Appendix 6.E

Burnup Credit in the MPC-32

6.E.0 Introduction

Two principal MPC basket designs are used for PWR fuel, the MPC-24 and MPC-32, providing space for 24 and 32 fuel assemblies, respectively. The MPC-24 contains flux traps (water gaps with neutron poison panels on each side), which significantly reduce the neutronic coupling between adjacent fuel assemblies when the MPC is flooded with water. Due to these flux traps, fresh fuel assemblies with enrichments between 4.0 and 5.0 % enrichment (depending on the assembly type) can be loaded into the MPC-24 without exceeding the regulatory limit on reactivity. In the high density MPC-32 there is only a single neutron poison panel between two adjacent fuel assemblies, and no water gap. The reactivity of the MPC-32 is therefore higher than the reactivity of the MPC-24 for the same fuel, and additional measures are necessary to ensure the reactivity of the MPC-32 is below the regulatory limit when the MPC is flooded. However, it is desirable to use the MPC-32 instead of the MPC-24 whenever possible, since this will result in a reduced dose to the general public and the plant personnel. This is a result of the increased self shielding of assemblies inside the basket in the MPC-32, and the reduced number of loading and transport campaigns for the MPC-32 compared to the MPC-24.

After being loaded, the MPC is a seal welded enclosure for the fuel basket and its contents, and is designed in accordance with the ASME codes for pressure vessels. The evaluations documented in Chapter 2, Section 2.7 demonstrate that there is no credible event or accident which would result in a breach of the boundary to allow water to enter the MPC. Therefore even under accident conditions the MPC cavity remains dry and the reactivity is below the regulatory limit by a large safety margin, with a typical k_{eff} for a dry system of less than 0.5. However, no application is made to exclude the potential presence of water in the MPC. Instead, water is assumed to be present in the MPC for the criticality evaluations, in accordance with 10CFR71.55(b), and it is shown that the reduction in reactivity due to the burnup of the fuel is sufficient to ensure that the reactivity does not exceed the regulatory limit even under this postulated condition. The result of the evaluation is a minimum burnup requirement as a function of initial enrichment to ensure criticality safety.

The NRC Interim Staff Guidance (ISG) 8, Rev. 2 [6.E.1] permits the use of burnup credit to qualify PWR assemblies for transportation in a spent fuel cask. The ISG 8 recommends a number of requirements and restrictions that have to be fulfilled and applied when evaluating burnup credit. Figure 6.E.1 shows burnups and enrichments of WE 17x17 assemblies [6.E.26], including a 5% burnup uncertainty, together with limiting burnup curves from burnup credit calculations. The dashed line in this figure represents the minimum burnup requirement based on scoping calculations for the MPC-32 performed in strict compliance with ISG 8. Due to the limitations in ISG 8 regarding burnup and isotope selection, only about 27% of the unloaded assemblies would qualify for transport in the MPC-32, predominantly assemblies with lower enrichments. This is not sufficient to make effective use of the advantages of the MPC-32. Note that the reactivity control incorporated into the MPC-32 basket in the form of neutron poison plates is already at the highest possible level and can therefore not be improved any further. The burnup credit methodology presented here generally follows the recommendations of ISG 8. However, in some areas, where it was deemed necessary in order to achieve the designated goal of making effective use of the MPC-32, the methodology uses alternative or additional methods. Subsection 6.E.7 provides a comparison between the analyses provided here and the ISG-8. It references the applicable subsection of this appendix for each of the requirements and restrictions. When alternatives are used, it provides the motivation and justification for the approach taken. The resulting minimum burnup requirement is shown in Figure 6.E.1 as a solid line for assemblies not exposed to control rod insertion during full power operation. For this condition, about 50% of the assemblies are qualified for transportation in the MPC-32 using the methodologies presented here. For assemblies potentially exposed to full control rod insertion during full power operation, burnup requirements are higher. For such assemblies, the percentage of qualifying assemblies could be as low as 30%. These are lower bound number due to the substantial conservatisms in the methodology. Future developments are expected to increase these percentages significantly (see also Section 6.E.6 and Section 6.E.9)

The following is a brief summary of the burnup credit methodology and evaluation.

