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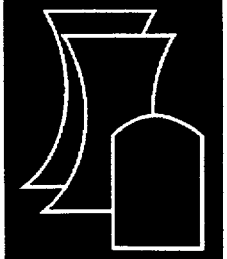

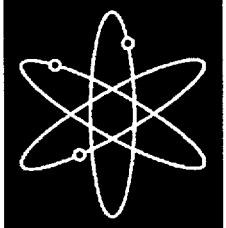

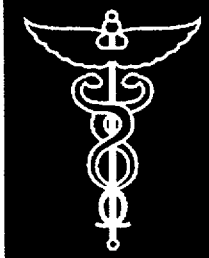

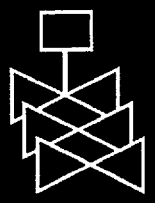

STARBUCS: A Prototypic SCALE Control Module for Automated Criticality Safety Analyses Using Burnup Credit

Oak Ridge National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

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STARBUCS: A Prototypic SCALE Control Module for Automated Criticality Safety Analyses Using Burnup Credit

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ABSTRACT

STARBUCS is a new prototypic analysis sequence for performing automated criticality safety analyses of spent fuel systems employing burnup credit. A depletion analysis calculation for each of the burnup-dependent regions of a spent fuel assembly, or other system containing spent fuel, is performed using the ORIGEN-ARP sequence of SCALE. The spent fuel compositions are then used to generate resonance self-shielded cross sections for each region of the problem, which are applied in a three-dimensional criticality safety calculation using the KENO V.a code. This prototypic burnup credit analysis sequence allows the user to simulate the axial and horizontal burnup gradients in a spent fuel assembly, select the specific actinides and/or fission products that are to be included in the criticality analysis, and apply isotopic correction factors to the predicted spent fuel nuclide inventory to account for calculational bias and uncertainties. Although STARBUCS was developed to address the burnup credit analysis needs for spent fuel transport and storage applications, it provides sufficient flexibility to allow criticality safety assessments involving many different potential configurations of spent nuclear fuel to be simulated.

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1 INTRODUCTION

The Nuclear Regulatory Commission (NRC) issued Revision 1 of the Interim Staff Guidance 8[1] (ISG8) on burnup credit in July, 1999. ISG8 provides guidance on the application of limited burnup credit in criticality safety analyses for pressurized water reactor (PWR) spent fuel in transportation and storage casks. Burnup credit is the concept of taking credit for the reduction in reactivity in spent fuel due to burnup. The reduction in reactivity that occurs with fuel burnup is due to the change in concentration (net reduction) of fissile nuclides and the production of actinide and fission-product neutron absorbers. In contrast to criticality safety analyses that employ a fresh-fuel assumption (i.e., conservatively assume unirradiated fuel compositions), credit for burnup requires the prediction of both fissile material and absorber nuclide inventories in spent nuclear fuel (SNF) and consideration of the many burnup-related phenomena, in addition to the criticality issues.

Consideration of the depletion aspects in the criticality assessment of SNF places an increasing reliance on computational tools and methods, and significantly increases the overall complexity of the criticality safety analysis. The credit for fuel burnup in criticality safety also necessitates consideration of many additional uncertainties associated with fuel depletion. ISG8 highlights, for example, the need for applicants employing burnup credit in criticality safety assessments to address the axial and horizontal variation of the burnup within a spent fuel assembly, uncertainties and bias in the isotopic predictions, and the additional reactivity margin available from fission products and actinides not credited in the licensing basis.

To assist in performing and reviewing criticality safety assessments of transport and storage casks that apply burnup credit, a new SCALE control sequence prototype, STARBUCS (Standardized Analysis of Reactivity for Burnup Credit using SCALE) has been created. STARBUCS automates the generation of spatially-varying isotopic compositions in a spent fuel assembly, and applies the assembly compositions in a three-dimensional (3-D) Monte Carlo analysis of the system. STARBUCS automatically prepares input files for each of the code modules in the sequence, executes the modules through the SCALE driver, and performs all flow control, module interface, and data management functions. The prototypic STARBUCS sequence uses the well-established code modules currently available in the SCALE-4 code system.[2]

The STARBUCS sequence automates the depletion calculations using the ORIGEN-ARP methodology[3,4] to perform a series of cross-section processing and depletion calculations to generate a comprehensive set of spent fuel isotopic inventories for each spatially-varying burnup region of an assembly. The spent fuel isotopics are subsequently input to the SCALE Criticality Safety Analysis Sequence (CSAS)[5] to generate the resonance self-shielded macroscopic cross sections for each burnup-dependent fuel region. Finally, a calculation using the KENO V.a code[6] is performed using the spatially-varying cross sections to determine the neutron multiplication factor (k_{eff}) for the system. Only minimal input is required by the user to perform a burnup credit analysis. The user may specify the assembly-average irradiation history of the assembly, the axial moderator density, the axial and horizontal burnup profile, and the nuclides that are to be credited in the criticality safety analysis. Isotopic correction factors may also be applied to account for known bias and/or uncertainty in the predicted SNF compositions.

2 TYPE OF PROBLEMS STARBUCS CAN ANALYZE

STARBUCS is designed to facilitate burnup credit criticality safety analyses employing burnup credit by automating and linking the depletion and criticality calculations. The STARBUCS burnup credit sequence has been designed to readily allow analysts and reviewers to assess the subcritical margins associated with many of the important phenomena that need to be evaluated in the context of the ISG8 guidance. However, STARBUCS is sufficiently general to allow virtually any configuration involving spent nuclear fuel to be analyzed. Some of the key capabilities of the STARBUCS prototype are described below.

1. The types of spent fuel configurations that can be analyzed are very general. STARBUCS can be used to perform criticality safety assessments of individual fuel assemblies, a spent fuel cask, a spent fuel storage pool, or any nuclear system containing SNF.

2. A spatially-varying burnup distribution is accounted for using a finite number of axial and, optionally, horizontal burnup zones. An arbitrary axial burnup profile may be used. Several built-in burnup-dependent profiles are provided as options.

3. Burnup calculations can incorporate any desired operating history. The user may specify the specific fission power, cycle lengths, cycle down time, post-irradiation cooling time, etc. The axial water moderator density variation may also be specified for the depletion analysis.

4. The effects of assembly design, burnable poison exposure, reactor operating conditions, etc., are accounted for in the ARP cross-section libraries used in the depletion calculations. These libraries can be readily created for any reactor and fuel assembly design that can be represented in the SAS2H depletion analysis sequence of the SCALE code system.

5. The user can select the specific actinide and/or fission product nuclides to be included in the criticality safety analysis. The user also has the option to perform a criticality calculation employing all nuclides for which cross-section data exist.

6. Isotopic correction factors may be input to adjust the calculated nuclide inventories to account for known bias and/or uncertainties associated with the depletion calculations.

7. STARBUCS may be extended to include an iterative search capability to automate the generation of loading curves, which define the acceptable enrichment and burnup combinations for a given configuration of spent fuel (e.g., SNF transport or storage casks, storage racks in a spent fuel pool, etc.).

3 METHODOLOGY

The STARBUCS program is a burnup credit sequence designed to perform a 3-D criticality safety calculation that includes the effects of spatially-varying burnup in a configurations of spent nuclear fuel. The sequence performs an automated fuel depletion analysis for each of the spatially-varying burnup regions of an assembly, creates resonance-corrected cross sections based on the fuel assembly design and spent fuel compositions, and perform a 3-D Monte Carlo calculation for k_{eff} using the KENO V.a code.[6] STARBUCS prepares input files for each of the codes used in the sequence, handles the data management and interface functions between the various codes, and executes each of the codes in the required order.

The burnup credit sequence uses the well-established code modules currently available in the SCALE-4 code system. These code modules include ARP[3] and ORIGEN-S[7] to perform the depletion analysis phase of the calculations. ORIGEN-ARP[4] is a sequence within the SCALE system that serves as a faster alternative to the SAS2H sequence[8] of SCALE to perform point-irradiation calculations with the ORIGEN-S code using problem-dependent cross sections. ARP (Automatic Rapid Processing) uses an algorithm that enables the generation of cross-section libraries for the ORIGEN-S code by interpolation over pregenerated SAS2H cross-section libraries. The ORIGEN-S code performs the isotopic generation and depletion calculations to obtain the spent fuel compositions. Cross sections for the criticality analysis are processed through the resonance self-shielding codes BONAMI[9] and NITAWL[10] using the region-dependent compositions from the depletion analyses. Finally, the cross sections are applied in KENO V.a,[6] which calculate the k_{eff} value for the 3-D system.

