ACTINIDE-ONLY BURNUP CREDIT METHODOLOGY FOR PWR SPENT NUCLEAR FUEL

D.B. LANCASTER, E. FUENTES, C. KANG
TRW Environmental Safety Systems, Inc.

M. RAHIMI
JAI Corporation

Vienna, Virginia, USA

Abstract

A conservative methodology is presented that would allow taking credit for burnup in the criticality safety analysis of spent nuclear fuel (SNF) packages. The method is based on the assumption that the isotopic concentration in the SNF and cross sections of each isotope for which credit is taken must be supported by validation experiments. The method allows credit for the changes in the U-234, U-235, U-236, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241 concentration with burnup. No credit for fission product neutron absorbers is taken. The methodology consists of five major steps:

1. Validate a computer code system to calculate isotopic concentrations of spent nuclear fuel created during burnup in the reactor core and subsequent decay.
2. Validate a computer code system to predict the subcritical multiplication factor, \( k_{\text{eff}} \), of a spent nuclear fuel package by use of \( \text{UO}_2 \) and \( \text{UO}_2/\text{PuO}_2 \) critical experiments.
3. Establish conditions for the SNF (depletion analysis) and package (criticality analysis) which bounds \( k_{\text{eff}} \).
4. Use the validated codes and bounding conditions to generate package loading criteria (burnup credit loading curves).
5. Verify by measurement that SNF assemblies meet the package loading criteria and confirm proper assembly selection prior to loading.

1. INTRODUCTION

This paper describes a methodology for validating analytical methods and for applying burnup credit in the design of criticality control systems for pressurized water reactor (PWR) spent fuel packages. The methodology was included in a Topical Report submitted to the NRC in May 1995 [1]. After considering the NRC's request for additional information, a revision was issued in May 1997 [2]. This paper describes the methodology submitted to the NRC for gaining burnup credit and a demonstration of the methodology with SCALE 4.2 [3] using the 27BURNUPLIB.

The burnup credit methodology presented here is expected to be used by commercial SNF storage and transportation package designers. Design-specific burnup credit criticality analyses will be defined, developed, and documented in the Safety Analysis Report (SAR) for each specific storage or transportation package that uses burnup credit. These SARs will then be submitted to the NRC for review and approval. The methodology presented here is expected to be referenced in a number of storage and transportation cask applications to be submitted by commercial cask and canister designers to the NRC.

2. SCOPE

The methodology presented here addresses only the reduced reactivity of SNF due to changes in actinide isotopes; specifically, U-234, U-235, U-236, U-238, Pu-238, Pu-239, Pu-240, Pu-241, Pu-242, and Am-241. The considerable additional negative reactivity effect of fission products is not included. Additionally the scope is limited to PWR spent fuel packages. BWR spent fuel packages could also benefit from burnup credit but since the transportation packages normally do not require flux traps and the designs are more complex, work on BWR burnup credit has been deferred.
Nevertheless, the actinide-only burnup credit methodology presented in this paper has a wide applicability. It applies to all current generation commercial PWR fuel, with the following restrictions due to data limitations:

- Burnup credit benefits can be gained from fuel burned up to 50 GW\cdot d/tU. SNF with an assembly average burnup greater than 50 GW\cdot d/tU shall be treated as having a burnup of 50 GW\cdot d/tU for the purposes of this methodology.
- Enrichments above five weight percent U-235 are not considered.
- Assemblies with integral fuel burnable absorbers (IFBAs) are not considered.
- The methodology applies to SNF with cooling times ranging from 1 to 100 years.
- Mixed oxide (MOX) initial content fuel is not considered.
- Reconstituted or disassembled fuel is not considered. Also not considered are fuel assemblies which have had any of their original rods removed or replaced.

Furthermore, there are analysis and modeling parameters that affect criticality which are not unique to burnup credit. None of those parameters or effects impact the proposed burnup credit methodology; therefore, they are not included in further discussion. A licensee’s Safety Analysis Report is required to address those parameters in the usual manner. Examples include:

- Material and fabrication tolerances;
- Uncertainties due to limitations in the geometric or material representations used in the computational method;
- Effects of symmetric or asymmetric fuel assembly clustering within the spent fuel basket.

3. THE ACTINIDE-ONLY BURNUP CREDIT METHODOLOGY

The burnup credit criticality analysis procedure has been developed to be consistent with the “fresh fuel” assumption criticality analysis procedure currently accepted by the NRC. The generic criticality safety analysis procedure using the fresh fuel assumption is illustrated in Figure 1. The purpose of the criticality safety analysis using the fresh fuel assumption is to develop a cask loading criterion that establishes the maximum initial enrichment of an SNF assembly design that can be loaded into a cask. Figure 2 illustrates the generic burnup credit criticality analysis procedure recommended in this paper. The burnup credit criticality analysis procedure builds upon the fresh fuel procedure. The burnup credit procedure results in spent nuclear fuel package loading criteria that specify minimum burnups necessary for a range of initial enrichment values for a specific fuel assembly design. The results are presented as burnup credit loading curves.

