ENHANCEMENTS TO THE BURNUP CREDIT CRITICALITY SAFETY ANALYSIS SEQUENCE IN SCALE

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STARBUCS is the SCALE sequence dedicated to criticality safety analyses employing burnup credit. STARBUCS enables simulation of important burnup credit phenomena, and its input options allow analysts or reviewers to investigate the impact on criticality safety of various assumptions related to the burnup credit calculation methodology for spent nuclear fuel in transport or storage casks. Options are provided to model the axial and radial burnup variations within a spent fuel assembly, to select the actinide and fission product nuclides to be included in spent fuel compositions, and to adjust the predicted inventories to account for isotopic composition bias and bias uncertainty. Sequence enhancements available with the SCALE 6 release include the capability to perform a burnup loading curve search and the ability to use continuous-energy Monte Carlo criticality calculations. This paper presents a review of the STARBUCS features available in SCALE 6, STARBUCS applications that illustrate the impact of various modeling assumptions on burnup loading curves, and a comparison between STARBUCS calculations using SCALE multi-group and continuous energy cross-section libraries in terms of computer time and k_{eff} results for various spent fuel configurations.

I. INTRODUCTION

Burnup credit is the approach of taking credit for the reduction in reactivity as a result of fuel irradiation in nuclear criticality safety analyses. This approach reduces considerable conservatism (20% – 50% Δk_{eff}) caused by the fresh fuel assumption commonly used within criticality safety analyses for various spent fuel applications, including pool storage at nuclear power plants, cask transport and storage, disposal, and reprocessing. The use of burnup credit enables increased capacity in casks or pools, therefore significantly reducing the required number of transport/storage casks, shipments, and handling operations, as well as the volume of storage/repository. Burnup credit introduces additional complexity into the criticality safety analysis because the effective neutron multiplication factor, k_{eff}, of a spent fuel system depends on assembly design, burnup, initial enrichment, reactor operating history, post-irradiation cooling time, etc. Credit for fuel burnup necessitates determination of appropriate depletion conditions,[1,2] selection of nuclides to be credited[3] in spent fuel composition based on nuclide importance and availability of validation data, consideration of spatial burnup distributions[4] and cooling time,[5] validation of analysis codes and nuclear data using applicable critical experiments[6,7] and radiochemical assay measurements, techniques for using data for validation,[8] and additional measures to ensure proper cask loading (e.g., generation of loading curves, use of reactor record burnup data/uncertainties, and administrative controls).

The U. S. Nuclear Regulatory Commission Spent Fuel Project Office initiated a burnup credit research program with Oak Ridge National Laboratory (ORNL) to provide the confirmatory analyses and technical basis for Interim Staff Guidance 8 (ISG–8), *Burnup Credit in the Criticality Safety Analyses of PWR Spent Fuel in Transport and Storage Casks*.[9] The current regulatory guidance published in ISG–8 Rev. 2 provides recommendations on limits for the licensing basis, code validation, licensing-basis model assumptions, loading curves, assigned burnup loading values, and estimation of additional reactivity margins. To assist in performing and reviewing the criticality safety assessments of transport and storage casks that apply burnup credit, ORNL has developed a SCALE (Standardized Computer Analyses for Licensing Evaluations) analytical sequence called STARBUCS (Standardized Analysis of Reactivity for Burnup Credit using SCALE).[10,11] STARBUCS enables modeling phenomena important to burnup credit and allows analysts and reviewers to investigate the impact on criticality safety of various assumptions related to the burnup credit calculation methodology for spent fuel in transport and storage configurations. SCALE 6 provides a burnup loading curve search capability in addition to the initial capability available in SCALE 5.1 for performing criticality safety analysis employing burnup credit for spent fuel systems. This paper reviews the STARBUCS features available in SCALE 6 and presents STARBUCS applications that demonstrate its capabilities to model phenomena important to burnup credit.

II. STARBUCS SEQUENCE FEATURES

The STARBUCS sequence in SCALE 6 performs two types of calculations, currently limited to UO_2 fuel types: (1) burnup credit criticality calculations for three-dimensional (3–D) spent fuel systems (e.g., spent fuel casks or pools) and (2) generation of burnup loading curves of spent fuel in transport/storage casks or pools. Users have the option to request one of these two types of calculations in an input file. STARBUCS uses existing, well-established, functional modules in the SCALE system to perform integrated depletion analysis, cross-section processing, and Monte Carlo criticality calculations for a 3–D spent fuel system. As a control module, STARBUCS creates input for the codes used by the sequence, executes the codes, and performs all data transfer functions. STARBUCS uses the Automatic Rapid Processing (ARP) methodology[12] for a fast point-depletion analysis with ORIGEN-S (Ref. 13), applies the ORIGEN calculated spent fuel compositions to the criticality model, and prepares an input file for the SCALE criticality analysis sequence CSAS5 (KENO V.a) (Ref. 14) or CSAS6 (KENO–VI) (Ref. 15).