For a selected number of fuel assembly classes, depletion calculations are performed, which establish the isotopic composition of the fuel as a function of the fuel burnup and initial enrichment. CASMO-4 is used as the depletion code. The depletion calculations assume plant operation conditions that are conservative in respect to the reactivity of the fuel. Also, the presence of inserts such as burnable poison rods or control rods in the assembly during depletion is considered in a conservative way. The isotopic compositions are then used in the criticality calculations to model the depleted fuel assemblies. Each assembly is modeled with 18 axial sections to account for the effect of the axial burnup distribution in the fuel assemblies. The criticality code used in the analyses is MCNP4a. Throughout the calculation, biases are applied to the results of the depletion calculations and criticality calculations, to ensure the overall results are valid and conservative. The biases are established based on benchmark calculations, i.e. on comparisons of calculations and measurements. Three sets of benchmark calculations are used in the evaluation, a set of isotopic benchmarks to validate the depletion calculations, a set of criticality benchmarks, and a set of reactor critical benchmarks. The results of the criticality calculations are evaluated, and for each assembly type, enrichment level, and various control rod insertion considerations, the minimum burnup is established that is required to ensure that the reactivity of the loaded cask is below the regulatory limit of 0.95. In addition to the design basis calculations, i.e. the calculations to determine the loading curves, numerous studies are performed to demonstrate that the design basis calculations are conservative. The resulting minimum burnups as a function of the initial fuel enrichment, specified as polynomial functions, are shown in Table 6.E.1. The four configurations A through D shown in the table refer to control rod considerations that are described in detail in Section 6.E.2.2.

The overall process of establishing burnup credit for the MPC-32 can be broadly divided into six distinct tasks, some of them with a number of subtasks. The tasks and subtasks, together with the corresponding section number where the task is described, are listed below.

1. Fuel Assembly Specifications (6.E.1)
    a. Assembly Types (6.E.1.1)
    b. Enrichments, Burnups and Cooling Times (6.E.1.2)
2. Depletion Calculations (6.E.2)
    a. Core Operating Parameters (6.E.2.1)
    b. Fuel Inserts and Burnable Poisons (6.E.2.2)
    c. CASMO calculations (6.E.2.3)
3. Benchmarks (6.E.3)

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4. Criticality Calculations (6.E.4)
    a. Axial Burnup Distribution (6.E.4.1)
    b. Planar Burnup Distribution (6.E.4.2)

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    d. Basket Tolerances (6.E.4.4)
    e. Eccentric Positioning of Fuel Assemblies in Basket Cells (6.E.4.5)
    f. Bounding Fuel Dimensions (6.E.4.6)

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5. Establish Loading Curves (6.E.5)
6. Margins (6.E.6)

Finally, Sections 6.E.7 through 6.E.10 discuss compliance with ISG 8 rev. 2, burnup measurement requirements, a further outlook regarding future improvements of the burnup credit methodology and application, and present a brief summary.

6.E.1 Fuel Assembly Specifications

6.E.1.1 Assembly Types

In Section 6.2, 17 PWR fuel assembly classes are defined, which represent practically all commercially used PWR fuel in the US. The predominant fuel assembly types in the US are the Westinghouse 17x17 and the B&W 15x15, or equivalent models manufactured by other fuel vendors. These fuel types are analyzed in this appendix. The Westinghouse 17x17 is represented by assembly classes 17x17A, 17x17B and 17x17C, and the B&W15x15 by assembly classes 15x15D, 15x15E, 15x15F and 15x15H. Therefore, these are the only assembly classes currently permitted for transport in the MPC-32.

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6.E.1.2 Enrichments, Burnups and Cooling Times

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All burnup credit calculations are performed for a five year cooling time.

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6.E.2 Depletion Calculations

6.E.2.1 Core Operating Parameters

The depletion calculations for the burnup credit application require the principal in-core operating parameters as input. The principal core parameters that affect the neutron multiplication factor (k_{eff}) are listed below:

- Specific Power in the Core
- Moderator Temperature
- Fuel Temperature

- Soluble Boron Concentration during Depletion

Other issues related to the operating conditions are inserts in the fuel assemblies during depletion, and axial burnup distribution. These are discussed in sections 6.E.2.2 and 6.E.4.1, respectively.

The operating parameters selected here were initially chosen to bound the vast majority of assemblies qualified for loading in the MPC-32 based on the loading curves. However, to ensure that no assemblies outside of these parameters are loaded into the MPC-32, selected parameters are specified in the CoC, as discussed in Section 6.E.2.1.6. Nevertheless, the selection process is still described in detail below, although this process is no longer necessary to ensure that loaded assemblies are within these parameters.