The key elements in Figure 2 that distinguish the burnup credit procedure from the fresh fuel procedure are shaded. Descriptions of each of these elements and their relevance to the regulatory requirements are provided in this paper. Figure 2 graphically illustrates where these key elements fit into the overall burnup credit criticality analysis procedure. As can be seen on Figure 2, there are five major steps to implementing burnup credit:

1. Validate a computer code system to calculate isotopic concentrations in SNF created during burnup in the reactor core and subsequent decay;
2. Validate a computer code system to predict the subcritical multiplication factor, $k_{\text{eff}}$, of a spent nuclear fuel package;
3. Establish bounding conditions for the isotopic concentration and criticality calculations;
4. Use the validated codes and bounding assumptions to generate package loading criteria (burnup credit loading curves);
5. Verify that SNF assemblies meet the package loading criteria and confirm proper assembly selection prior to loading.
It should be noted that steps one through four are to be performed by the package designer, while step five is the particular utility's responsibility.

**FIG. 1. Criticality Safety Requirements Using the "Fresh Fuel" Assumption**

**FIG. 2. Criticality Safety Requirements Using Actinide-Only Burnup Credit**
3.1 Isotopic Validation

The isotopic composition of fresh fuel is well known through extensive, routine measurements by fuel manufacturers. However, after fuel is irradiated in a reactor, the isotopic composition of the spent fuel is routinely determined through analysis, rather than through measurement. Routine measurement of the isotopic content of discharged fuel using chemical assays is not practical due to radiological health, safety, and cost concerns. Confidence in the analytical capabilities is high due to the good agreement between the analytical predictions used for core reload analyses and the continual measurements of reactivity and power distributions at power plants. Source terms generated for thermal analyses have also shown good agreement with experiments.

For the burnup credit methodology presented in this paper, the computer code system used for predicting isotopic content must be validated using chemical assays of spent fuel. The chemical assays represent measured data for which best estimate predictions are generated with the computer code. Since there is very little data on chemical assays which include fission products, the isotopes for burnup credit are limited to the uranium and plutonium isotopes (and Am-241 as a daughter of Pu-241). Specifically, the isotopes selected are U-234, U-235, U-236, U-238, Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242. Credit will be taken for Am-241 produced by post irradiation decay of Pu-241.

Fifty-four chemical assay experiments have been identified for the validation. They are from:

1) One Yankee Rowe assembly (8 samples from 3 fuel pins) [4];
2) Three Mihama-3 assemblies (8 samples from 5 pins) [4];
3) Three Trino Vercellese assemblies (14 samples from 6 fuel pins) [5]
4) Two Turkey Point assemblies (5 samples from 5 fuel pins) [6];
5) Three Calvert Cliffs Unit 1 assemblies (9 samples from 3 fuel pins) [7,8,9];
6) One H. B. Robinson assembly (4 samples from one fuel pin) [10]; and
7) Five Obrigheim assemblies (6 samples from dissolved halves of five assemblies) [11,12].

A compilation of all the measurements along with details of benchmark calculations is provided in References [5, 6, and 13]. Table I summarizes some of the key features of these chemical assays.

The validation procedure begins with the ratio of the measured benchmarks and the computed best estimate predictions, which are used to determine multiplicative biases and uncertainties. The biases and uncertainties for each isotope are combined in a conservative manner into a correction factor for each isotope. The correction factors are calculated and applied conservatively to ensure that criticality safety evaluations employing the burnup credit method result in a neutron multiplication factor that is conservative for the system being evaluated.

For example, if an isotope has a bias of 0.98 and an uncertainty of 5%, the isotopic concentration correction factor would be calculated as 0.98+0.05= 1.03 for a fissile material but 0.98-0.05 = 0.93 for an absorber.

To put the above in terms of an equation, define a bias (x) as:

\[ x = \frac{M}{C} \quad (1) \]

where M and C are the measured and calculated isotopic content, respectively. Now the correction factor (f) for an absorber would be:

\[ f = x \cdot \sigma_{t_{95,n-1}} \left[ \left( \frac{n+1}{n} \right) \right]^{0.5} \quad (2) \]