II.A STARBUCS Input

STARBUCS input includes input parameters for ARP, ORIGEN–S, and either CSAS5 or CSAS6 and additional parameters related to burnup credit methodology. The input is organized into data blocks including: (1) a standard *composition* data block used to define initial (fresh) fuel compositions and all other materials in the criticality analysis problem, (2) a *control* data block containing parameters related to the burnup credit methodology, (3) either a *history* or a *search* data block, and (4) either a KENO V.a or KENO VI geometry model. The *history* data block provides assembly irradiation parameters for a single criticality calculation employing burnup credit, whereas the *search* data block contains parameters specific to burnup loading curve calculations. A KENO V.a geometry model is required for burnup loading curve calculations.

II.B Depletion Analysis Method

The STARBUCS control module calls SCALE functional modules ARP and ORIGEN-S to determine the isotopic composition for each burnup-dependent assembly region. The ARP methodology employs generation of a problem-specific, burnup-dependent, cross-section library for ORIGEN by interpolating over parameterized cross-section data produced in advance for specific fuel assembly designs using reactor physics transport methods. For uranium-based fuels, the independent parameters best suited for interpolation include initial enrichment, burnup, and optionally, water moderator density (only for boiling water reactor assemblies).[12] Validation studies have demonstrated that the ARP interpolation algorithm produces accurate cross sections for ORIGEN depletion and decay calculations.[16,17] The SCALE code package includes pre-generated reactor cross-section libraries for a wide range of fuel designs and representative operating conditions.[12] ORIGEN–ARP cross-section libraries for fuel types and/or operating conditions not included in SCALE may be generated by the user. Conservative fuel design and in-reactor operating parameters with respect to criticality are recommended for use in transport calculations for generating ORIGEN-ARP cross-section libraries for burnup credit calculations with STARBUCS. The basic procedure to be used to generate ORIGEN–ARP cross-section libraries is described in the SCALE manual, Section D1.A.2 (Ref. 12).

II.C Criticality Calculation Method

The STARBUCS control module calls either the CSAS5 or CSAS6 control module to perform a Monte Carlo criticality calculation for a 3–D spent fuel system. The CSAS modules use either a SCALE multi-group or a SCALE continuous energy cross-section library. Continuous energy libraries based on ENDF/B–VI.8 or ENDF/B–VII.0 and multi-group cross-section libraries are available in SCALE 6 for use in criticality calculations with KENO V.a and KENO VI. Problem-dependent multi-group cross-section libraries are automatically generated by the SCALE resonance cross-section processing modules BONAMI, and NITAWL (libraries based only on ENDF/B–V evaluations) or CENTRM. The SCALE multi-group[18,19] and continuous cross-section libraries[20] have been validated against hundreds of benchmark critical experiments. The use of continuous energy cross-section libraries in STARBUCS eliminates the need for resonance cross-section processing for each burnup-dependent zone and generally reduces the overall computer time, as shown in Sec. IV.B.

II.D Burnup Loading Curve Search Method

A new STARBUCS capability is available in SCALE 6 that enables burnup loading curve generation. The purpose of the new capability is to determine the combination of assembly initial enrichment and burnup values that will result in a user-specified upper subcritical limit (USL) within a specified tolerance interval by performing iterative calculations for a set of user-specified assembly burnup values over a range of initial assembly enrichments. For each user-specified burnup value, the STARBUCS sequence (1) performs a burnup credit criticality calculation using a specified initial fuel enrichment; (2) applies the convergence criterion to the calculated k_{eff} value; (3) if convergence was not achieved, performs a least-squares analysis of the results to determine an initial fuel enrichment value that will yield the USL value; (4) performs a new burnup credit criticality calculation using the newly selected initial enrichment; and (5) terminates the iterative process if convergence is achieved or no solution exits.

