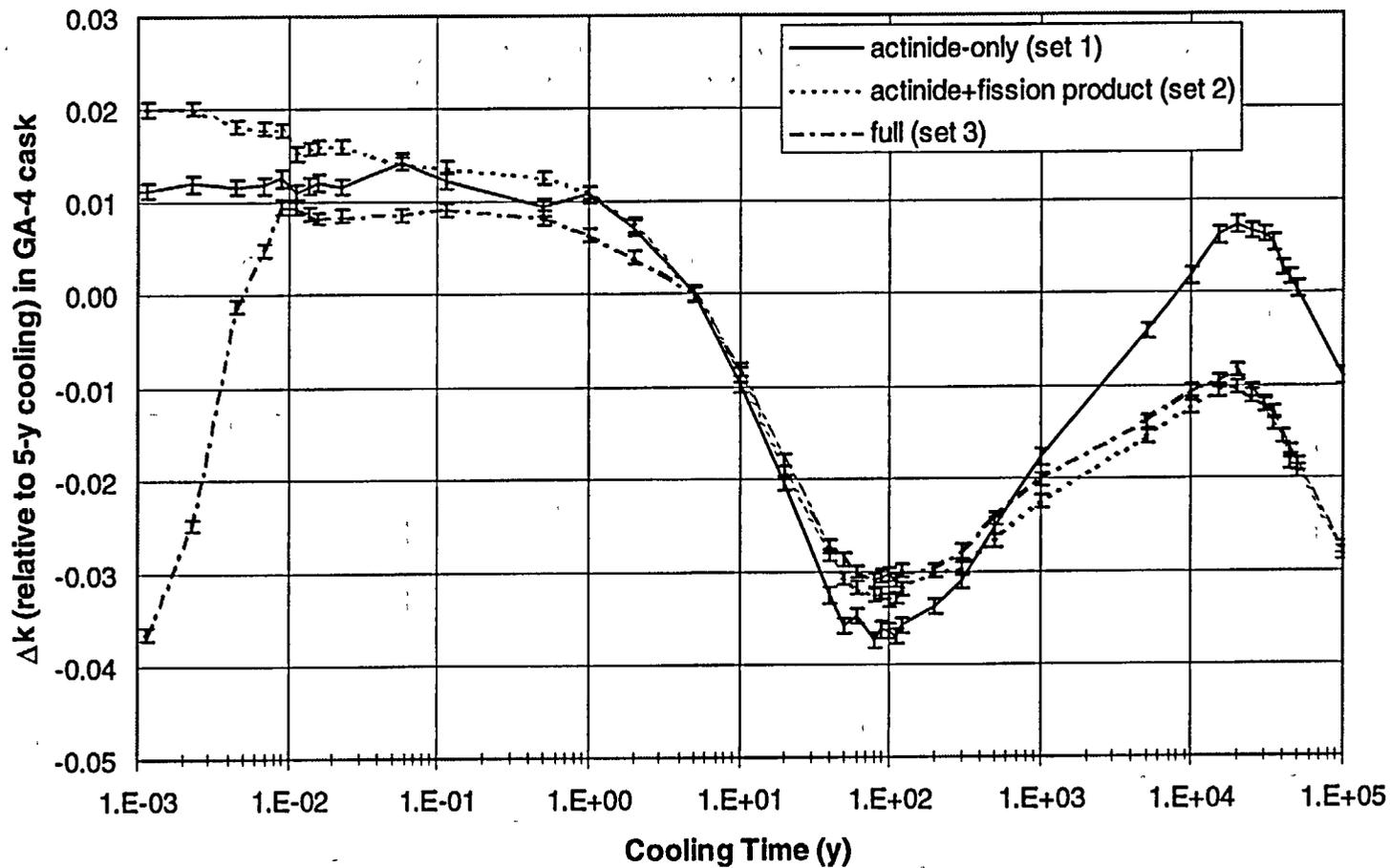
Figure 24 Δk values in the GA-4 cask relative to the suggested five-year cooling time, as a function of cooling time for the three classifications of burnup credit (defined in Table 1). The calculations correspond to fuel with 4.0 wt % [235]U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.