where s is the standard deviation, \( t_{95,n-1} \) is the Student's t value for 95% confidence, and n is the number of samples. The calculated atom density of the isotope of interest should be multiplied by f before the criticality calculations are performed.
**TABLE I. PROPERTIES OF THE CHEMICAL ASSAYS**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Burnups</th>
<th>Average Lethargy of Absorption</th>
<th>Enrichment (wt.% U-235)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yankee Rowe</td>
<td>15.95, 30.39, 31.33, 20.19, 32.03, 31.41, 35.97, 35.26</td>
<td>15.6 - 15.7</td>
<td>3.40</td>
</tr>
<tr>
<td>Mihama</td>
<td>8.30, 6.92</td>
<td>16.2 - 16.4</td>
<td>3.21</td>
</tr>
<tr>
<td>Assembly:86b</td>
<td>15.36, 21.29</td>
<td>16.2 - 16.3</td>
<td>3.20</td>
</tr>
<tr>
<td>Assembly:86g</td>
<td>29.50, 32.20, 33.71, 34.32</td>
<td>16.1-16.3</td>
<td>3.21</td>
</tr>
<tr>
<td>Assembly:87c</td>
<td>12.04</td>
<td>15.82</td>
<td>3.90</td>
</tr>
<tr>
<td>Trino Vercellese</td>
<td>15.38, 15.90, 11.53</td>
<td>15.8 - 16.0</td>
<td>3.13</td>
</tr>
<tr>
<td>Assembly: 069</td>
<td>30.72, 30.51, 31.56, 31.26, 31.31</td>
<td>16.3</td>
<td>2.56</td>
</tr>
<tr>
<td>Turkey Point</td>
<td>27.35, 37.12, 44.34</td>
<td>16.3 - 16.4</td>
<td>3.04</td>
</tr>
<tr>
<td>(5 assemblies)</td>
<td>18.68, 26.62, 33.17</td>
<td>16.3 - 16.5</td>
<td>2.72</td>
</tr>
<tr>
<td>Calvert Cliffs</td>
<td>31.40, 37.27, 46.46</td>
<td>16.2 - 16.3</td>
<td>2.45</td>
</tr>
<tr>
<td>Assembly D047</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly D101</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly BT03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H. B. Robinson</td>
<td>16.02, 23.81, 28.47, 31.66</td>
<td>16.2 - 16.5</td>
<td>2.56</td>
</tr>
<tr>
<td>Obrigheim</td>
<td>25.93</td>
<td>16.3</td>
<td>3.13</td>
</tr>
<tr>
<td>Assembly 170</td>
<td>26.54</td>
<td>16.3</td>
<td>3.13</td>
</tr>
<tr>
<td>Assembly 172</td>
<td>27.99, 29.52</td>
<td>16.3</td>
<td>3.13</td>
</tr>
<tr>
<td>Assembly 176</td>
<td>28.40</td>
<td>16.3</td>
<td>3.13</td>
</tr>
<tr>
<td>Assembly 168</td>
<td>29.04</td>
<td>16.3</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Multiple burnups are due to taking the samples from different axial heights or different locations in the fuel assembly.

Since it is possible that the bias, $x$, could be a function of key parameters, trend analyses are required. Upon review of the parameters that can affect $x$, the following relationship is assumed:

$$x_{fit} = (M/C)_{fit} = 1.0 + b_1 * B + b_2 * B \cdot S + b_3 * B \cdot E + b_4 * B \cdot P$$  \hspace{1cm} (3)$$

where:

- $x_{fit}$ = bias as a function of input parameters
- $B$ = burnup (GW-d/tU)
- $b_1$ = slope for burnup
- $S$ = a spectral index (Average Lethargy of Absorption (ALA))
- $b_2$ = slope for product of burnup*spectral index
- $E$ = initial enrichment (wt.% initial U-235)
- $b_3$ = slope for product of burnup*initial enrichment
- $P$ = specific power (MW/tU)
- $b_4$ = slope for product of burnup* specific power
As seen above, the burnup variable appears in each of the terms on the right side of the equation. This is because the amount of change in $x_{fr}$ due to spectrum, enrichment and specific power related problems is proportional to burnup. The $x_{fr}$ value at zero burnup is one because the calculated value becomes the initial condition (measured value) if there is no burnup.

Since non-zero coefficients (i.e., $b_i$ through $b_j$) would always be expected, a statistical test to determine the significance of each coefficient is required. The null hypothesis of this test is that the coefficient is zero. For all statistically significant trends a prediction band technique is used to cover the uncertainty in the bias. Finally, since regulatory practice does not allow biasing in a direction that results in less safety margin, the final correction factor is called $f_{buc}$ and is defined as $f$ with the limit of 1.0 (max. or min.) applied.

The isotopic validation method is applicable to any computer code system. For the purpose of demonstrating the method, the SAS2H sequence of SCALE 4.2 and the 27BURNUPLIB was used. The following equations are the correction factors consistent with the use of SCALE 4.2 and the 27BURNUPLIB:

- $f_{buc}(U-234) = 0.814$ (4)
- $f_{buc}(U-235) = 1.0 + 0.00105B + 0.000255 \cdot \text{SQRT}(41,100 + B^2)$ (5)
- $f_{buc}(U-236) = 0.936$ (6)
- $f_{buc}(U-238) = 0.991$ (7)
- $f_{buc}(Pu-238) = 0.866$ (8)
- $f_{buc}(Pu-239) = 1.0 - 0.000852B + 0.000378 \cdot \text{SQRT}(41,100 + B^2)$ (9)
- $f_{buc}(Pu-240) = 1.0 + 0.00231B - 0.000179 \cdot \text{SQRT}(41,100 + B^2)$ for $B < 15.7$ (10)
- $f_{buc}(Pu-240) = 1.0$ for $B > 15.7$ (11)
- $f_{buc}(Pu-241) = 1.0 - 0.00142B + 0.000347 \cdot \text{SQRT}(41,100 + B^2)$ (12)
- $f_{buc}(Pu-242) = 1.0 + 0.00300B - 0.000607 \cdot \text{SQRT}(38,500 + B^2)$ for $B < 40.5$ (13)
- $f_{buc}(Pu-242) = 1.0$ for $B > 40.5$ (14)
- $f_{buc}(Am-241) = 1.0 - 0.00142B - 0.000347 \cdot \text{SQRT}(41,100 + B^2)$ (15)

where $B$ is burnup in GW·d/tU.