III. STARBUCS CAPABILITIES

STARBUCS enables simulation of important burnup credit phenomena and can be used to investigate the impact on criticality safety of various assumptions related to the burnup credit calculation methodology for spent fuel in transport or storage casks. The input options, analysis assumptions, and geometry modeling allow an adequate representation of the physical characteristics of the spent fuel.

III.A Selection of Burnup Credit Nuclides

ISG–8 Rev. 2 recommends taking burnup credit for actinides only. However, some recent designs for spent fuel transport cask have been based on burnup credit for both actinide and fission product nuclides. A STARBUCS input option is available to select nuclides relevant to burnup credit to be included in spent fuel compositions. The concentrations for all spent fuel nuclides are available from ORIGEN–S and may be included in the criticality analysis if cross sections are available to KENO. Omitting nuclide specifications in an input file results in all nuclides being included in the spent fuel compositions. A calculation using full burnup credit (i.e, using all spent fuel nuclides with available cross-section data) is useful in evaluating the safety margin from non-credited nuclides.

III.B Isotopic Concentration Adjustment

ISG-8 Rev. 2 provides recommendations related to depletion code and cross-section data validation for spent fuel in transport and storage casks. Isotopic composition bias and bias uncertainty values may be determined using benchmarks of applicable fuel assay measurements. An input option is available to provide conservative isotopic correction factors (ICFs) for the burnup credit nuclides included in spent fuel compositions. STARBUCS uses these factors to adjust the predicted inventories to account for isotopic composition bias and uncertainty associated with the bias.

III.C Representation of Axial and Radial Burnup Variation

The user has the option to model the axial and radial variations of the burnup within a spent fuel assembly to account for local reactivity effects. A user-supplied or a default burnup-dependent 18-zone axial-burnup profile[21] can be used in STARBUCS calculations. The lengths of the burnup-dependent axial zones may be uniform or non-uniform. Reference 22 is recommended in ISG–8 Rev. 2 as a source of realistic, representative data that can be used to establish a conservative axial burnup profile for use in the licensing basis safety analysis. STARBUCS performs a separate ARP–ORIGEN run for each burnup-dependent axial zone using the supplied ORIGEN–ARP library, assembly-specific power, and zone-averaged burnup derived from assembly average burnup and the burnup-dependent axial and radial profiles. The KENO model uses the axial and radial zones for which a burnup profile is supplied in the *control* data block, and the mixture numbers assigned to the burnup-dependent zones follow the convention described in the SCALE manual, Sec. C10.4 (Ref. 10). The total number of axial and radial zones with varying burnup is limited to 100 (e.g., up to five radial burnup zones can be modeled for an 18-zone axial burnup profile).

III.D Burnup Loading Curve Search

STARBUCS enhancements available with the SCALE 6 release include the capability of performing burnup loading curve searches. A prototypic STARBUCS version not integrated into the SCALE code system has been used in previous burnup credit studies.[23] A loading curve is the minimum allowed burnup as a function of initial ^{235}U enrichment for a fuel assembly to be considered acceptable for loading. All points above the loading curve represent burnup-enrichment combinations that yield k_{eff} values that are below the user-specified USL. ISG–8 Rev. 2 provides recommendations to be applied in establishing acceptable loading curves of pressurized water reactor spent fuel in transport and storage casks. The recommendations include establishing separate loading curves for each set of applicable licensing conditions (e.g., minimum cooling time considered in the cask loading) and justifying the applicability of the loading curve to bound various fuel types or burnable absorber.

STARBUCS input parameters for burnup loading curve calculations include a burnup value array, the range of initial enrichment values for the fuel assembly, the USL value, and a USL convergence criterion. The burnup values and initial enrichment range must be within the range of burnup and enrichment values of the applicable ORIGEN–ARP library. A single USL value and a single set of ICFs that are considered to be applicable across the range of the user-supplied burnup values are used in burnup loading curve calculations. In accordance with the ISG–8 Rev. 2 recommendations, the USL value should be derived from benchmark experiments that closely represent the important features of the cask design and spent fuel contents using the burnup credit methodology computational methods and nuclear data. The USL convergence criterion value should be greater than the standard deviation of the STARBUCS calculated k_{eff} to ensure calculation convergence. Generally, STARBUCS requires between two and six iterations for each burnup value to achieve eigenvalue convergence, with an average of four iterations per burnup value. The maximum number of iterations allowed for each burnup value is 10. The computer time per iteration may vary from a few minutes to tens of minutes, mainly depending on the number of burnup-dependent zones, the number of credited nuclides in spent fuel compositions, the size of the modeled system, and the SCALE cross-section library selected for criticality calculations. Reduced output is produced by retaining the results for the last iteration calculations. The CSAS5 input files created for the burnup loading curve calculations are saved and may be used subsequently in cross-section sensitivity and uncertainty analyses with SCALE/TSUNAMI.