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6.E.2.2 Fuel Inserts and Burnable Poisons

Fuel assemblies can contain various forms of control components during in-core depletion, such as Burnable Poison Rods (BPRs), Control Rods (CRs), Axial Power Shaping Rods (APSRs) and similar devices. All these components are inserted into the guide tubes of the assembly during depletion. Additionally, assemblies can contain Integral Burnable Absorbers (IBAs), consisting of neutron absorbing material as part of, or replacing fuel pellets. Below, each of these devices is briefly described, and its reactivity effect is characterized. At the end of this subsection, the approach taken in the burnup credit evaluation is outlined.

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6.E.2.2.1 <u>Inserts Considered</u>

The principal specifications of the inserts considered are summarized in the following table. More detailed specifications are listed in tables at the end of this appendix, which are referenced below.

Assembly Type	Insert Type	Absorber	Cladding	Details
B&W 15x15	Poison Rods	Al_2O_3 with 3% B_4C	Zircaloy	Table 6.E.4
B&W 15x15	Control Rods (RCCAs and Black APSRs)	AgInCd	St. Steel	Table 6.E.5
WE 17x17	Poison Rods (Pyrex)	SiO_2 with 12.5% B_2O_3	St. Steel	Table 6.E.6
WE 17x17	Poison Rods (WABA)	Al_2O_3 with 14% B_4C	Zircaloy	Table 6.E.7
WE 17x17	Control Rods	AgInCd	St. Steel	Table 6.E.8

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To account for the many potential operating histories in a conservative way, several loading configurations are evaluated and a separate burnup versus enrichment curve is determined for each configuration and each assembly type. The design basis configurations that are considered are:

- Configuration A: All assemblies in a basket must satisfy the following conditions
    - Assemblies that have not been located in any cycle under a control rod bank that was permitted to be inserted during full power operation (per plant operating procedures); or
    - Assemblies that have been located under a control rod bank that was permitted to be inserted during full power operation (per plant operating procedures), but where it can be demonstrated, based on operating records, that the insertion never exceeded 8 inches from the top of the active length during full power operation.
- Configuration B:
    - Of the 32 assemblies in a basket, up to 8 assemblies can be from core locations where they were located under a control rod bank, that was permitted to be inserted more than 8 inches during full power operation. There is no limit on the duration (in terms of burnup) under this bank.
    - The remaining assemblies in the basket must satisfy the same conditions as specified for configuration A.
- Configuration C:
    - Of the 32 assemblies in a basket, up to 8 assemblies can be from core locations where they were located under a control rod bank, that was permitted to be inserted more than 8 inches during full power operation. Location under such a control rod bank is limited to 20 GWd/mtU of the assembly.

  - The remaining assemblies in the basket must satisfy the same conditions as specified for configuration A.
- Configuration D:
  - Of the 32 assemblies in a basket, up to 8 assemblies can be from core locations where they were located under a control rod bank, that was permitted to be inserted more than 8 inches during full power operation. Location under such a control rod bank is limited to 30 GWd/mtU of the assembly.
  - The remaining assemblies in the basket must satisfy the same conditions as specified for configuration A.

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6.E.2.3 <u>CASMO Calculations</u>

CASMO-4 [6.1.11] is used as the depletion code for the burnup credit evaluations, i.e. to determine the isotopic composition of the depleted fuel for a given burnup and enrichment.

CASMO is a multigroup two-dimensional transport theory code for burnup calculations of BWR and PWR fuel assemblies. It allows modeling of a planar cross section of an individual fuel assembly, including all relevant details such as individual pellet and cladding diameters, locations of guide tubes and instrument tube, and material compositions of all materials including burnable poisons and control rods. The calculations assume a planar and axially infinite array of the fuel assembly. CASMO requires the fuel and absorber dimensions, the operating parameters (see Subsection 6.E.2.1), an initial enrichment and a maximum burnup. CASMO then performs a depletion calculation and calculates the reactivity of the assembly, and pin specific and assembly average isotopic compositions.

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6.E.3 Benchmarks

ISG-8 requires that the depletion and criticality codes used in burnup credit are validated through comparison of calculated results with results obtained from experiments. Three different sets of benchmark calculations are performed to validate different aspects of the overall methodology.