The ORIGEN-ARP depletion analysis methodology represents a significant increase in computational speed as compared to equivalent calculations performed using the SCALE depletion analysis sequence SAS2H, without sacrificing accuracy. ARP uses an algorithm that enables the generation of cross-section libraries for the ORIGEN-S code by interpolation over pregenerated cross-section libraries using initial fuel enrichment, burnup and, optionally, moderator density as the interpolation parameters. STARBUCS creates input files for ARP and ORIGEN-S for each burnup-dependent region of an assembly and calculates the spent fuel compositions for the region using a user-specified assembly irradiation history, cooling time, and burnup profiles. The ARP cross-section libraries must be available in advance of a STARBUCS burnup credit calculation, and may be created using the SAS2H depletion analysis sequence of SCALE. These libraries include the effects of assembly design and operating conditions on the cross sections. Several ARP libraries are distributed in the SCALE code system (for boiling water reactors an 8×8 library, and for pressurized water reactors a 14×14, 15×15, and 17×17 library) and can be applied in a burnup credit analysis. Alternatively, a user may create a specific ARP library for other assembly types or operating conditions to capture reactor operating or design effects not available in the default libraries. The generation of ARP libraries is discussed in Ref. 4.

The depletion phase of the sequence uses ARP and ORIGEN-S to calculate the compositions of each fuel region (axial or horizontal). After a single ORIGEN-ARP depletion calculation is completed, control is passed back to the STARBUCS module which reads the spent fuel inventories generated by ORIGEN-S, saves them, prepares the ARP and ORIGEN-S input files for the next burnup region, and executes the codes in sequence. This cycle continues until the fuel compositions for all axial and horizontal regions have been calculated and saved, completing the depletion phase of the analysis. The depletion calculations for each axial and radial zone are performed using an initial fuel basis of 1 MTU (10^6 g U).

After all depletion calculations are completed, the STARBUCS control module reads the spent fuel isotopic inventories for all regions and prepares input for the resonance cross-section self-shielding calculations, converting the saved nuclide concentrations from gram-atom units to atoms/b-cm. Resonance-corrected cross sections for the criticality calculation are generated using the capabilities in the CSAS control module. Specifically, STARBUCS prepares input to the CSASI sequence of the CSAS module of SCALE, which performs Bondarenko self-shielding of the unresolved resonance range using the BONAMI code, and applies Nordheim self-shielding corrections in the resolved resonance range for nuclides with resonance parameters. The CSASI sequence applies the ICE module[11] to produce mixed, or macroscopic, cross sections for each mixture (burnup-

dependent region). This greatly reduces the data management complexity of STARBUCS since it eliminates the need to store and manage the concentrations and microscopic shielded cross sections for the individual isotopes in the spent fuel by reducing the mixture data to a single set of effective macroscopic fuel cross sections. Following each CSASI case, the WAX utility[12] code takes the macroscopic cross sections generated by CSASI and renumbers the fuel cross-section identifier (to avoid generating duplicate numbers) to a unique identifier for the specific axial or horizontal burnup region, and appends the cross section to create a single cross-section library containing the cross sections for all fuel regions. The CSASI and WAX cases are stacked sequentially for each fuel region and are executed by the SCALE driver. Following completion of these cases the KENO V.a criticality calculation is performed using the input data provided by the user and the burnup dependent cross sections prepared from the depletion analysis calculations. The overall program structure and flow is illustrated in Figure 1.

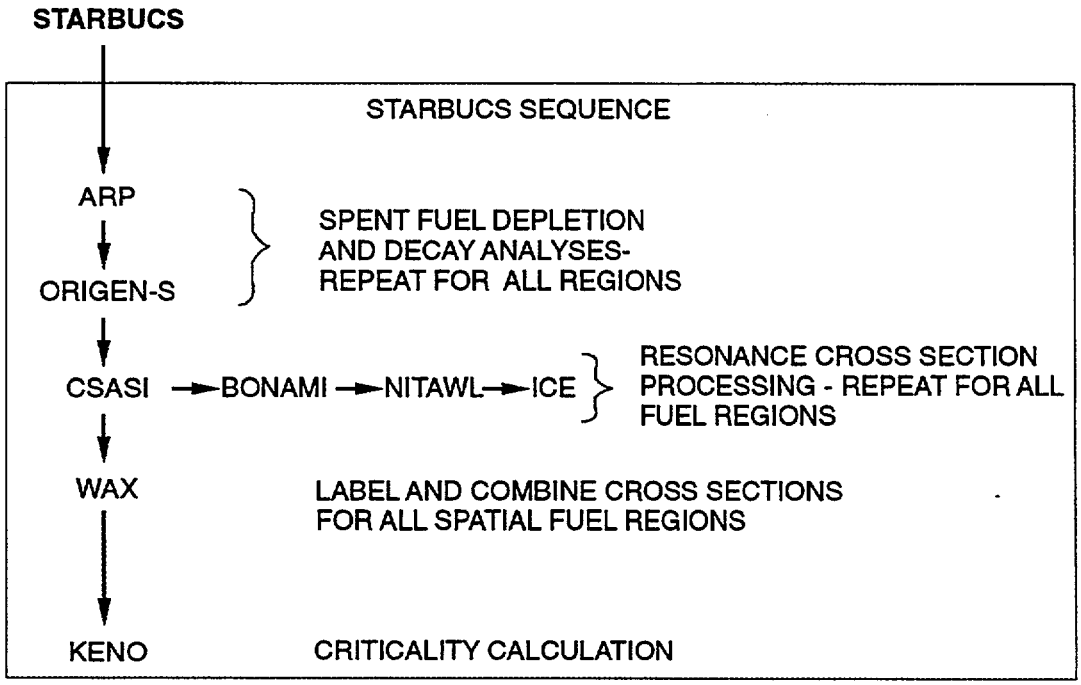

Figure 1 Modules and flow of STARBUCS sequence

4 PROGRAM FLOW

4.1 Overview

The STARBUCS program is designed to run as a control module within the SCALE system. The depletion phase of the analysis, used to generate the spatially-varying isotopic compositions in the spent fuel, is performed using repeated ARP and ORIGEN-S calculations. The input files for these codes are generated automatically by STARBUCS. A decision was made early in the development of this sequence to use formatted, standard text input files for these codes (ORIGEN-S has an option to read unformatted binary input which is used in the other control modules in the SCALE-4 code system). The formatted input allows the user to readily verify the input used by the depletion analysis modules. This decision however, required the input routines of both ARP and ORIGEN-S be slightly modified in order to function as modules within the STARBUCS sequence. The changes allow formatted input to be read from a unit other than unit 5.

The cross-section processing phase of a STARBUCS analysis is performed using the Criticality Safety Analysis Sequence, CSAS. This is an unconventional approach since the SCALE system driver is not designed to allow a control module (i.e., STARBUCS) to call another control module (i.e., CSAS). However, this approach significantly simplifies the sequence and expedited development of STARBUCS. It is not necessary to generate input files for the functional modules BONAMI, NITAWL, and ICE, because this capability was already available in the CSAS sequence. In order to implement this capability within SCALE, the formatted input generated for CSAS is written to the input file used by the SCALE driver (SYSIN). During a burnup credit calculation, the STARBUCS program reads the input file transferred by the driver. After the depletion phase of the calculation has been completed, STARBUCS writes/appends the input files for all CSAS cases, plus the input for the KENO V.a criticality calculation, to the SYSIN file. STARBUCS instructs the driver that it has finished its processing, and the driver then continues to read the SYSIN file and executes each of the CSAS cases and the KENO V.a calculation. Consequently, any additional cases stacked after the STARBUCS case (after the END) will be overwritten during the sequence. Therefore, no additional cases may be placed after a STARBUCS case (e.g., multiple stacked STARBUCS cases or other modules following a STARBUCS case are not allowed).

Ultimately, it is planned to integrate the STARBUCS control module more fully within SCALE to allow multiple cases to be run consecutively. This will be done by integrating the relevant subroutines from CSAS directly into STARBUCS and calling each of the functional modules in the sequence directly (see Section 10, Future Developments). Instead of using CSAS to generate the input for each of the cross-section shelf-shielding function modules BONAMI, NITAWL, and ICE (see Figure 1), all the functional modules would be controlled by STARBUCS alone.