For more detail on the method and analysis refer to references [2 and 5].

### 3.2. Criticality Validation

With the isotopic content conservatively determined, the next step is to conservatively determine the multiplication factor, $k_{eff}$. Criticality analyses under the fresh fuel assumption use criticality experiments to validate the cross sections and computer codes. The burnup credit criticality analyses are also validated using criticality experiments. Fresh fuel assumption methods are typically benchmarked against low enrichment, unirradiated heterogeneous UO$_2$ fueled systems. The actinide-only burnup credit method is additionally benchmarked against low enrichment, unirradiated heterogeneous mixed oxide (MOX) fueled systems. MOX experiments provide benchmark data for other transuranic isotopes present in spent fuel and included in the actinide-only burnup credit analysis procedure.

The criticality validation method combines biases, uncertainties, and an administrative safety margin to arrive at an Upper Safety Limit (USL) for $k_{eff}$ [5,14]. First, a lower prediction band is defined by the 95% confidence level for a single future calculation. The prediction band width accounts for the statistical uncertainty in the bias. Then an administrative safety margin of 5% $k_m$ is added to establish the USL, which becomes the bounding value for the criticality safety criterion. The USL technique provides a statistically sound method of establishing the bias as a function of any parameter while incorporating an additional safety margin that is consistent with the current practice.
Since spent nuclear fuel contains less than 2% Pu at discharge, using UO$_2$ criticals and MOX criticals with 2% or greater Pu bounds the actinide concentrations in spent fuel. A USL can be calculated separately on the UO$_2$ criticals and the MOX criticals. The most limiting of the USL curves would then be the actinide-only burnup credit USL.

Fifty-seven critical experiments have been selected to establish the bias over the anticipated range of PWR burnup credit package conditions. They span the range of the various parameters associated with a spent fuel shipping package. The experiments consist of 21 UO$_2$ criticals (including two gadolinium criticals) and 36 mixed oxide configurations. References [3,7] describe the experiments selected.

To demonstrate the criticality validation, the CSAS criticality sequences of SCALE 4.2 using the 27BURNUPLIB cross section set were employed to analyze the 54 experiments. The USL as a function of the Average Lethargy for Absorption (ALA) is presented in Figure 3, along with results for each of the 54 validation experiments.

Further information on criticality validation can be found in the technical report prepared on validation [5].

**FIG. 3. Upper Safety Limit on $k_{eff}$ for Actinide-Only Burnup Credit Using SCALE 4.2 and the 27BURNUPLIB**

### 3.3. Analysis and Modeling Parameters

The analysis for burnup credit must be performed with validated codes at limiting conditions for the SNF package. These limiting conditions apply to the generation of SNF isotopic compositions as well as the package criticality analysis. The actual values of the limiting conditions depend on the set of assemblies that they are intended to address.

The isotopic analysis depends on the reactor conditions during the burnup. These conditions are specific power, moderator temperature, fuel temperature, soluble boron concentration, and power
versus time for the life of the fuel. The fuel reactivity is maximized by using the highest specific power (MW/tU) and temperatures [15]. A specific power of 60 MW/tU bounds PWR fuel designs and does not overly burden the analysis with conservatism. For the moderator temperature, the core outlet temperature represents a high value that conservatively covers the reactivity of discharged fuel. A high fuel temperature can be determined by calculating the average pellet temperature assuming the outlet moderator temperature and the plant technical specification for the radial peaking factor [15].

The higher the average soluble boron concentration during burnup, the more reactive the fuel assembly would be following the discharge [15]. The highest average boron concentration for any cycle for each fuel design should be used. The less time the reactor is shut down during the burnup, the more reactive the fuel assembly [15]. Therefore, the burnup analysis should be performed as one continuous burn with no down time.

The criticality analysis of the SNF package must also be done at the most limiting conditions. There are three effects that are treated slightly differently for burnup credit. First, the optimum moderator density must be established for each specific package design for at least two burnup-enrichment conditions. The second consideration is the axial burnup modeling. A large database of axial burnup profiles has been developed [16] and the most limiting shapes (as a function of burnup) have been selected [15]. Package criticality analysis is to be performed with 18 axial nodes and the limiting shapes presented in Table II. If the package has large margins, \( k_{\text{eff}} \) bias curves can be used to account for the "end effects." If \( k_{\text{eff}} \) bias curves are used, axially uniform analysis is allowed. A sample \( k_{\text{eff}} \) bias curve for a twelve-foot active fuel length is shown as Figure 4. The final effect is the horizontal burnup gradient modeling. Again, a database of assembly quadrant horizontal burnup gradients has been created [17]. Conservatively assumed burnup tilts as a function of burnup are provided in Figure 5. All package analyses must assume each assembly has two different burnups at each of the 18 axial nodes such that the maximum variation per half conforms to the tilt shown on Figure 5. The tilt can be flat to flat or corner to corner depending on which configuration produces the highest \( k_{\text{eff}} \).