From each set, a bias or set of biases is determined if necessary, which is then used in the criticality calculations or the evaluation of the burnup vs. enrichment curves.

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6.E.4 Criticality Calculations

The Monte Carlo code MCNP4a [6.1.4] is used for all criticality analyses in the burnup credit methodology. The following data is combined to generate the input to MCNP for the cases to be analyzed:

- The principal model with MPC basket, the HI-STAR overpack and the fuel assemblies is the same detailed model as used for the calculations assuming fresh fuel.
- The assemblies are subdivided into 18 axial sections, corresponding to the 18 axial sections of the axial burnup profiles (see Section 6.E.4.1).
- In each axial section, the isotopic composition of the fuel is taken from the corresponding depletion calculations.

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  The isotopic composition is based on the assembly class, the initial enrichment and the local burnup in the section, which is calculated from the assembly average burnup and the axial burnup profile (see also Section 6.E.4.3).
- Isotopic compositions in all 18 sections of an assembly are based on the same initial enrichment. Axial blankets, i.e. regions of reduced enrichment at the top and bottom of the active region, which could result in a reduction in reactivity in these regions, are conservatively assumed to be the same enrichment as the central region of the fuel.
- All criticality calculations are performed for an active length of 150 inches, which is an upper bound for the active lengths of PWR assemblies, and larger than the actual active lengths of the WE 17x17 and B&W 15x15 assembly types.

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- Bounding fuel and basket dimensions are used, and the eccentric positioning of fuel in the basket cells is considered (see Sections 6.E.4.4, 6.E.4.5 and 6.E.4.6)

These and other considerations regarding the models used in the criticality calculations are discussed in more detail in the following sections.

6.E.4.1 Axial Burnup Distribution

Irradiated Fuel Assemblies are not burned evenly over the height of the assembly. Rather, they exhibit an axial burnup distribution, i.e. the burnup of the fuel is a function of the axial location of the fuel within the assembly. In general, the fuel at the top and bottom end of the assembly shows a lower burnup than the fuel in the axial center of the assembly. This is caused by the increased neutron loss and therefore decreased neutron flux towards the top and bottom end of the assembly during irradiation in the reactor core. The reactivity of spent fuel is a strong function of the fuel burnup, with reactivity decreasing when the burnup increases. For irradiated fuel assemblies, the reactivity at the top and bottom ends is therefore higher than the reactivity in the center of the assembly. Obviously, no axial burnup distribution is applicable in the analysis of fresh fuel. However, when credit is taken for the reduction in reactivity due to the burnup of the fuel, it is important that the axial burnup distribution is accounted for in a conservative way. Therefore, bounding axial burnup profiles need to be established, i.e. axial profiles which maximize the reactivity under the given conditions.

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6.E.4.2 Planar Burnup Distribution

Due to the neutron flux gradients in the reactor core, assemblies can show a tilted burnup distribution, i.e. differences in burnup between portions or quadrants of the cross section of the assembly. An evaluation documented in [6.E.23] shows that the differences between the quadrant burnup and the average burnup can be as much as 25%, and that this difference is higher at low burnups and decreases as the burnup increases.

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6.E.4.4 <u>Basket Tolerances</u>

MCNP calculations with spent fuel are performed to evaluate the tolerances of the various basket dimensions for the MPC-32. The results are presented in Table 6.3.2 in the main part of this chapter. The highest reactivity corresponds to a minimum cell pitch, minimum cell ID and nominal wall thickness (see also Table 6.3.3). This combination of basket dimensions is conservatively assumed in all design basis calculations.

6.E.4.5 Eccentric Positioning of Fuel Assemblies in Basket Cells

The aspect of eccentric positioning of fuel assemblies is discussed in general in Section 6.3.3 of this chapter. The calculations specific to the MPC-32 are presented in Table 6.E.36, for assembly classes 15x15F and 17x17A. For both assembly classes, moving the assemblies towards the center on the basket results in a small, but not insignificant increase in reactivity. Therefore, for all design basis calculations, i.e. all calculations to determine the loading curves for the MPC-32, and for some of the studies, it is conservatively assumed that all assemblies are moved towards the center of the basket.