The overall program call structure is illustrated in Figure 2. Calls to the SCALE subroutine library, and intrinsic procedures, are shown as the routine name with no box. The main program module, STARBUCS, controls the program flow. This module is divided into two major sections; the first section reads the user input, processes the initial material compositions, and performs the depletion analysis; the second section processes the spent fuel isotopic compositions required for the cross-section processing, and subsequently performs the criticality safety analysis. The program subroutines are described below in the order of the program flow.

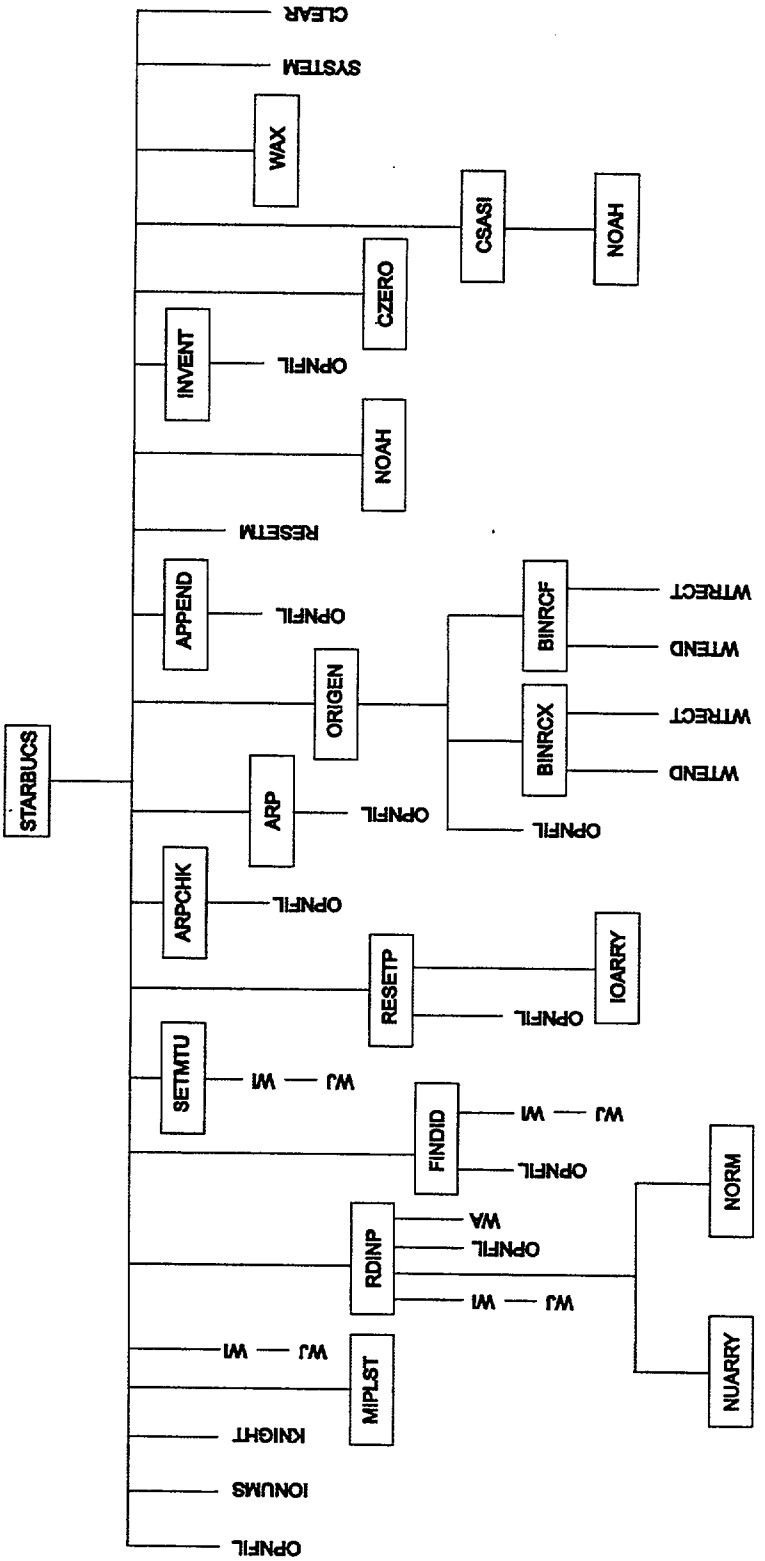

Figure 2 STARBUCS subroutine call tree

4.2 Subroutine Descriptions

Routine Name: STARBUCS

Routines Called: OPNFIL, IONUMS, KNIGHT, MIPLST, WI, RDINP, FINDID, SETMTU, RESETP, ARPCHK, ARP, ORIGEN, APPEND, RESETM, NOAH, INVENT, CZERO CSASI, WAX, SYSTEM, CLEAR

Function: STARBUCS is the main program called by the SCALE driver. The main function is the overall control of the program flow. During the initial execution of STARBUCS in the sequence, the program reads the standard compositions (initial material specifications) via subroutine KNIGHT that is a standard routine in the Material Information Processor of the SCALE system. KNIGHT provides the array data containing the nuclide IDs, the mixture numbers, zone temperatures, and the atomic number densities for all materials in the problem. The OPNFIL subroutine is used to open files using standard SCALE filename conventions. IONUMS is used to initialize the file input and output units used by the SCALE read routines. MIPLST prints the results of the material compositions from KNIGHT. The WI subroutine is also used to print array data to the output if the debug option (BUG=yes) is requested. The rest of the input file is read by RDINP. RESETM is another SCALE subroutine that is used to set the control parameters for communication between the control module and the driver.

Routine Names: RDINP, FINDID, SETMTU, RESETP

Function: RDINP reads all user input after the standard composition data. All reading is performed using the SCALE reading functions AREAD, CREAD, IREAD, LREAD and FREAD (for character*4 character*8, integer, logical, and floating-point input data, respectively). The character nuclide identifiers used to specify the burnup credit nuclides and isotopic correction factors are read and parsed by the NUARRY subroutine. A user-input axial or horizontal burnup profile is normalized, optionally, using a call to subroutine NORM. FINDID converts the SCALE nuclide IDs to ORIGEN-S IDs and determines the library type (e.g., actinide, light element, or fission product) of the nuclide. SETMTU calculates the volume of fuel that will result in 1 MTU. The volume is used to convert the atomic number densities calculated by KNIGHT into mass units used in the depletion calculation with a basis of 1 MTU. After all of the input has been read and processed, the input and other data parameters are saved to a formatted file by subroutine RESETP using calls to subroutine IOARRY.

Routine Names: ARPCHK, ARP, ORIGEN, APPEND

Function: ARPCHK verifies that the initial fuel enrichment and discharge burnup of each burnup-dependent region is within the range of the ARP library specified, and halts the sequence if the ranges are exceeded. The ARP and ORIGEN subroutines create the formatted input files for the depletion modules. The ORIGEN subroutine uses calls to BINRCX and BINRCF to write FIDO input fields of floating-point and integer type, respectively, for the ORIGEN-S code. These routines call WTEND and WTRECT to write data end and block terminators. Input files are created for each node, one node at a time. That is, after an ARP-ORIGEN calculation is performed for the first node, control is returned to STARBUCS where the nuclide inventories are saved to a binary file by APPEND, and the input data for the next node are created and the depletion modules are executed. This cycle is repeated until the spent fuel compositions for all nodes have been computed and saved.

Routine Names: INVENT, CZERO, NOAH, CSASI, WAX

Function: After the depletion analysis phase is complete, the spent fuel isotopic compositions are read and processed, and the criticality analysis modules are prepared. INVENT reads the binary file created by APPEND during the depletion calculations that contains the complete nuclide inventory for each node. Subroutine CZERO is then called to perform two functions. It first checks for the nuclides that are available on the cross-section library that will be used in the criticality calculation, and secondly checks for the nuclides that have been specified as burnup credit nuclides that are to be used in the criticality analysis. If neither criteria is met, the concentration of the nuclide is set to zero which is a flag that it will not be used in the criticality analysis. NOAH is called to convert the ORIGEN-S nuclide IDs for the nuclides in the criticality analysis into alphanumeric names recognized by the SCALE Material Information Processor (e.g., 922350 is the identifier for ^{235}U). Subroutine CSASI is called to write the input for the CSAS for each of the fuel regions in the problem. After the input for each region is created, a WAX case is appended. The WAX case is required to copy the cross-section set generated by CSAS for the given fuel region to another file containing the cross-section data for all fuel regions. This is required since the cross-section file created by CSAS is overwritten during each run.