3.4. Spent Nuclear Fuel Package Loading Criteria

Burnup credit loading curves are the criteria used to determine whether it is permissible to load an assembly in an SNF package using burnup credit. This section describes the steps required to develop burnup credit loading curves. These curves identify the lowest acceptable burnup as a function of the initial enrichment.

To generate a loading curve, the maximum fresh fuel enrichment meeting the upper safety limit on \( k_{\text{eff}} \) is determined. Subsequently, a curve of required minimum burnup versus initial enrichment is developed by applying the burnup credit methodology at various initial enrichments. Loading curves may be developed for each assembly type which will be put in the SNF package. Since additional cooling time makes the loading curves less restrictive, the loading curves can also be generated as a function of cooling time.

The maximum fresh fuel U-235 enrichment that may be used in a given SNF package is determined first. The \( k_{\text{eff}} \) is calculated with a validated code system for a range of initial enrichments to determine the enrichment that produces a \( k_{\text{eff}} \) (or \( k + 1.645 \) for Monte Carlo results) equal to the upper safety limit. This is the maximum fresh fuel enrichment point and is labeled as \( (E_4, 0) \) on the loading curve (Figure 6). The loading curve consists of an abscissa that represents initial (fresh) fuel enrichment and an ordinate that represents the required minimum burnup for a given initial enrichment. Next, a vertical line is drawn at the maximum fresh fuel enrichment limit. All assemblies that have initial U-235 enrichments less than or equal to the maximum fresh fuel enrichment limit, \( E_4 \), may be stored or transported regardless of burnup.
The required minimum burnup for a specific initial enrichment value is the burnup at which the calculated $k_{eff}$, using the burnup credit methodology, is just equal to the upper safety limit. The process for determining a required minimum burnup for a given initial enrichment is illustrated in Figure 7. A series of runs of validated computer codes (i.e., SAS2H and CSAS25) is performed to calculate $k_{eff}$ values for a range of burnups to search for the burnup value that produces the reactivity limit, the upper safety limit. As indicated in Figure 7, the calculated $k_{eff}$ is plotted against the burnup that produced that value of $k_{eff}$. The curve is then fitted to estimate the burnup that crosses the upper safety limit. The process is repeated for various initial enrichments, as illustrated in Figure 7. A “verifying” calculation is performed near that burnup (for each initial enrichment value) which will be less than or equal to the upper safety limit. This limiting burnup will be used with the corresponding initial enrichment to establish a point on the burnup credit loading curve.

The loading curve may contain discontinuities. These are due to changing the axial and horizontal burnup profiles at certain burnups (18 and 30 GW·d/tU using the current axial and radial burnup profile databases). The process of determining required minimum enrichments at the burnup discontinuities is shown in Figure 8. The process is similar to the description in the previous paragraph; however, the initial enrichment is varied this time while the burnup is fixed. Two different
minimum initial enrichments result depending on the axial burnup profiles (or $k_{eff}$ bias values from Figure 4) and horizontal burnup gradient utilized at 18 and 30 GW·d/tU. It is required that the lower of the two minimum initial enrichments be determined. This is achieved by adopting axial burnup profiles 1 and 2 in Table II (or higher $k_{eff}$ bias values) and the horizontal burnup gradients of 33% and 25% for 18 and 30 GW·d/tU, respectively. Determining the other initial enrichment is not required. However, it can be achieved by adopting axial burnup profiles 2 and 3 in Table II (or lower $k_{eff}$ bias values) and the horizontal burnup gradients of 25% and 20% for 18 and 30 GW·d/tU, respectively. The distance between $E_5$ and $E_6$ or $E_7$ and $E_8$ is expected to be on the order of 0.2 or 0.1 wt. % U-235, respectively.

FIG. 4. $k_{eff}$ Bias Curve for End Effects for a 12 Foot Active Core and Five Years Cooling Time

FIG. 5. Quadrant Burnup Deviation Requirements and Database as a Function of Burnup
After the above calculations are performed, a curve of minimum burnup as a function of the initial enrichment is generated (see Figure 6). Calculations of the required minimum burnup must be performed at the maximum enrichment for the SNF package (E₀). Calculations of the required minimum burnup must also be performed at the maximum fresh fuel enrichment for the package (E₄). Burnup credit calculations will not show a zero minimum burnup for the maximum fresh fuel limit demonstrated using fresh fuel assumptions. This is because in performing the calculations, the isotopic correction factors on U-238 and U-235 are used that only need to be applied for irradiated fuel. The required minimum burnup for the highest enrichment is indicated as point C₀ on Figure 6. Subsequent values C₁ through Cₙ are obtained by decreasing the initial enrichment parameter by a value not to exceed 0.5 weight percent U-235 until an initial enrichment equal to the maximum fresh fuel enrichment limit is reached. The optimum moderation must be checked at point (E₄, 0) and the
point \((E_0, C_0)\). The required minimum initial enrichments, \(E_5\) and \(E_7\), must be found at 18 and 30 GW·d/tU. The loading curve is created by a segmented straight line through the data points. As previously mentioned, points \((E_6, 18)\) and \((E_8, 30)\) may be determined and incorporated into the loading curve, but this is optional. If there is significant curvature in the loading curve at burnups other than 18 and 30 GW·d/tU, the enrichment points should be spaced so that the loading curve is smooth, with no abrupt direction changes.