IV. STARBUCS APPLICATIONS

The following burnup loading curve calculations are presented to demonstrate the code capability of modeling phenomena important to burnup credit. Further, a comparison between STARBUCS calculations using SCALE multi-group and continuous energy cross-section libraries in terms of computer time and k_{eff} results is shown for various spent fuel configurations.

IV.A Burnup Loading Curve Calculations

The loading curves illustrated in Figs. 1 through 3 were obtained for a generic burnup credit cask, referred to as the GBC-32 cask,[24] which has been proposed as a reference configuration for burnup credit studies. The cask contained Westinghouse 17×17 optimized fuel assembly (OFA) spent fuel. The target k_{eff} value was 0.94 with a convergence criterion of ± 0.001. Either the STARBUCS default 18-zone axial burnup profile or a uniform axial burnup profile was used in the calculations. Note that the discontinuities in the loading curves at 18 GWd/MTU and 30 GWd/MTU are caused by the discontinuities in the axial burnup profiles at those burnup values.[21] The loading curves were plotted on a chart showing the number of spent fuel assemblies permanently discharged as of the end of 2002 (Ref. 25) with enrichment values within each 0.4 wt % ^{235}U initial enrichment interval and burnup values within each 5-GWd/MTU burnup interval. The burnup loading curves presented illustrate the impact on cask reactivity of various assumptions related to the burnup credit methodology.

The loading curves shown in Fig. 1 were obtained for the two different sets of burnup credit nuclides listed in Table 6 of Ref. 24, one set consisting of major actinides only and the other set containing additional minor actinide and fission product nuclides. For each set of nuclides, two different loading curve calculations were performed: one calculation used the ORIGEN calculated isotopic compositions for the spent fuel, and the other used adjusted spent fuel isotopic compositions to conservatively account for bias and uncertainty in the depletion conditions. The loading curves in Fig. 1 show (1) crediting minor actinide and fission products in addition to major actinides causes a larger spent fuel inventory to be acceptable for loading compared with crediting major actinides only, and (2) taking into account the uncertainties in depletion conditions in a manner that is conservative with respect to criticality causes a reduction in the spent fuel inventory considered to be acceptable for loading compared with neglecting these uncertainties. Figure 2 illustrates loading curve shifts with post-irradiation cooling time and a comparison between loading curves obtained by assuming an assembly uniform burnup and by using the default assembly axial burnup profile. To illustrate the effects of burnable absorber on loading curves, ORIGEN-ARP cross-section libraries for assemblies irradiated with and without burnable absorber were used in the calculation of burnup loading curves shown in Fig. 3. A spent fuel assembly with burnable absorber may have a higher reactivity than an assembly without burnable absorber. The graph demonstrates the importance of using appropriate assembly irradiation conditions in burnup credit analyses.

IV.B STARBUCS Computing Time for Continuous Energy Monte Carlo Calculations

Generally, a reduction in computer time is obtained by using SCALE continuous energy cross-section libraries in place of the multi-group cross-section libraries. Table I shows a comparison of the computer time obtained on a personal computer for various burnup credit criticality calculations using KENO V.a and the SCALE multi-group and continuous energy cross-section libraries V6–238 and CE_V6, respectively. The STARBUCS sample problems selected for comparison have different levels of complexity, varying from a basic infinite pin-cell model with uniform burnup to a more complex assembly configuration with burnup-dependent zones on the axial and radial directions. As shown in the table, the computer time for the calculations using the SCALE continuous energy cross-section libraries is significantly shorter than the computer time for the calculations using the SCALE 238-group cross-section library and CENTRM for resonance cross-section processing for all cases except for the simplest configuration.