After the input for the cross-section processing modules has been created for each of the spatial zones, STARBUCS appends the input, in addition to the KENO V.a file, to the SCALE input file (SYSIN) using the intrinsic procedure SYSTEM. Control is then passed back to the SCALE driver, which executes each of the CSAS and WAX cases, and finally the KENO V.a criticality calculation.

5 CAPABILITIES AND LIMITATIONS

STARBUCS is designed to perform criticality safety analyses that employ burnup credit. Minimal user input is required to perform many types of analyses. Default values are supplied for many of the input parameter keywords. The user may select from built-in burnup-dependent 18-axial-zone profiles,[13,14] or the user may input an arbitrary user-defined burnup distribution with up to 100 axial zones and up to 10 horizontal zones. The depletion analysis calculations for each zone are always performed for all nuclides (the ORIGEN-S data libraries contain cross-section and decay data for more than 1000 unique nuclides). The specific nuclides to be considered in the k_{eff} analysis may be input by the user. If no nuclide set is explicitly selected, then all nuclides that have cross-section data in the library will be automatically applied in the criticality analysis, resulting in a "full" burnup credit criticality assessment. A capability to adjust the calculated isotopic inventories using correction factors that can account for biases and/or uncertainties in the calculated isotopic concentrations is also provided.

An appropriate ARP cross-section library must be available for the depletion analysis using STARBUCS. The user may use the libraries distributed with SCALE (e.g., 14 × 14, 15 × 15, 17 × 17) or the user may generate their own problem-specific libraries using SAS2H.[8] Methods for generating the ARP libraries are described in Section D1.A.2 of the SCALE manual.[4]

The user is required to provide a complete KENO V.a model of the spent fuel configuration. Although STARBUCS was designed with spent fuel transportation and storage casks in mind, any valid KENO V.a criticality model can be used for the analysis. For example, STARBUCS could be used to analyze a spent fuel storage pool, transportation cask accident configurations, fuel processing/reprocessing operations, or fissile solution storage tanks.

The initial material composition information is defined in a standard composition data block. The fuel material is automatically depleted in the sequence for each of the axial and/or horizontal burnup-dependent regions of the problem, and macroscopic self-shielded cross sections are generated for each region. The macroscopic cross sections applied in the KENO V.a analysis contain all composition information, and therefore no compositions are explicitly required in the KENO V.a input model. The cross sections for each of the fuel regions are identified by unique mixture numbers assigned by STARBUCS based on the axial and horizontal region in the problem (see Figure 3). The user is required to specify the geometry/extent of the axial and horizontal zones in the KENO V.a model and apply the appropriate mixtures for the desired configuration. STARBUCS performs no checking of the criticality model to verify that all mixtures in the problem have been used or if the order of the mixture numbers in the KENO V.a model corresponds to the order of the input profile. This provides the user a great deal of flexibility in setting up problems. However, it also requires that the user accurately prepare the input files to ensure that the spent fuel region cross sections are assigned to the correct KENO V.a geometry region. For instance, the user could (intentionally) reverse the order of the axial material identifiers in the KENO V.a model to simulate inverted fuel, or simulate a problem using only a subset of the available fuel regions.

There are several conventions that must be followed when using STARBUCS. In general, these relate to the specification of materials and mixture numbering of the cross-section mixing table.

1) All structural materials in the problem (MX > 3) must be numbered contiguously.

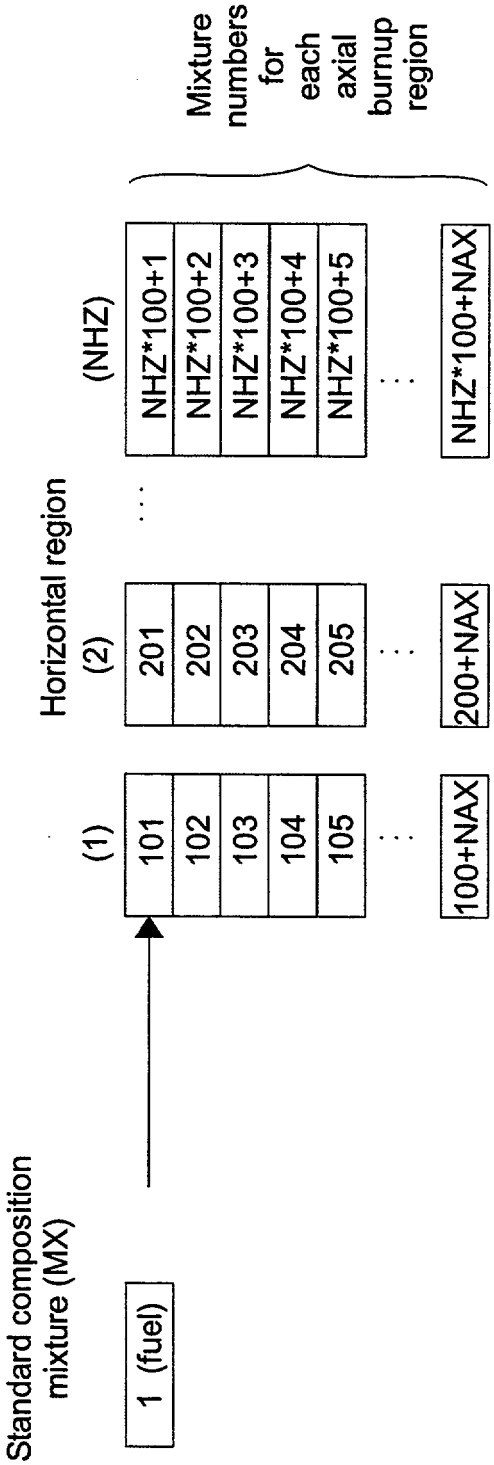

Figure 3 Fuel and material mixture numbering convention used in STARBUCS

2) Not all SCALE standard composition alphanumeric names[15] (see Section M8 of SCALE manual) are currently recognized by STARBUCS. The use of special materials (e.g., C-GRAPHITE, NIINCONEL, H-POLY) that have nuclide identifiers that are not readily translated to ZA numbers should presently be avoided.

3) SCALE cases may not be stacked after the STARBUCS input file. Any cases placed after the STARBUCS case will not be executed by the SCALE driver.

4) Only a single initial fuel material may be defined in the problem for depletion. Therefore, only one initial enrichment may be used.

6 SPECIAL SETUP REQUIREMENTS

The STARBUCS control module has been designed to create formatted, card-image text input files for all codes (functional modules and control modules) in the sequence. This allows the user to easily read the input files created by STARBUCS and verify the input. To accomplish this, minor modifications were required for the ARP and ORIGEN-S codes to allow the codes to read card-image input from a file other than logical unit 5 (a restriction in SCALE-4). In addition, an updated version of the SCALE driver that allows the STARBUCS control module to call the CSAS control module is needed. The Standard Composition Library must be Rev. 17 or later. The user must establish links, or place the modified versions of these codes and the Standard Composition Library in the SCALE working directory prior to executing a STARBUCS case. The links may be established prior to executing a STARBUCS case by overriding the links established by the SCALE script, or new links may be created in the STARBUCS input file using the `=shell` command followed by the new link directives, and terminated with an `end`. A link to the STARBUCS program executable must also be present in the SCALE working directory.

Note that the special requirements needed to run STARBUCS under SCALE-4 will not be required with SCALE-5.

7 LOGICAL UNIT ASSIGNMENTS

Table 1 lists the logical unit Nos. created and accessed by STARBUCS and the functional and control modules it executes. All input file interfaces are in text (BCD) format.

Table 1 File parameters for logical units

Unit No.	Variable	Type of file	Description
5	N5	BCD	Free-format input file
6	N6	BCD	Printed output
71	N71	Binary	ORIGEN-S nuclide inventories
72	NSAV	Binary	ORIGEN-S nuclide inventories (all cycles)
92	NICE	BCD	CSAS input file (scratch)
91	N91	BCD	ARP input file
(33)[a]	NDSET	Binary	ARP generated cross-section library (default)
93	N93	BCD	KENO V.a input (scratch)
94	N94	BCD	ORIGEN-S input file
99	N99	BCD	Data storage

[a] Units in parentheses may be reset by user input data.