A spent fuel assembly that has a verified burnup greater than the required minimum burnup on the loading curve at the assembly's initial enrichment may be loaded into the SNF package. Note that an assembly that has an initial enrichment less than the maximum fresh fuel enrichment limit does not require any burnup. Conversely, an assembly that has an initial enrichment that exceeds the highest enrichment on the loading curve may not be loaded into the package regardless of its burnup. If an assembly is initially loaded with fuel of different enrichments, the maximum enrichment value anywhere in the assembly is used to compare against the loading curve. Using the maximum enrichment value conservatively bounds the reactivity of a multi-enrichment assembly.

Burnup credit loading curves should be generated for each assembly design. Separate loading curves may be generated for assemblies with removable burnable absorbers. The burnup credit loading curve will specify the minimum cooling time used in the analysis. Cooling times longer than the minimum specified are conservative for the first 100 years of cooling.

3.5. Physical Implementation and Controls

The loading of spent nuclear fuel transportation packages designed for burnup credit requires the implementation of controls during loading to ensure design basis fuel requirements and licensing conditions are met. These controls are in addition to those that are already being implemented for fresh-fuel based packages. ANSI/ANS-8.17 [18] indicates that credit may be taken for fuel burnup by establishing a maximum spent fuel reactivity and ensuring that each fuel assembly has a reactivity no greater than the maximum established by "analysis and verification of the exposure history of each fuel unit." The previous sections introduced the methodology for determining a conservative reactivity for the SNF assemblies. In addition, the actinide-only methodology [2] requires a physical measurement of each SNF assembly to verify the reactor records before loading burnup credit packages.
The analysis of an SNF package using burnup credit results in loading criteria to identify assemblies that may be placed in a burnup credit package. These criteria provide the relationship between the minimum allowable average burnup and the initial enrichment of an assembly for a given assembly design, burnable absorber (BA) loading, and cooling time. Therefore, the package loading procedure requires knowledge of the burnup, enrichment, BA loading and cooling time for a candidate assembly. This data resides in the reactor operating records. The reactor records associate this data with a storage rack location and the ID of the assembly. Part of the record, the initial enrichment, cooling time, and storage rack location, is used to satisfy the criterion for current spent fuel shipments. Thus, the operational aspects of burnup credit require only an extension of the reliance of reactor records currently used for package loading. However, such an extension increases the reliance on administrative controls to ensure criticality safety. In order to guard against an error in the reactor records, the burnup credit process includes a measurement to verify that the reactor records specified for a specific assembly correlate with the measured neutron or gamma emissions for the assembly. The verification measurement reduces reliance on administrative controls and provides sufficient additional protection against misloading to satisfy ANSI/ANS 8.1 [19].

The burnup on the loading curve is to be compared to the utility's reactor records after accounting for the uncertainty in that record. The independent burnup verification by a physical measurement is to confirm the recorded burnup prior to loading specific fuel assemblies into a burnup credit package. This confirmation approach is taken since it is generally believed that the reactor record burnup is more accurate than that from a measurement. However, the assembly is accepted for loading in a burnup credit package only if a measurement criterion for acceptance is met. This criterion must be established to be consistent with the need for confirmation as well as the technology available to do the verification. The acceptance criterion is that the measured burnup must be within 10% of the nominal reactor record burnup. This is a two-sided requirement since it is desirable to reject any assembly with an unexpected result. Although an assembly with a measured burnup greater than the reactor record by more than 10% may be safe with regard to burnup, the measurement implies a problem with the reactor record. Since no direct measurement of enrichment is required, any indication of an erroneous record is grounds for rejection of the assembly.

The question arises as to whether an unnoticed error of up to 10% would lead to an unsafe condition. First, it is projected that approximately half of this difference is accounted for in the reduction of the assembly burnup due to uncertainty in the reactor records. However, if the assembly was at the low end of the reactor record uncertainty, the maximum error in burnup would be 10%. This would imply a 10% error in the reactivity change due to burnup. Since about 30% of the change in reactivity due to burnup is from fission products [2], this unexpected event is well within the available safety margin.

The measurement acceptance criterion should not be so restrictive that the current state of the art of burnup measurement systems would produce large numbers of spurious rejections. Five percent is an engineering approximation of the uncertainty in both of the reactor records and measurement systems. Using this estimate, it would appear that deviations of greater than 10% between the measurement and reactor records would be unlikely and a reasonable basis for rejection.

Burnup measurement systems fall into two broad classes, herein termed "dependent," and "independent." Dependent systems (e.g., gross neutron detection systems) rely on knowledge of the reactor record burnup values for a set of assemblies for calibration. Therefore, these systems cannot truly "measure" burnup independently. The primary use for such systems is detection of "outlier" assemblies which for some reason have a radiation signature at odds with their reactor record burnup value. On the other hand, independent measurement systems (e.g., gamma spectrum detection systems) are capable of performing a true independent measurement of assembly burnup, without reliance on reactor records, using the gamma emission signatures of fission products (principally cesium isotopes).
For dependent systems, a calibration curve of the following form is used to correlate the neutron counts to the reactor record burnup:

\[ y_{\text{counts}} = a + b x_{\text{reac}} \]  \hspace{1cm} (16)

where \( a \) and \( b \) are constants, \( y_{\text{counts}} \) is the count rate (or, for neutron detection systems, typically the logarithm of the neutron count rate), and \( x_{\text{reac}} \) is the reactor record burnup value (or, for neutron detection systems, typically the logarithm of the reactor record value). Constants \( a \) and \( b \) are determined using standard linear regression techniques, following measurement of a group of assemblies.