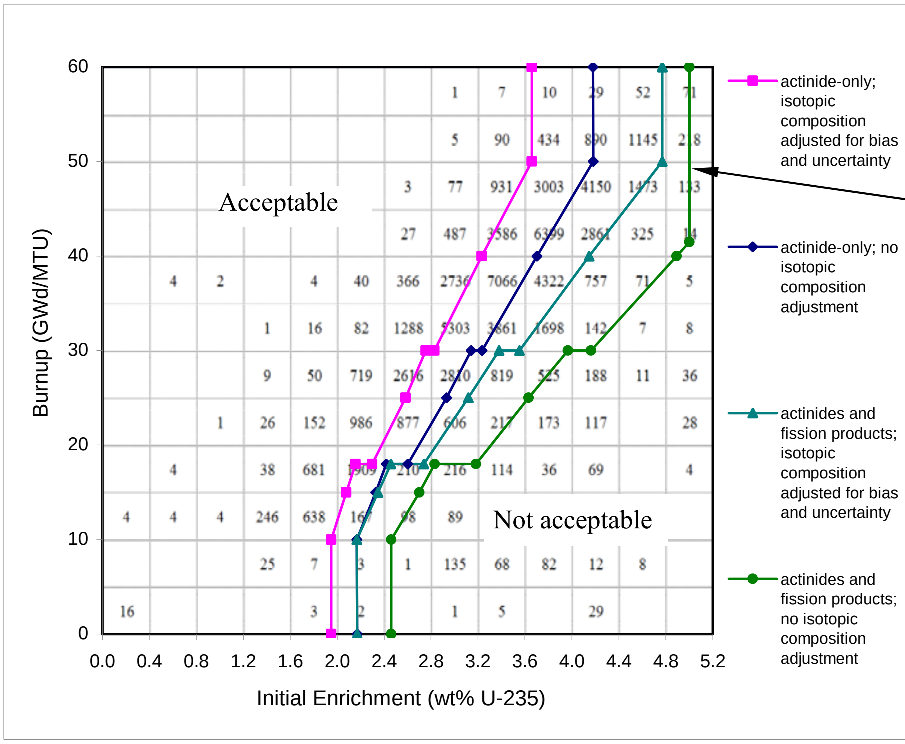

Fig. 1. Impact of credited nuclides and isotopic composition uncertainty on burnup loading curves.

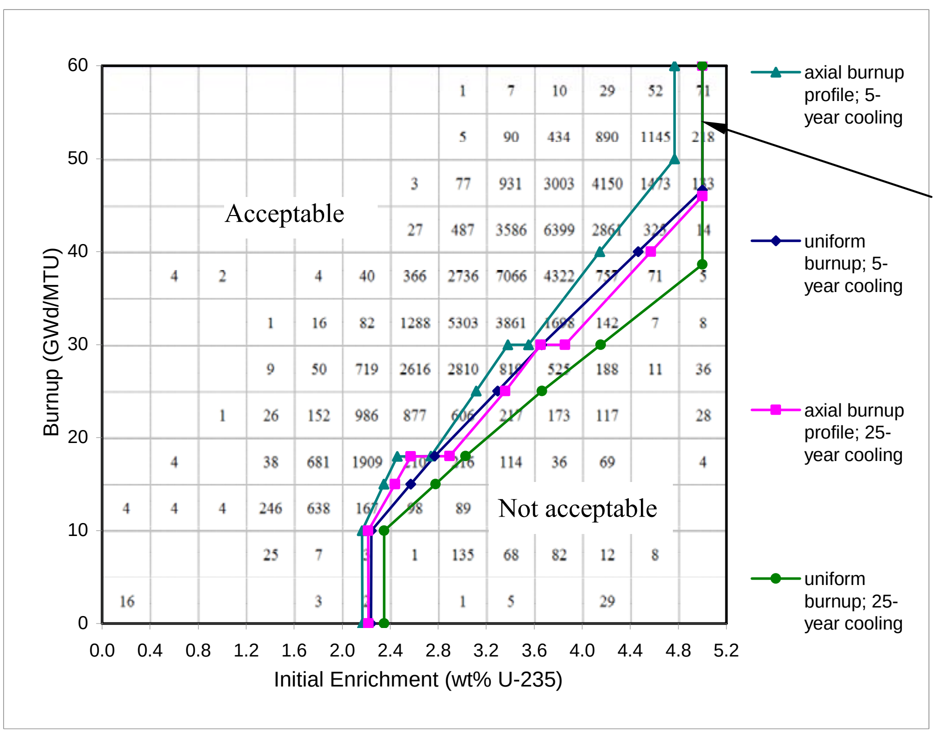

Fig. 2. Impact of burnup axial variation and decay time on burnup loading curves.