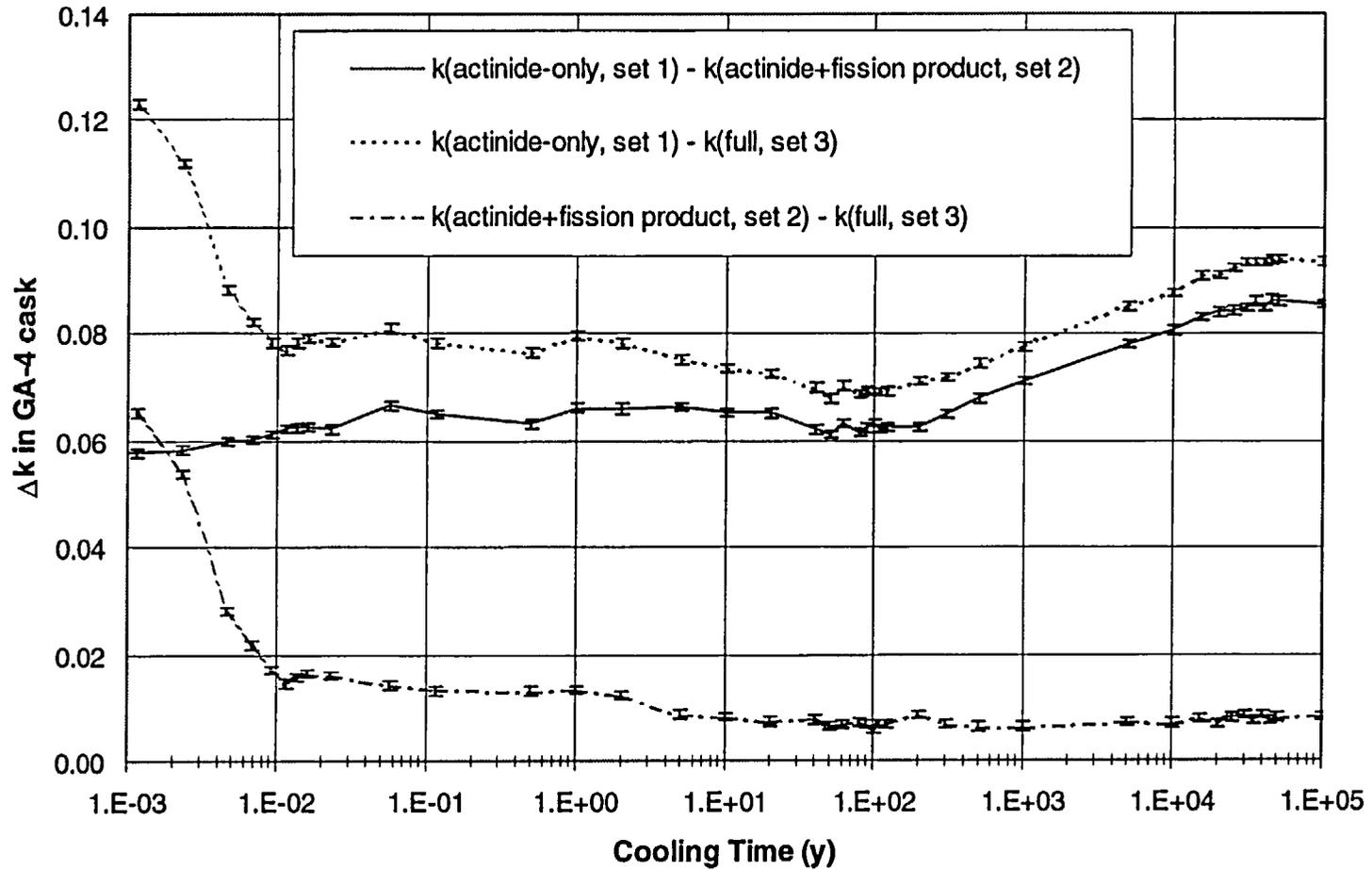
Figure 25 Δk values in the GA-4 cask corresponding to differences in the various nuclide sets (defined in Table 1). The calculations correspond to fuel with 4.0 wt % ^{235}U initial enrichment that has accumulated 40 GWd/MTU burnup, and include an axial burnup distribution as described in Section 2.1.