6.E.4.6 Bounding Fuel Dimensions

Bounding fuel dimensions for fresh fuel are determined in Section 6.2 of this chapter based on calculations for the MPC-24 basket. Results for the corresponding calculations for spent fuel in the MPC-32 are shown in Table 6.E.37 for assembly class 15x15F at 4 wt% enrichment and 40 GWD/MTU. Similar results were obtained for assembly class 17x17A.

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The system of assembly classes established in Section 6.2 is therefore valid for the MPC-32 with burnup credit, and it is therefore only necessary to evaluate the assembly with the bounding dimensions in each assembly class.

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6.E.5 Establish Loading Curves

The multiplication factor (k_{eff}), including all biases and uncertainties at a 95-percent confidence level, should not exceed 0.95.

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For each assembly type and configuration A through D, the required burnups are then matched by a third-order polynomial fit as a function of enrichment. The resulting equations are listed in Table 6.E.1, and shown graphically in Figures 6.E.63 and 6.E.64. Note that ISG 8 Rev. 2 prescribes an upper limit for burnup credit of 50 GWd/mtU. Following this ISG, assemblies that would require a burnup higher than 50 GWd/mtU are therefore not acceptable for loading in the MPC-32. This restriction is incorporated into Table 6.E.1 and Figures 6.E.63 and 6.E.64. To validate these curves, calculations are then performed for all assembly types and configurations A through D for selected enrichments, and burnups that are calculated from the polynomial functions. All results of these calculations are summarized in Table 6.E.40. Below 2 wt%, the polynomial functions would reach the 0 GWD/MTU burnup level, i.e. fresh fuel, at an enrichment between 1.7 and 1.8 wt% for both the B&W and Westinghouse assembly (see Figures 6.E.63 and 6.E.64). To demonstrate that the loading curves are also valid in this enrichment range below 2 wt%, calculations with fresh fuel were performed at 1.8 wt% enrichment. These results are also shown in Table 6.E.40. The highest value for the maximum k_{eff} value is 0.9483, consistent with target value of 0.948, and below the regulatory limit of 0.95.

All these calculations were performed for a single package, internally flooded, and no external reflection. To satisfy the requirements of 10CFR71.55 and 10CFR71.59, additional calculations were performed. For these calculations, the B&W assembly at 5 wt% and the Westinghouse assembly at 3.5 wt% are used. These represent the cases with the highest or close-to highest reactivities. The results are listed in Table 6.E.41, and are below the regulatory limit of 0.95 in all cases.

It is noted that the EALF (Energy of the Average Lethargy of Fission) values listed in tables 6.E.40 and 6.E.41 differ from the energy of the thermal peaks shown in the flux spectra. To explain this behavior, a more detailed evaluation of the EALFs is presented in Table 6.E.41a. In this table, ALF and EALF values are presented for two energy ranges, one up to an energy of 1eV, and one for energies above 1 eV. The table also shows the overall fraction of fissions in each range, and the total ALF and EALF. The cases shown are the design basis cases for B&W 15x15 assemblies from Table 6.E.40, which vary in their EALF value from about 0.21 to about 0.44. The results in Table 6.E.41a clearly show that the EALF values of the two energy ranges do not show any significant trend. Further, the EALF value for the lower energy range is consistent with the peak in the flux spectra. However, the fraction of fissions change between the cases, having almost 87% in the lower energy range for the low enriched fuel, which reduces down to 82% for the high enriched fuel. Therefore, the overall change of the EALF is not a result of a change in the energy of the thermal peak, but a result of a smaller percentage of the overall fission in that energy range. The EALF values in Table 6.E.40 and 6.E.41 are therefore not in conflict with the neutron spectra.

6.E.6 Margins

6.E.6.1 Isotopic Compositions and Cross Sections

Throughout the burnup credit evaluations, margins are added to account for uncertainties in the calculations methods, either as correction factors for individual isotopes, or as reactivity margins. These margins are based on benchmark experiments, i.e. on the comparison of calculated and measured values. The underlying assumption in all cases is that the experiments are correct, and that all differences between measured and calculated values are due to inaccuracies in the calculational methods or the data. This section presents a brief evaluation and discussion of the overall amount of margin added for these uncertainties.