8 INPUT DESCRIPTION

The input is divided into different data blocks containing related types of information. The standard composition data block used to define initial (fresh) fuel composition and all other materials in the criticality analysis problem, is read and processed by the Material Information Processor of SCALE and conforms to the standard input conventions (summarized in Section 8.3). In addition to the standard composition data, STARBUCS defines three more main input data blocks. The data blocks are entered in the form

READ XXXX input data **END XXXX**

where **XXXX** is the data block keyword for the type of data being entered. The types of data blocks that are entered include general control parameter information, irradiation history and decay data, and the KENO V.a input specifications. The valid block keywords are listed in Table 2. A minimum of four characters is required for a keyword. However, the keywords can be up to twelve characters long, the first four of which must be input exactly as listed in the table. Entering the words **READ XXXX** followed by one or more blanks activate data input. All input data pertinent to block **XXXX** are then entered. Entering **END XXXX** followed by two or more blanks terminates data block **XXXX**.

All input within a data block is entered using keywords and is free format. Keyword entries may be of variable or array type. Variable keyword entries include the keyword plus the "=", followed by the value. Array keywords are usually followed by a series of entries, each separated by a blank or comma, and must always be terminated with an END that does not begin in column one. In some instances a single value may be input as an array entry; however, the word END is still always required. Within a given input data block the keyword entries may be in any order.

The input records are limited to a maximum of 80 columns. A single data entry may be entered anywhere in a record but can not be divided between two records; however, array data entries may be divided over many records. The code identifies keywords using only the first four (maximum) characters in the keyword name. Beyond the first four characters, the user may enter any alphanumeric or special character acceptable to FORTRAN, including single blanks, before the "=" character. Floating-point data may be entered in various forms; for example, the value 12340.0 may be entered as: 12340, 12340.0, 1.234+4, 1.234E+4, 1.234E4, or 1.234E 04. Also, the value 0.012 may be entered as 12E-3, 12-3, 1.2-2, etc. Numeric data must be followed immediately by one or more blanks.

Table 2 Valid data block keywords

Data block type	Keyword*
Control parameters	CONTROL
Irradiation history	HISTORY
KENO V.a input	KENOVA or KENO-VA

*Only the first four characters of keyword are required

8.1 Overview of Input Structure

An overview of the input to the STARBUCS sequence is given in Table 3. This table provides an outline of the input data block structure. The input in data positions 1 to 6 (see Table 3) are read and processed by the Material Information Processor[16] of SCALE. These are the first data read by the code and must be in the order indicated. Data positions 7, 8 and 9 are read directly by STARBUCS and may be in any order.

Table 3 Outline of input data for the STARBUCS sequence

Data position	Type of data	Data entry	Comments
1	Sequence specification	=STARBUCS	Begin in column 1.
2	TITLE	Enter a title	80 characters
3	Cross-section library name	27GROUPNDF4 44GROUPNDF5 238GROUPNDF5 etc.	The cross-section library to be used in the criticality analysis (available in SCALE system).
4	Type of calculation	INFHOMMEDIUM LATTICECELL MULTIREGION	These are the available options. See the explanation in Section M7.4.3. of the SCALE manual.
5	Standard composition Data	Enter the data	Terminate this data block with END COMP.
6	Cell geometry specification	Enter the appropriate data (Omit for INFHOMMEDIUM)	Omit for INFHOMMEDIUM See Table M7.4.7 for LATTICECELL. See Table M7.4.8 for MULTIREGION.
7	Control parameter data block	Enter the desired data	Start with READ CONT, and terminate with END CONT. See Table 5.
8	Power history data block	Enter the desired data	Start with READ HIST, and terminate with END HIST. See Table 6.
9	KENO V.a data block	Enter KENO V.a model	Start with READ KENO, and terminate with END KENO.
10	Terminate analytic sequence	END	Must begin in column 1.

8.2 Sequence Specification Card

The STARBUCS analytical sequence is initiated with "=STARBUCS" (or "#" can be used in place of "=") beginning in column 1 of the input. This instructs the SCALE driver module to execute the STARBUCS sequence. The input data is then entered in free-format. The input is terminated with the word "END" card starting in column 1. An "END" is a special data item, which may be used to delimit an input data block, end an array of input items, and terminate the input for the case. In the context of input data blocks, the "END" has a name or label associated with it. An "END" used to terminate an array of entries must not begin in column 1 as this instructs the SCALE driver to terminate input to the sequence.

8.3 Material Information Processor

The Material Information Processor is used to read and process the standard composition specification data that define the initial compositions of the fuel, and all structural materials in the problem, into mixing tables and unit cell geometry information that are used by STARBUCS. All composition data required for the problem are entered as standard composition entries. The formats and options available for the standard composition entries are only summarized here. A detailed description of this portion of the input can be found in Section M7 of the SCALE manual.

The types of data required for the Material Information Processor are given in Table 4. The individual entries are briefly explained below.

1. TITLE. An 80-character title is required. The title is the first 80 characters of the Material Information Processor data.

2. CROSS-SECTION LIBRARY NAME. This item specifies the cross-section library to be used in the criticality analysis. Any library available in the SCALE system may be used. However, the user must be aware that some libraries have a limited set of nuclides. For a burnup credit calculation it is important that the library selected has the actinides and/or fission products required for the analysis. The libraries frequently used are the 44GROUPNDF5 and 238GROUPNDF5 libraries.

3. TYPE OF CALCULATION. The options are INFHOMMEDIUM, LATTICECELL, and MULTIREGION. The type of calculation is used only to define the geometry for the cross-section self-shielding analysis.

4. STANDARD COMPOSITIONS. These data are used to define the mixtures that will be used in the problem. These data are required for every problem. Only one fuel type is permitted. The composition defined for the fuel should correspond to the initial, fresh fuel compositions. Additional mandatory entries are required for the cladding and any moderator mixtures as required by the Material Information Processor. Other materials may be defined to specify compositions for any other material required for the criticality analysis problem. The words "END COMP" end the standard composition entries.

5. CELL GEOMETRY SPECIFICATION. These data are used to define geometry specifications for the cross-section self-shielding analysis. The entries are dependent on the type of calculations selected (INFHOMMEDIUM, LATTICECELL, or MULTIREGION). **The geometry is only used in the self-shielding analysis of the cross sections for the criticality analysis.**

Table 4 Standard composition specification[a]

Entry number	Variable name	Type of data	Entry requirement	Comments
1	SC	Standard composition component name	Always	Enter once for each standard composition. Enter the alphanumeric description from Table M8.2.1 of the SCALE manual. Additional allowed names include those beginning with ARBM for arbitrary materials, and SOLN for solutions
A1	ROTH	Theoretical density of material (g/cc)	ARBM	Enter once for each standard composition component that is an arbitrary material
A2	NEL	Number of elements in the material	ARBM	Enter once for each standard composition component that is an arbitrary material
A3	IVIS	No longer used but must still be entered	ARBM	Enter once for each standard composition component that is an arbitrary material. Enter 0 or 1.
A4	ICP	Compound indicator	ARBM	Enter once for each standard composition component that is an arbitrary material. Enter 1 for a compound and 0 for alloys, mixtures, etc.
A5	IRS	No longer used but must still be entered	ARBM	Enter once for each standard composition component that is an arbitrary material. Enter 0 or 1.
A6	NCZA	ID number (from far right column of Table M8.2.1 of the SCALE manual)	ARBM	Repeat the sequences A6 and A7 for each element in the arbitrary material before entering entry number 2. Enter the number from the far right column of Table M8.2.1. (Premixed standard compositions cannot be used in an arbitrary material definition.)
A7	ATPM	Number of atoms of this element per molecule of arbitrary material	ARBM and ICP=1	Repeat the sequence A6 and A7 for each element in the arbitrary material before entering entry 2. Do not enter a value unless ICP=1
		or	or	or
		Weight percent of this element in this arbitrary material	ARBM and ICP=0	Repeat the sequence A6 and A7 for each element in the arbitrary material before entering entry number 2. Do not enter a value unless ICP=0
2	MX	Mixture ID number	Always	Enter once for each standard composition component
S1	FD	Fuel density grams of U	SOLN	Enter once for a solution or Pu per liter of solution

Table 4 (continued)