The burnup uncertainty of dependent measurement systems is most conveniently stated in terms of a count rate prediction band. (Note that for dependent measurement systems, the count rate prediction band incorporates both reactor records errors and intrinsic measurement system errors.)

For dependent measurement systems, the count rate for a particular assembly should not differ from the calibration line by more than the following amount:

\[ \text{Prediction Band Width (count rate)} = t_{0.025,n-2} \left\{ \left[ (n+1)/n + (x_i - x_{avg})^2 / S_{XX} \right] S_{R} (n-2)^{0.5} \right\} \]  \hspace{1cm} (17)

where, \( t_{0.025,n-2} \) is the Student’s t-distribution statistic bounding 95% of distribution for \( n-2 \) degrees of freedom (two-sided distribution),

\( n \) is the number of assemblies in a calibration run,

\( x_i \) is the \( x_{\text{reac}} \) (burnup or log of burnup) for assembly \( i \),

\( x_{avg} \) is the average of the \( x_{\text{reac}} \)’s for all assemblies in a calibration run,

\( S_{XX} = (x_i - x_{avg})^2 \),

\( S_{R} = (y_i - y_{\text{fit}})^2 \),

\( y_i \) is the count rate (or log of the neutron count rate) measured for assembly \( i \),

\( y_{\text{fit}} \) is the value from equation 16 for assembly \( i \).

Since, for dependent measurement systems, prediction band width on uncertainty depends on the number of assemblies measured, an appropriate bound on the band width is required to ensure an adequate sample size for the calibration curve. Thus, dependent measurement systems must demonstrate, via analysis and confirmatory testing, that the following criterion can be met:

\[ \text{Prediction Band Width (converted to burnup units)} / \text{Assembly Burnup} < 0.1 \]  \hspace{1cm} (18)

The 10% requirement on the prediction band width is consistent with the 10% value used as an acceptance criterion so the measurement system will not cause random rejections or acceptances.

Independent measurement systems should demonstrate, via analysis and confirmatory testing, the uncertainty associated with a single assembly-average burnup measurement. That uncertainty should be 10% or less. This again is consistent with the acceptance criteria.

4. CONSERVATISM IN THE ACTINIDE-ONLY BURNUP CREDIT METHOD

The methodology for utilizing actinide-only burnup credit described in this paper includes substantial conservatism. The conservatisms are included to compensate for the limited knowledge of the fuel isotopic composition (including the spatial distribution), cross sections and burnup profiles, and uncertainties in the measurements and calculational tools. This section will explore some of the issues associated with the methodology’s conservatisms.

Analyses have been performed to quantify the reactivity effects due to three of the conservatisms in the methodology: the bounding depletion parameters, the isotopic correction factors,
and the exclusion of the fission products [5]. To assess each of the three effects, criticality calculations are performed using four sets of calculations with different modeling conditions. Each set consists of several combinations of typical burnups and enrichments, using a standard Westinghouse 17x17 assembly with a 5-year cooling time after the final cycle. The initial set represents best-estimate conditions, using nominal modeling parameters for the isotopic calculations, bias corrected isotopics, and fission products. The nominal modeling parameters represent average values for the fuel, clad and moderator temperatures, soluble boron concentration, and specific power. The bias corrected isotopics are computed using the isotopic biases but the concentrations are not corrected for the uncertainties.

The remaining three sets vary the modeling conditions in order to be able to quantify the various effects on the system's reactivity. The second set excludes the fission products; the third set excludes fission products and uses bounding modeling parameters for the isotopic calculations. The fourth set represents the actinide-only burnup credit methodology values, which requires bounding depletion parameters, use of conservative correction factors for isotopic concentrations, and no fission products. Using the various sets, the effects of each of the modeling considerations are computed at different burnups and enrichments, and are presented in Table III. Results shown are differences in k between the corresponding cases.

The fission product conservatism shown on Table III is large. Nevertheless, since strong documentation of individual fission products' worth is not available at this time, credit cannot be taken for fission products, and thus negative reactivity is present that is not taken credit for. Although fission product yields can be measured, the transmutation in the reactor has little experimental verification, and thus fission products' concentrations cannot be easily predicted. Therefore, although obviously present in SNF providing considerable negative reactivity, fission products are not included in the burnup credit methodology and are left as added conservatism.