Calculations were performed for assembly classes 15x15F and 17x17C to show stepwise the effect of the uncertainties. The results are listed in Table 6.E.42 for 15x15F and in Table 6.E.43 for 17x17C. All evaluations were performed for an enrichment of 4 wt%. Each table shows 5 cases, listed down the left side of the table, each characterized by the isotopes, isotope corrections and bias values applied. Each table then shows three result columns, each of which shows the effect of the respective case in a different way. The first column shows the reactivity for an assembly of 40 GWd/mtU. The second column shows the required burnup for a reactivity of 0.9470. This is determined by performing calculations for various burnups, and then interpolating the results to obtain the burnup that corresponds to the reactivity of 0.9470. The third column gives an indication what percentage of actual assemblies meet this burnup requirement. For 17x17 assemblies, this is based on the assemblies shown in Figure 6.E.1 for an enrichment between 3.9 and 4.1 wt%. For the 15x15 assemblies, it is based on a corresponding dataset for this assembly type. Note that the comparison is performed here only for a narrow enrichment range. The percentages determined here are therefore different from the percentages listed in Section 6.E.0, since these were determined as an integral value for assemblies of all enrichments. A burnup uncertainty of 5% is applied to the actual assembly burnups before comparing them to the limit. Note that in all cases, two standard deviations of the statistical uncertainty from MCNP are included in the calculation of the k_{eff}. For the first case, calculations were performed with all isotopes available in CASMO, all at 100% of the amount determined by CASMO. This is consistent with the CRC calculations. The results are a k_{eff} of about 0.89, or a burnup requirement of about 30 to 32 GWd/mtU. For the second case, all isotopes that are not supported by any isotopic benchmark calculation (assays of spent fuel) were removed. The increase in reactivity is about 0.02 delta-k, while the increase in the required burnup is about 2.0 GWd/mtU. For the next case, the isotopic correction factors determined in Section 6.E.3.1.3 are applied to the minor actinides and fission products. The reactivity and burnup increase further to 0.93 and 37 to 38 GWd/mtU, respectively. For next case, the combined bias and bias uncertainties for major actinide composition, and for the reactivity effects of minor actinides and fission products are added, without setting the bias values that reduce reactivity to zero. The reactivity and burnup requirements increase further, to 0.945 and 39 GWd/mtU. Finally, for the last case, bias values that reduce reactivity are set to zero. This last case corresponds to the design basis calculations that are used to determine the loading curves. Reactivity and burnup requirement increase further, to about 0.957 and about 42 GWd/mtU, respectively. Overall, i.e. between the first and last case, the reactivity increases by about 0.065 delta-k, and the Burnup requirement increases by 10 to 12 GWd/mtU. This level of uncertainty, just in the isotopic composition and cross section, appears extremely high. From a engineering rather than statistical perspective, it appears questionable whether operations of nuclear power stations would be at all possible, if the reactivity of spent fuel can not be determined with an uncertainty much better than ± 0.055 delta-k, or the equivalent of almost 10 GWd/mtU, using state-of-the-art methodologies. Reviewing the benchmark experiments and corresponding calculations leads to the conclusion that the assumption that is most likely responsible for this situation is that all measurements are assumed correct. Note that within the evaluation presented here, no attempts were made to verify the correctness of the data, since this would be far beyond the scope of this work. There appears to be ample evidence suggesting that uncertainties in the measurements or measurement conditions could account for most of the difference between measured and calculated values. As an example, if there would be any principal problems determining the behavior of spent fuel, then bias and bias uncertainties would be expected to increase with burnup. However, the comparisons performed here do not show any such behavior.

To determine whether there is a real need to address these issues, the impact of these margins on the number of qualifying assemblies needs to be reviewed. In the first case, with a burnup requirement of 30 to 32 GWd/mtU, almost all of the assemblies would qualify. For the last case, this is reduced to less than 50%. This is undoubtedly a substantial change in the number of assemblies that qualify. The effect of the uncertainty margin is therefore highly significant. Future work in the area of improving the accuracy of the existing measurements, including the measurement conditions, might therefore result in a significant improvement of the calculated loading curves, without requiring any extension of the methodology or additional measurements.