Entry number	Variable name	Type of data	Entry requirement	Comments
S2	AML	Acid molarity of the solution	SOLN	Enter once for a solution. AML=0 if there is no acid in the solution
01	SPGR	Specific gravity of the solution	Optional	If the specific gravity (SPGR) of the solution is known, it should be entered as SPG=SPGR
		or		or
	ROTH	Density of the basic standard composition		If the density of a basic standard composition (ROTH) is to be entered, use DEN=ROTH
3	VF	Density multiplier	See comment column	Enter the density multiplier (density fraction, volume fraction, or a combination). Default value is 1. This item can be omitted if entries 4, 5, 6a, and 6b are also omitted. VF=0 is not allowed for SOLN or ARBM
4	ADEN	Number density (atoms/b-cm) for the nuclide	VF=0	Enter only if VF=0.0
5	TEMP	Temperature, in degrees K	See comment column	Default value is 293 K. The temperature is applied in the criticality model. This entry can be omitted if entries 6a and 6b are also omitted
6a	IZA	Isotope's ZA number	VF≠0	Enter for each isotope in the standard composition component. Omit if VF=0. Entries 6a and 6b are entered in pairs until each isotope in the component is defined
6b	WTP	Weight percent of the isotope	VF≠0	Enter for each isotope in the standard composition component. Omit if VF=0. Entries 6a and 6b are entered in pairs until each isotope in the component is defined
7[b]	END	Terminate a standard composition	Always	Enter once for each standard composition component. This terminates the data for a standard composition component. Enter END to terminate the component. Repeat entries 1 through 7 until all the mixtures have been defined. At least two blanks must separate entry 7 from the next entry
	END COMP	Terminate the data block	Terminus	Enter once for a problem. Enter the words END COMP when all the standard composition components have been described. At least two blanks must follow the keyword END COMP

[a]See Section M7.4.4 of the SCALE manual for detailed description of each input variable.
[b]NOTE: Entry 7 should not begin in column 1 unless a name is associated with it. At least two blanks should separate the last entry 7 from the keyword END COMP.

8.4 Control Parameter Data

The control parameter data block allows the user to specify control parameters and array data for the problem. All input is by keyword entries. All keywords are three-character identifiers that must be followed immediately by an equals sign ("="). The keywords may be in any order within a data block. Input to the parameter data block is initiated with the data block keywords **READ CONTROL** (only first four characters of block name are required). The data block is terminated by the keywords **END CONTROL.**

The types of control parameter data that may be input is summarized in Table 5. The individual keyword entries are briefly explained below.

1. NCY= NUMBER OF IRRADIATION CYCLES defined in the burnup history data block. This is an optional input entry, and is automatically determined from the user input in the power history data block if not input explicitly. If NCY is input, the value is only used to check the value determined from the power history data block. If multiple libraries are requested for a cycle using the NLIB= keyword in the power history data block, the code subdivides the input cycle into NLIB cycles. A separate depletion cross-section library is generated for each cycle.

2. ARP= NAME OF THE ARP LIBRARY TO BE USED. A character string with the name of the ARP library to be used in the depletion calculation. This is a required entry. The library must be defined in the SCALE text file ARPDATA.TXT that contains the cross-section library names and interpolation data used by ARP.

3. NAX= NUMBER OF AXIAL ZONES. This is the number of **axial burnup subdivisions**. For a user-input profile the value of NAX is determined automatically by the code, and the **NAX** keyword is optional, provided the AXP= array has been entered. The maximum value of NAX is 100. By default, the profile is automatically normalized by the code unless NPR=no. Built-in 18-axial zone profiles may be selected with entries of –18 or –19. These built-in profiles, and the burnup range over which they are applied, are listed in Table 6 and Table 7. These profiles have been proposed elsewhere (Refs. 13 and 14) as bounding axial profiles, and are included as options for convenience only. The default value is –18 (built-in profiles).

4. NHZ= NUMBER OF HORIZONTAL ZONES. This is the number of uniform horizontal burnup subdivisions in the assembly. Optional entry if no horizontal profile is requested. Maximum value of 10.

5. NUC= THE BURNUP CREDIT NUCLIDES USED IN THE CRITICALITY CALCULATION. A list of actinides and/or fission products that are to be included in the criticality safety calculation. Any nuclides in the fuel matrix that are neither actinides nor fission products are always automatically included in the analysis. This is an array entry keyword and is delimited by an END. The nuclides are entered using their standard composition alphanumeric names, as listed in Section M8 of the SCALE manual. Isotopic correction factors (multiplied times the nuclide concentration) may be entered, optionally, immediately following the nuclide name. The concentration of any nuclide that does not have a correction factor is not adjusted. To select all available nuclides (with cross-section data) for the criticality calculation, the user may select NUC= ALL, without an END terminator. This is the only situation where an array entry does not require an END.

6. AXP= AXIAL BURNUP PROFILE. The axial burnup profile of the assembly to be used in the analysis. This is an array entry and must be delimited by an END. If NAX is input, the AXP array must contain NAX entries. Otherwise, the value of NAX is determined automatically by the code. By default (NPR=yes), the profile is automatically normalized by the code unless NPR=no. If the burnup profile is normalized, it is implicitly assumed that the height/volume of each axial region is uniform when determining the average fuel burnup (i.e., the burnup of each axial region is equally weighted). **The user is cautioned that if nonuniform axial subdivisions are used, normalization should not be used and the user must ensure a correct correspondence between the axial profile input and the axial regions specified in the criticality calculation.**

7. HZP= HORIZONTAL BURNUP PROFILE. The horizontal burnup profile of the assembly. This is an optional array entry and must be delimited by an END. If NAZ is input, the HZP array must contain NAZ entries. Otherwise, the value of NAZ is determined automatically by the code. The profile will be normalized if NPR=yes (default).

8. FIX= FIXED ASSEMBLY POWER OPTION. Option to select a constant specific power level for the depletion analysis for all axial and horizontal zones of the assembly. For FIX=yes, the depletion analysis for all zones is performed using the specific power input in the power history data block for the POWER= keyword. The irradiation time is adjusted to achieve the desired burnup. The default of FIX=no applies a variable power for all zones and a constant irradiation time as defined by the BURN= keyword.

9. NPR= NORMALIZE PROFILE. Option to control whether the user input axial and horizontal burnup profiles will be normalized. The input profiles are automatically normalized using NPR=yes (default).

10. PRT= PRINT LEVEL. Option to set the type and level of printed output. Values range from 0 to 10. This option is currently not functional.

11. BUG= DEBUG PRINT OPTION. BUG=yes will print program debugging variables and arrays in STARBUCS. The default is BUG=no.

Table 5 Table of control parameter data

Keyword Name	Data Type	Default Value	Comments
READ CONTROL			Initiate reading the control parameter block of data
NCY=	Integer variable	None	Optional keyword. Number of irradiation cycles. If not used, NCY is set automatically from the power history data input.
ARP=	Character variable	None	Name of the ARP library to be used. Required. Library must be defined in SCALE text file ARPDATA.TXT.
NAX=	Integer variable	−18	Number of axial burnup subdivisions in fuel assembly. The value of NAX is determined automatically if an axial profile is input using AXP= entries. The maximum value of NAX is 100. Default value (−18) applies a built-in 18-axial region burnup profile.
NHZ=	Integer variable	1	Number of uniform horizontal burnup subdivisions. Maximum value of 10. No entry is required if horizontal profile is not used.
NUC=	Character and real mixed array[a]	None	List of burnup credit nuclides, and optionally the corresponding isotopic correction factors, to be included in the criticality calculation. Array entry generally delimited by END, unless ALL is selected. Nuclides are input using their standard composition alphanumeric identifiers.
AXP=	Real array[a]	See NAX	Axial burnup profile array. Required if NAX > 0. NAX entries that define the axial burnup shape. The profile is automatically normalized if NPR=1. Delimited by END.
HZP=	Real array[a]	None	Horizontal burnup profile array. Required if NHZ > 1. Array containing NHZ entries that define the horizontal, or radial, burnup profile for the analysis. Array is automatically normalized by the code. Delimited by END.
MOD=	Real array[a]	1.	Axial moderator density, applied in the fuel depletion analysis. Note that MOD= is only used if the ARP library contains variable moderator density cross sections. NAX entries ordered as AXP= array. Delimited by END.
FIX=	Character	No	Option to select a constant specific power level for all axial and horizontal zones of the assembly using FIX=yes.
NPR=	Character	Yes	Option to normalize user-input axial and horizontal burnup profiles. Default is to automatically normalize profiles.
PRT=	Integer variable	1	Optional print level control. Currently not implemented.
BUG=	Character	No	Optional debug printout with BUG=yes.
END CONTROL			End of the control parameter block of data

[a] Terminate with END. Do not place this END in column 1.