3 DISCUSSION AND IMPLICATIONS

The information and figures in Section 2 demonstrate that it is not straightforward to select a practical, yet bounding value for the cooling time in a safety evaluation that includes burnup credit. Based on the results presented for full burnup credit, it can be observed that a fixed five-year cooling time provides a conservative reactivity relative to that of longer cooling times except for SNF with low burnup beyond ~10,000 years. Also, the five-year cooling time is not bounding relative to the reactivity of shorter cooling times. Thus, as Figure 3 indicates, it appears best to select a timeframe of interest for the application and develop criteria that provide for implementation within the given timeframe. This section discusses the issues associated with selection of a timeframe of interest and considerations for allowing multiple cooling times in the burnup-credit safety analysis.

Although the timeframe of interest for dry storage and transportation is not well defined, it is generally assumed to be between 1 and 200 years. Storage and transportation systems are currently licensed for periods of 20 years, and thus, 200 years represents 10 license periods (i.e., the initial license followed by 9 license renewals). Considering typical plant-life expectations (on the order of 40–60 years) and that SNF may reside in a SFP for a short period of time after final reactor shutdown (probably less than 10 years), it is expected that fuel loaded into dry storage and transportation casks will have cooling times less than 50 years. Therefore, credit for cooling time beyond 50 years does not seem to be of any direct benefit for current storage and transportation analyses. Furthermore, Figures 15–18 indicate that there is little reactivity credit to be gained from consideration of cooling times beyond 50 years. However, referring back to the 200-year timeframe assumed for dry cask storage and transportation, the results of Section 2 indicate that burnup credit for cooling times out to 50 years can potentially present some long-term concerns if the SNF remains in dry storage long enough for the reactivity to rise above the reactivity associated with the cooling time used in the safety analysis. However, the results of Section 2 indicate that for all three classes of burnup credit the reactivity remains below the 40-year level for all cooling times greater than 40 years and less than 200 years. A limit of 40 years also corresponds well to the 50-year maximum cooling time proposed above based on practical benefits related to dry storage and transportation casks. A similar argument (with conservatism added) led to the maximum cooling time limit of 25 years suggested in a DOE Topical Report on actinide-only burnup credit.[6]

Thus, assuming a practical lifetime of 200 years for dry storage, the technical information discussed above indicates that the cooling time to use in burnup credit evaluations should be between 1 and 40 years. An important point to note is that the uncertainty associated with reactivity changes due to cooling time in the 1 to 40 year time period should be very small because decay data for the nuclides important to changes in this time period are very accurate.[17]

The increase in the number of loading curves due to the use of multiple cooling times will result in increased complexity in the cask loading procedures and corresponding complication in the administrative controls. Administrative procedures to confirm cooling time during cask loading and ensure proper use of loading curves will need to be developed for use with burnup credit. However, if the regulatory guidance recommendations are expanded to allow multiple cooling times, each cask license may contain a separate loading curve for each time of interest. Current loading procedures have limits on the following parameters: initial enrichment, burnup and cooling time (for shielding and decay heat considerations), and assembly design. In addition to the current limits, loading procedures for burnup credit casks will necessarily include loading (burnup-enrichment) curves that may be assembly dependent and procedures for verification of accumulated burnup. To provide some bound to this increased complexity, it may be prudent to place a limit on the total number of cooling times considered. For example, a limit of 4 curves would still enable an applicant to develop loading curves that span the portion of the curve corresponding to the greatest change in reactivity (e.g., loading curves at 1, 5, 10, and 20 years).

The limit on cooling time allowance hinges on the timeframe of interest. Should it be considered plausible that some unanticipated scenario might cause SNF to remain in a dry storage cask beyond the 200 years assumed here, then the cooling time allowance may need to be reconsidered based on the class of burnup credit allowed. For actinide-only burnup credit, Figure 1 shows that the absolute minimum reactivity as a function of time is always greater than the absolute maximum reactivity as estimated by both full and actinide + fission product burnup credit. Thus, storage casks licensed with actinide-only assumptions (consistent with the current regulatory recommendations) would have sufficient subcritical margin to accommodate storage beyond the 200-year timeframe. However, if cask licensing is based on actinide + fission products, this subcritical margin is no longer available and one must consider whether the risk of storage beyond 200 years warrants limiting the cooling time credit to a value less than 40 years. For example, a limit of 10 years based on the observation that, except for SNF that is highly under-burned (e.g., 5.0 wt %, 20 GWd/MTU), the best-estimate results for k_{eff} at 10-year cooling are always greater than the maximum k_{eff} in the secondary peak (10,000- to 30,000-year timeframe).