6.E.6.2 Operating Parameters

There are even further margins embedded in the calculations presented here, as a result of the assumed operating parameters. The parameters that have the most significant impact on the reactivity of the assemblies are the moderator temperature and soluble boron level during depletion, and the axial burnup distribution. It is not possible to generically quantify the effect of these margins, since they are dependent on the actual assembly conditions. However, a large number of sets of actual assembly conditions are available from the CRC calculations. The isotopic compositions of these assemblies have already been determined in conjunction with the CRC calculations. To present an indication of the magnitude of this additional margin, calculations for these assemblies in the MPC were performed. For simplification, each calculation assumes that all positions in the MPC are occupied by the same assembly. Isotopic compositions of the assemblies are extracted at the assembly-average burnup that corresponds to the loading curve, which might be lower than the burnup in the CRC model. For example an assembly might have a burnup of 35 GWd/mtU in a CRC state point, while the minimum burnup for the assembly is only 30 GWd/mtU based on its enrichment. In this case, the isotopic composition at 30 GWd/mtU is extracted from the depletion calculations and used in the MPC model, rather than at 35 GWd/mtU. Only the benchmarked isotopes were used in the calculation, without any correction factors, plus Eu-155 and Gd-155, and the calculations were performed for a cooling time of 5 years, consistent with the design basis calculations. The results are therefore directly comparable to the second cases in Tables 6.E.42 and 6.E.43. Calculations were performed for a total of 80 assemblies from all of the 5 plants analyzed in the CRC benchmarks. The results are shown in Figure 6.E.65 as a function of burnup. The calculations show a keff range between 0.825 and 0.88. Compared to a value of 0.915 in Tables 6.E.42 and 6.E.43, this indicates that the difference between actual and bounding operating conditions can account for a margin between 0.03 and 0.08 delta-k, in addition to the margin regarding the fuel composition discussed before. However, this margin cannot be easily used, since it is assembly specific. To use this margin would require a change in the general approach, although not necessarily in the methodology. An approach to use this margin would require an outline of the methodology and bounding or sample calculations, but permit determination of acceptability of a specific cask in a cask specific analysis. No further investigations have been made to determine whether such an approach is feasible. However, based on the potential benefits, this might be worth considering in the future.

6.E.7 Comparison with ISG-8 Rev. 2

In Table 6.E.44, a cross reference is presented between ISG-8, Rev. 2, and the approach outlined here. For each of the recommendations in the ISG, the table lists the section or sections of this chapter where the implementation of the recommendation is discussed, or where an alternative to the recommendation is presented. Additionally, the alternatives to, and extensions of the ISG-8 recommendation are summarized below.

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6.E.9 Outlook

The burnup credit approach and methodology presented here qualifies a significant portion of fuel assemblies for transportation in the MPC-32. However, there is still a large fraction of assemblies, specifically at higher enrichments, that do not qualify since they do not meet the minimum burnup requirement. The reasons for this are predominantly the many bounding assumptions, and conservative way uncertainties are determined and applied. Reducing these assumptions and conservatisms should therefore be the focus of further studies and evaluations, with the expectation that almost all assemblies would be transportatble in the MPC-32. The various aspects of further improvements are listed and briefly discussed below. Some of these have already been discussed in sections of this appendix. Others are possible implementations based on experiences in other projects in wet and dry storage that could be helpful in achieving the final goal.

- The margin for uncertainties in the fuel isotopic compositions and reactivity effects are based on benchmark experiments. For the isotopic benchmarks and reactor critical benchmarks it does not appear that observed uncertainties are clearly related to burnup. A review of these experiments with the intent to identify and remove any uncertainties not related to burnup, and/or to identify outlier data that exaggerate the uncertainty might well be able to significantly reduce the related margin.
- Site, cask and/or assembly specific evaluations would be able to overcome some of the conservatively bounding assumptions regarding the operating conditions of fuel assemblies.
- Additional loading curves with lower burnup requirements could be generated for a variety of conditions, such as
    - Longer cooling times.
    - Non-fuel hardware in assemblies in the MPC-32. This could be just for the water replacement, or for any additional poison in this hardware, such as in control components.
    - Regionalized loading. Positioning lower burned assemblies on the periphery and higher burnup assemblies in the center of the basket reduces the reactivity significantly.

Further studies will need to be performed to identify the measures to be implemented.

6.E.10 Burnup Credit Summary

The burnup credit evaluations demonstrate that with the minimum burnups as specified by the formulas in Table 6.E.1, the reactivity in the MPC-32 is below the regulatory limit of 0.95 for all relevant conditions in 10CFR71. The evaluations also show that the results still contain substantial safety margins, sufficient to offset potential uncertainties in the condition of the fuel assemblies. The methodology generally follows ISG-8 Rev. 2, with additional benchmarks for alternative approaches.

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