Table 6 Built-in burnup-dependent axial profiles, NAX= –18 (from Ref. 13)

Axial node	Fraction of core height	>30 GWd/t	18–30 GWd/t	< 18 GWd/t
		1	2	3
1	0.0278	0.649	0.668	0.652
2	0.0833	1.044	1.034	0.967
3	0.1389	1.208	1.150	1.074
4	0.1944	1.215	1.094	1.103
5	0.2500	1.214	1.053	1.108
6	0.3056	1.208	1.048	1.106
7	0.3611	1.197	1.064	1.102
8	0.4169	1.189	1.095	1.097
9	0.4722	1.188	1.121	1.094
10	0.5278	1.192	1.135	1.094
11	0.5833	1.195	1.140	1.095
12	0.6389	1.190	1.138	1.096
13	0.6944	1.156	1.130	1.095
14	0.7500	1.022	1.106	1.086
15	0.8056	0.756	1.049	1.059
16	0.8611	0.614	0.933	0.971
17	0.9167	0.481	0.669	0.738
18	0.9722	0.284	0.373	0.462

Table 7 Built-in burnup-dependent axial profiles, NAX= –19 (from Ref. 14)

Axial node	Fraction of core height	>46 GWd/t	42–46 GWd/t	38–42 GWd/t	34–38 GWd/t	30–34 GWd/t	26–30 GWd/t	22–26 GWd/t	18–22 GWd/t	14–18 GWd/t	10–14 GWd/t	6–10 GWd/t	<6 GWd/t
		1	2	3	4	5	6	7	8	9	10	11	12
1	0.0278	0.573	0.674	0.660	0.585	0.652	0.619	0.630	0.668	0.649	0.633	0.662	0.574
2	0.0833	0.917	0.949	0.936	0.957	0.967	0.924	0.936	1.034	1.044	0.989	0.930	0.947
3	0.1389	1.066	1.053	1.044	1.091	1.074	1.056	1.066	1.150	1.208	1.019	1.049	1.091
4	0.1944	1.106	1.085	1.080	1.121	1.103	1.097	1.103	1.094	1.215	0.857	1.059	1.105
5	0.2500	1.114	1.095	1.091	1.126	1.108	1.103	1.108	1.053	1.214	0.776	1.108	1.094
6	0.3056	1.111	1.095	1.093	1.111	1.106	1.101	1.109	1.048	1.208	0.754	1.144	1.087
7	0.3611	1.106	1.093	1.092	1.094	1.102	1.103	1.112	1.064	1.197	0.785	1.168	1.086
8	0.4169	1.101	1.091	1.090	1.093	1.097	1.112	1.119	1.095	1.189	1.013	1.183	1.087
9	0.4722	1.097	1.089	1.089	1.092	1.094	1.125	1.126	1.121	1.188	1.185	1.189	1.091
10	0.5278	1.093	1.088	1.088	1.091	1.094	1.136	1.132	1.135	1.192	1.253	1.190	1.096
11	0.5833	1.089	1.086	1.088	1.092	1.095	1.143	1.135	1.140	1.195	1.278	1.183	1.102
12	0.6389	1.086	1.084	1.086	1.099	1.096	1.143	1.135	1.138	1.190	1.283	1.167	1.105
13	0.6944	1.081	1.081	1.084	1.096	1.095	1.136	1.129	1.130	1.156	1.276	1.135	1.105
14	0.7500	1.073	1.073	1.077	1.087	1.086	1.115	1.109	1.106	1.022	1.251	1.079	1.096
15	0.8056	1.051	1.053	1.057	1.073	1.059	1.047	1.041	1.049	0.756	1.193	0.976	1.066
16	0.8611	0.993	0.987	0.996	1.003	0.971	0.882	0.871	0.933	0.614	1.075	0.806	0.986
17	0.9167	0.832	0.800	0.823	0.796	0.738	0.701	0.689	0.669	0.481	0.863	0.596	0.806
18	0.9722	0.512	0.524	0.525	0.393	0.462	0.456	0.448	0.373	0.284	0.515	0.375	0.474

8.5 Power History Data

The power history data block defines the irradiation history for the assembly. These data are entered by keyword. The keywords are summarized in Table 8. Only the first four characters of the keywords are used, and any characters after the first four characters may be input. A minimum of two entries are required for each cycle, (1) the average assembly power (**POWER=**) and (2) the irradiation time (**BURN=**). The decay time (**DOWN=**), if any, at the end of the cycle, and the number of cross-section libraries (**NLIB=**) are optional. The word **END** is required to delimit the entries for each cycle. The entries within a given cycle may be in any order. Logarithmic time intervals may be requested for the final cooling time by entering a negative value for the down time of the last cycle.

If the optional **NCY=** keyword (in control parameter data block) is omitted, the number of cycles is determined automatically from the power history data. If the keyword is input, it is used only to check the number of cycles input in the power history data block.

POWER= THE AVERAGE SPECIFIC POWER OF THE ASSEMBLY FOR THIS CYCLE. The units of the specific power are in W/g of initial uranium. The axial and horizontal profiles are multiplied by the specific power to achieve the desired spatially-dependent burnup profiles for the assembly when FIX=no (default). If FIX=yes, the specific power input using this keyword is assumed to be uniform over all fuel regions (axial and horizontal) and the code will adjust the irradiation time to obtain the desired burnup for each region.

BURN= THE IRRADIATION TIME FOR THIS CYCLE. The cycle irradiation time in days.

DOWN= CYCLE DOWN TIME. An optional entry to specify the down time, in days, at the end of an irradiation cycle. The down time is simulated as an irradiation time step of effectively zero power after the irradiation cycle. The down time for the last cycle is simulated as a separate ORIGEN-S decay case with nine equally spaced time steps. If a negative down time is input, the time steps are spaced logarithmically.

NLIB= LIBRARIES PER CYCLE. An optional entry to request multiple cross-section libraries during a depletion cycle. If requested, the code automatically subdivides the cycle in **NLIB** segments of uniform duration and generates a separate library for the depletion analysis for each segment using ARP. Generating multiple libraries provides a more accurate representation of the time-dependent cross-section variation during the burnup analysis. Each segment of the cycle is assumed to have the same specific power, and no down time is assumed between each segment of the cycle.

END The word END is required to terminate the input for each cycle.

Repeat the above entries for each cycle to define the complete assembly power history. The word END is required to terminate the input for each cycle.

Table 8 Table of power history data

Keyword Name	Data Type	Default Value	Comments
POWER=	Real variable	None	Average assembly power for this cycle (W/g)
BURN=	Real variable	None	Cycle irradiation time (days)
DOWN=	Real variable	0	End-of-cycle decay time (days). Optional. A negative down time may be used to select logarithmic decay time intervals for the last decay case.
NLIB/CYCLE=	Integer variable	1	Number of ARP libraries to be applied in this cycle. Optional. If multiple libraries are requested for this cycle, the cycle is subdivided into equal time segments, and an updated library is generated for each segment. No down time is simulated between segments.
END			Required. Defines the end of the data for the current cycle. **Repeat the above entries for each cycle in the irradiation history. An END, not to begin in column 1, must terminate each cycle definition.**
END HIST			End of the power history block of data

8.6 KENO Input Data

The KENO V.a input for the problem is specified in the KENO data block. Input to the data block is initiated with the data block keywords **READ KENO** and is terminated by the keywords **END KENO**. STARBUCS performs no error checking of the KENO V.a input. The data within the data block delimiters is copied, without change, and executed. The user is advised to first verify the KENO V.a input using the SCALE Criticality Safety Analysis Sequence, CSAS, before using the input in STARBUCS.

The input requirements for KENO V.a are not described in this section, but are described in detail in Section F11 of the SCALE manual. This section only describes the input requirements as related to execution of KENO V.a within STARBUCS and the conventions used for module compatibility. Any valid KENO V.a input may be used within STARBUCS, providing a large degree of flexibility in the types of spent fuel systems that may be effectively analyzed.

The STARBUCS module automatically generates a macroscopic cross-section library for each of the spatially-dependent spent fuel regions of a fuel assembly. Therefore, no isotopic composition information is required in the KENO V.a input since the macroscopic cross sections already include all concentration information. The cross sections are prepared as an AMPX working library stored on logical unit 40. The library contains a cross-section set for each region of the spent fuel assembly, plus cross sections for all of the structural and non-fuel materials required for the problem, as defined in the standard composition data (see Table 4).