Existing cask designs, which utilize flux-traps, may accommodate SNF with initial enrichments up to approximately 4.0 wt % ^{235}U. In order to expand the upper-enrichment limit, cask vendors may seek burnup credit for these existing cask designs. To maintain the subcritical margin for enrichments up to 5.0 wt % ^{235}U, these applications would require modest credit for burnup, and thus would not benefit greatly from credit for cooling time (in terms of reactivity reduction). However, the thermal and/or shielding characteristics for these casks may benefit from the use of shorter cooling times (i.e., less than 5 years) through the use of preferential loading strategies.

A final issue for discussion is the sensitivity of the reactivity reduction associated with cooling time to the axial burnup distribution. Figures 10 and 11 demonstrate that the reactivity reduction associated with cooling time is overestimated when uniform axial burnup is assumed in the calculational model. Therefore, a burnup-credit safety analysis must properly account for the effect of the axial burnup distribution with cooling time. Initial studies suggest that bounding axial burnup profiles are insensitive to cooling time; hence, a bounding axial burnup profile for one cooling time is expected to be bounding for all cooling times within the timeframe relevant to cask storage and transportation.

4 RECOMMENDATIONS

For burnup credit criticality safety analyses, increasing the cooling time of the SNF beyond five years results in an increasing conservative safety margin out to approximately 100 years. The magnitude of the conservatism depends on the initial enrichment and discharge burnup of the fuel. Additional conservatism may be added by basing calculated isotopic compositions on a shorter assumed cooling time period (e.g., cooling periods as short as one year). However, there is no apparent justification for the additional conservatism as the reduction in reactivity associated with cooling time in the range of 1 to 100 years is well understood. Therefore, it is recommended that the current regulatory guidance be revised to allow cooling times other than five years.

The analyses and discussions presented in this report provide a technical basis for revising the current regulatory guidance (Refs. 2, 3) to allow burnup credit for cooling times between 1 and 40 years. Further, the analysis shows that allowance for cooling times outside of the 1 to 40 year range does not yield significant benefits. The number of individual cooling times allowed should be limited until such time as need for more cooling times values is demonstrated and/or the procedural process has sufficiently matured.

The above recommendations are made for actinide-only burnup credit assuming a practical cask lifetime of 200 years. If SNF loaded with an assumed cooling time of 40 years remains in the cask beyond the 200-year timeframe, then the potential may exist for a reactivity increase beyond that allowed in the safety assessment. A study of the reactivity margin provided by the conservative actinide-only assumption could be used to dispense with this concern. To address this concern and lay a consistent foundation that enables future extension beyond the actinide-only assumption, the allowed maximum cooling time could be reduced to about 10 years. The rationale is that, except for SNF that is highly under-burned (e.g., 5.0 wt %, 20 GWd/MTU), the best-estimate results for k_{eff} at a 10-year cooling time are always greater than the maximum k_{eff} in the secondary peak (10,000- to 30,000-year timeframe). Finally, a lower limit on cooling time will continue to be dictated by thermal and shielding requirements.

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2. TITLE AND SUBTITLE

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in PWR Burnup Credit Analyses

5. AUTHOR(S)

J. C. Wagner and C. V. Parks

8. PERFORMING ORGANIZATION — NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Oak Ridge National Laboratory, Managed by UT-Battelle, LLC
PO Box 2008, Bldg. 6011, MS-6370
Oak Ridge, TN 37831-6370 USA

11. ABSTRACT *(200 words or less)*

The U.S. Nuclear Regulatory Commission's guidance on burnup credit for pressurized-water-reactor spent nuclear fuel (SNF) recommends that analyses be based on a cooling time of five years. This recommendation eliminates assemblies with shorter cooling times from cask loading and limits the allowable credit for reactivity reduction associated with cooling time. This report examines reactivity behavior as a function of cooling time to assess the possibility of expanding the current cooling time recommendation for SNF storage and transportation. The effect of cooling time on reactivity for various initial enrichments, burnups, and selected nuclide sets is shown and discussed. Further, the benefits of additional credit for cooling time are quantified based on a realistic high-capacity rail-type cask designed for burnup credit. While this report is primarily focused on cask storage and transportation, analyses are extended out to 100,000 years to understand the relevant concerns associated with long-term disposal and their possible influence on storage and transportation practice. The report concludes with a discussion on the issues for consideration and recommendations for expanded allowance of credit for cooling time in criticality safety analyses using burnup credit for cask storage and transportation.

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

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

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