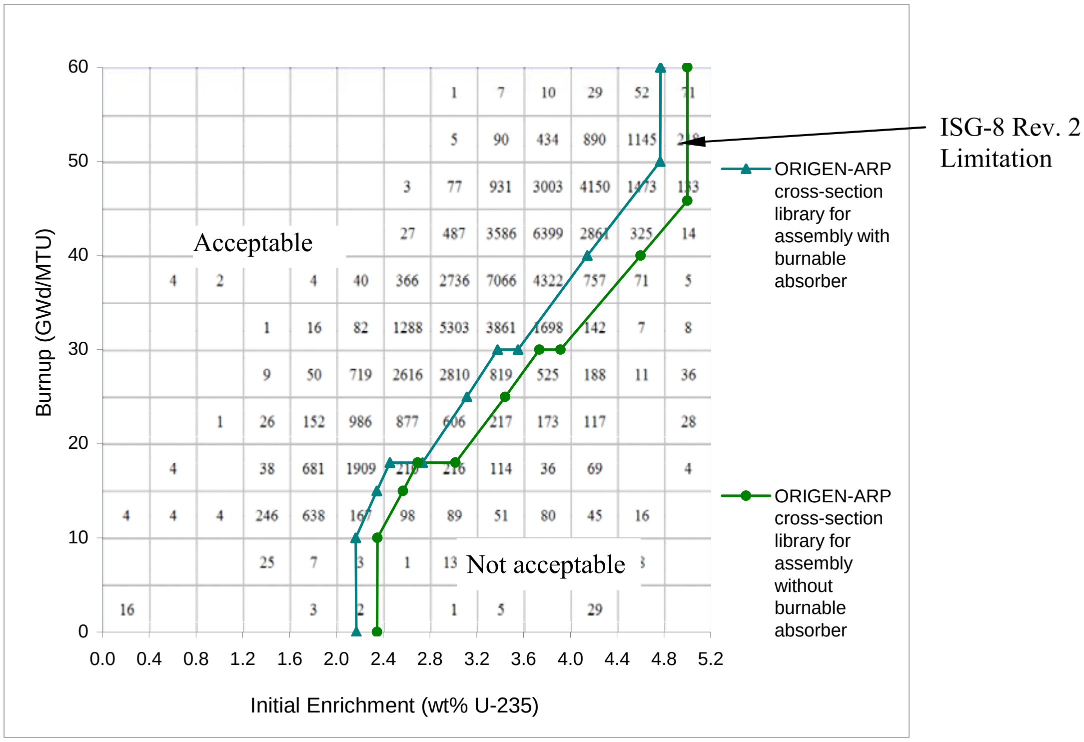

Fig. 3. Impact of fuel irradiation conditions on burnup loading curves.

Table I. Comparison of STARBUCS computer time using
SCALE multi-group and continuous energy cross-section libraries

Case No.	Model description	Computer time [a] (minutes) SCALE library V6–238 [c]	Computer time [a] (minutes) SCALE library CE_V6 [d]	k_{eff} [b] SCALE library V6–238 [c]	k_{eff} [b] SCALE library CE_V6 [d]
1	Infinite pin-cell model with uniform axial burnup; actinide only	1.5	4	1.1795	1.1863
2	Infinite pin-cell model with 18 burnup-dependent axial zones; actinide only	23.1	6	1.1033	1.1043
3	2 × 8 array of CE 14 × 14 assemblies; 18 burnup-dependent axial zones; actinide + fission products	31.6	17.3	0.8724	0.8723
4	2 × 2 array of CE 14 × 14 assemblies; 18 burnup-dependent axial zones; 2 burnup-dependent radial zones; actinide + fission products	64.5	14.7	0.7529	0.7545

[a] The CSAS5 computer time.
[b] k_{eff} standard deviation is approximately 0.1%.
[c] SCALE 238-group library based on ENDF/B–VI; resonance cross-section processing using BONAMI and CENTRM.
[d] SCALE continuous cross-section library based on ENDF/B–VI.

V. CONCLUSIONS

SCALE is an established code for use in criticality safety analyses. STARBUCS, the SCALE sequence for criticality safety analysis employing burnup credit, enables simulation of important burnup credit phenomena, evaluation of the impact of various assumptions related to the application of burnup credit methodology to nuclear criticality safety, and development of burnup loading curves for spent fuel systems. This paper presented a review of the STARBUCS features available in SCALE 6, STARBUCS applications that illustrate the impact of various modeling assumptions on burnup loading curves, and a comparison between STARBUCS calculations using SCALE multi-group and continuous energy cross-section libraries in terms of computer time and k_{eff} results for various spent fuel configurations.

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