### Table III. Conservatisms in the Actinide-Only Burnup Credit Methodology

<table>
<thead>
<tr>
<th>Enrichment (wt.% U-235)</th>
<th>Burnup (GWd/tU)</th>
<th>Fission Product Conservatism (% k)</th>
<th>Bounding Depletion Parameters Conservatism (% k)</th>
<th>Isotopic Correction Factors Conservatism (% k)</th>
<th>Added Conservatism (% k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>15</td>
<td>7.8</td>
<td>1.1</td>
<td>1.8</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>12.2</td>
<td>3.1</td>
<td>2.4</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>15.2</td>
<td>5.2</td>
<td>3.1</td>
<td>23.5</td>
</tr>
<tr>
<td>3.6</td>
<td>15</td>
<td>7.5</td>
<td>0.8</td>
<td>1.6</td>
<td>9.9</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>11.9</td>
<td>2.3</td>
<td>2.2</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>15.2</td>
<td>4.4</td>
<td>2.9</td>
<td>22.5</td>
</tr>
<tr>
<td>4.5</td>
<td>15</td>
<td>7.1</td>
<td>0.4</td>
<td>1.4</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>11.4</td>
<td>1.4</td>
<td>1.9</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>15.0</td>
<td>3.0</td>
<td>2.6</td>
<td>20.6</td>
</tr>
</tbody>
</table>

The other conservatisms shown on Table III are due to the modeling parameters and isotopic correction factors. Although not as large as the fission product values, considerable margin is provided by both of these bounding modeling conditions. It may not seem to be appropriate to talk about the correction factors since they account for the uncertainty in the data. This would be logical if these correction factors were being determined for only one isotope but since they are determined for
each isotope, the implication is that each isotope deviates from its expected value in the same direction (in the direction that creates more reactivity). Unfortunately, since the isotopes are all of different worths, it is not clear how to statistically combine the uncertainties. It is anticipated that future work may allow the combination of these errors.

Table IV uses the same analyses results to show the change in reactivity due to burnup. The third column presents the difference in $k$ between the zero burnup case and cases at the various burnup values for the best estimate set (which includes fission products). The fourth column presents analogous results, but the computed difference is between the zero burnup case and the actinide-only burnup credit set. The fifth column gives the ratio of the values in columns four and three to show the reactivity percentage accounted for with actinide-only burnup credit. It is easily noted that credit is taken for only half of the reactivity change.

![TABLE IV. CONSERVATISMS IN THE CHANGE IN REACTIVITY AS A FUNCTION OF BURNUP](image)

<table>
<thead>
<tr>
<th>Enrichment (wt.% U-235)</th>
<th>Burnup (GW-d/tU)</th>
<th>Best Estimate Change in Reactivity with Burnup (% k)</th>
<th>Actinide-Only Change in Reactivity with Burnup (% k)</th>
<th>Percent of Best Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>15</td>
<td>19.4</td>
<td>8.7</td>
<td>45%</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>34.5</td>
<td>16.9</td>
<td>49%</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>46.6</td>
<td>23.1</td>
<td>50%</td>
</tr>
<tr>
<td>3.6</td>
<td>15</td>
<td>18.2</td>
<td>8.3</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>32.8</td>
<td>16.4</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>45.6</td>
<td>23.1</td>
<td>51%</td>
</tr>
<tr>
<td>4.5</td>
<td>15</td>
<td>16.5</td>
<td>7.7</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>29.9</td>
<td>15.2</td>
<td>51%</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>42.5</td>
<td>21.9</td>
<td>52%</td>
</tr>
</tbody>
</table>

Tables III and IV review only the conservatisms in the isotopic calculations and exclusion of the fission products. In addition to those, conservatism is also present due to the use of the most limiting axial burnup profiles. Again, since these profiles are all possible profiles, it might not be appropriate to consider this as a conservatism, yet most fuel assemblies have burnup profiles that do not produce positive end effects with the actinide-only assumption. In the methodology, it is assumed that the package is full of assemblies with the limiting profile. Clearly, most packages will contain assemblies with a mix of axial profiles. The magnitude of this conservatism can be estimated similar to the $k_{eff}$ bias curves (Figure 4). This results in a few more % $k$ conservatism.

There is also a conservatism due to the horizontal burnup tilt. Although small for large packages, the effect is considerably large for four assembly packages. For this conservatism, it is not only assumed that strong horizontal gradients exist in every assembly, but that they are loaded in the most limiting way.

Other conservatisms are also introduced in the criticality validation and measurement sections. Additionally, the method does not give credit for those assemblies with reactivities below the maximum allowed. The aggregate of these below design basis reactivities provides additional criticality safety margin and conservatism.
The methodology presented in this paper has been developed to meet the regulatory assumption of limiting $k_{eff} = 0.95$, which has been determined to provide an adequate safety margin. The conservatisms that have been discussed here are in excess of that margin.

5. SUMMARY

A conservative methodology has been presented that can allow higher capacity spent fuel packages. The higher capacity will result in reduced public risk to reduced transportation accident potential as well as an economic benefit. The method treats all aspects of the analysis in a demonstratively conservative way and maintains as added conservatism the fission products. It also maintains the standard assumptions of flooded conditions with a 5% $k$ administrative margin.

In order to implement burnup credit, the method requires validating the computer code’s predictions of isotopic content and reactivity worth. It also requires limiting parameters be used in the depletion modeling and package modeling. Finally, the method requires a measurement to confirm the utility reactor records of burnup.
REFERENCES