The cross-section identifiers (*MIXTURE ID*) for each of the non-fuel materials are defined as the mixture numbers (MX) specified in the standard composition input (see Table 4). The control module automatically defines the

MIXTURE ID for each of the fuel regions according to the axial and/or horizontal zone. The first axial zone mixture is assigned a *MIXTURE ID* of 101, and is incremented by one for each additional axial zone. Therefore, in a problem that defines 18 axial zones, spent fuel mixtures will be generated with identifiers that range from 101 to 118. The correspondence of these mixtures to the assembly locations is determined by the ordering of the AXP= array input that define the axial burnup profile for the assembly. If the AXP= array is ordered from the bottom of the assembly to the top of the assembly, the resulting *MIXTURE ID* 101 would correspond to the bottom axial zone, and *MIXTURE ID* 118 would correspond to the top axial zone. If multiple horizontal zones are defined, then the numbering sequence of the second horizontal zone will start at 201 and, in the example given above, would range up to 218. This number convention allows a maximum of 99 unique axial zones, and 9 unique horizontal zones, to be defined. The mixture-numbering scheme is illustrated in Figure 3.

The AMPX cross-section library generated for KENO V.a is stored on logical unit 40. Therefore, the library unit number (LIB=) in the KENO V.a parameter data block must equal 40 in order to access the macroscopic cross sections for the problem, e.g., LIB=40. If the LIB= keyword is input by the user, it must equal 40. If the LIB= keyword is not entered in the parameter data block it is automatically added by STARBUCS, with the correct unit number assignment. An AMPX library requires that a cross-section mixing table data (MIXT data block) in KENO V.a of the form

READ MIXT *MIXING TABLE* **END MIXT**

The *MIXING TABLE* is used to specify each mixture and the nuclide IDs and number densities used in the mixtures. This data block is always automatically added to the KENO V.a input file by STARBUCS. Therefore, entering this data manually is neither required nor permitted.

The following input illustrates a typical KENO V.a mixing table data block added by STARBUCS for six burnup-dependent axial zones:

```
READ MIXT
MIX=101 101 1
MIX=102 102 1
MIX=103 103 1
MIX=104 104 1
MIX=105 105 1
MIX=106 106 1
MIX=  2   2 1
MIX=  3   3 1
MIX=  4   4 1
MIX=  5   5 1
END MIXT
```

In this example, the six axial burnup regions are defined with mixture numbers of 101, 102, 103, 104, 105, and 106. Non-fuel mixtures 2, 3, 4, and 5 are also defined. These MIXTURE IDs defined by the first entry after the MIX= keyword are the cross-section identifiers for each region available in the library, and the second entry is the material identifier used in defining the KENO V.a geometry. The last entry for each mixture card is the atomic number density for this material. Note that the largest mixture number allowed for the non-fuel materials is MIX=100, since larger values will conflict with the predefined fuel mixture numbers. This example is provided only to illustrate the data required by KENO V.a. The mixing table is entered automatically by STARBUCS and no mixing table entries in the user input are needed or allowed.

9 SAMPLE PROBLEMS

A series of sample problems are presented to illustrate the application of STARBUCS to burnup credit criticality safety analyses. Sample problem 1 is a simple pin-cell problem with one axial burnup zone (i.e., uniform axial burnup). It is useful to illustrate the main features of the system and demonstrate functionality of the system modules within SCALE. Problem 2 illustrates the same problem with 18-axial burnup-dependent zones. Problem 3 extends the pin-cell model to an array of spent fuel assemblies residing in water. The burnup credit model applied 18-axial burnup-dependent zones. Problem 4 is a generic cask model, and this problem exercises more of the options available in STARBUCS. Problem 5 illustrates the use of the horizontal burnup option for a simple array of spent fuel assemblies.

9.1 Sample Problem 1

Sample problem 1, listed in Table 9, defines a simple infinite UO_2 pin-cell model with uniform axial burnup. The initial fuel enrichment is 2.0 wt %. The control parameter data block specifies that the standard 17×17 ARP library is to be used for the depletion analysis. The burnup credit criticality calculation uses a subset of the actinides in SNF. An illustrative power history is input that selects three cycles having different specific power levels, with a down time of 100 days after the second cycle, and a 1 year cooling time after irradiation. Multiple libraries per cycle are requested in the first and last cycle to provide a more accurate representation of the cross-section variation with burnup over the extended irradiation times of these cycles.

9.2 Sample Problem 2

Sample problem 2, listed in Table 10, illustrates a simple pin-cell model using 18-axial burnup-dependent zones. In this example, the built-in axial profiles for three burnup ranges are applied using the NAX= −18 option (see profiles in Table 6). STARBUCS determines the average assembly burnup from the power history data input, and automatically selects the appropriate profile based on the discharge burnup. The axial profile data are based on a predefined axial zoning structure (i.e., fraction of the core height). It is important that the KENO V.a model therefore also reflects this axial structure. That is, the height of each axial zone in the criticality model must conform to the axial zones for profiles applied in the analysis. In this example, the total pin height is 365.7 cm (144 in.), which is subdivided into 18 equal-height segments of 20.32 cm each.

The burnup-dependent cross sections generated for the criticality analysis have material identifiers ranging from 101 (bottom) to 118 (top). There is no constraint on how the fuel materials can be applied in the KENO V.a model. For example, the order of the material numbers could easily be reversed, which would effectively invert the profile and could be used to simulate an assembly loaded upside down. It is also not necessary to use all of the materials in the problem. For instance, all fuel regions in the KENO V.a model could be assigned the same fuel mixture number to represent a flat axial profile having a burnup value equal to that of the particular mixture used. The average assembly burnup would also be equal to that of the particular mixture used, and not that defined by the power history data block.

Table 9 STARBUCS input listing for sample problem 1

```
=starbucs
w17x17 pwr uniform axial burnup pin cell model
44groupndf5  latticecell
 uo2    1 den=10.96 0.95 293.0 92235 2.0 92238 98.0 end
'zircalloy
 cr     2  0  7.5891E-05  end
 fe     2  0  1.4838E-04  end
 zr     2  0  4.2982E-02  end
'water
 h2o    3  1  end
end comp
'
' --- fuel-pin-cell geometry:
 squarepitch   1.2598  0.8192 1 3  0.8357 2 end
'
read parm
 arp=17x17
 axp= 1 end
 nuc= u-234 u-235 u-236 u-238 pu-238 pu-239 pu-240
      pu-241 pu-242 am-241 am-242m am-243 np-237 end
end parm
read hist
  power=35.00 burn=100 nlib=2 end
  power=28.7  burn=23 down=100 end
  power=24.   burn=300 nlib=4 down=365.25 end
end hist
read keno
' infinite pin cell lattice
'
'*************************************
'* materials
'* 101 = uo2, uniform axial region
'* 2 = Zircaloy
'* 3 = Water
'*************************************
keno model for infinite pin cell lattice
read param tme=10000 gen=510 nsk=10 npg=1000 end parm
read geom
'           Fuel Pin
unit           1
 cylinder   101  1   0.4782  50.0  -50.0
 cylinder   2    1   0.5588  50.0  -50.0
 cuboid     3    1 4p0.7366  50.0  -50.0
'
end geom
read bounds  all=reflect  end bounds
end data
end keno
end
```

Table 10 STARBUCS input listing for sample problem 2

```
=starbucs
w17x17 pwr pin cell model - 18 axial zones
44groupndf5  latticecell
 uo2    1 den=10.96 0.95 293.0 92235 2.0 92238 98.0 end
'zircalloy
 cr     2  0  7.5891E-05  end
 fe     2  0  1.4838E-04  end
 zr     2  0  4.2982E-02  end
'water
 h2o    3  1  end
end comp
'
' --- fuel-pin-cell geometry:
 squarepitch   1.2598  0.8192 1 3  0.8357 2 end
'
read control
arp=17x17  nax=-18
nuc= u-234 u-235 u-236 u-238 pu-238 pu-240
    pu-241 pu-242 am-241 am-242m am-243 np-237 end
end control
read hist
  power=35.001 burn=100 nlib=1 end
  power=28.5   burn=230 down=100 nlib=2 end
  power=24.001 burn=300 nlib=2 down=1826 end
end hist
read keno
' infinite pin cell lattice
'
'*************************************
'* materials
'* 101-118 = uo2, 18-axial zone model
'* 2 = Zircaloy
'* 3 = Water
'*************************************
keno model for infinite pin cell lattice
read param  tme=10000 gen=510 nsk=10 npg=1000 end param
read geom
'           Fuel Pin
unit           1
 cylinder   101  1  0.4782 -162.53  -182.85
 cylinder   102  1  0.4782 -142.22  -182.85
 cylinder   103  1  0.4782 -121.90  -182.85
 cylinder   104  1  0.4782 -101.58  -182.85
 cylinder   105  1  0.4782  -81.27  -182.85
 cylinder   106  1  0.4782  -60.95  -182.85
 cylinder   107  1  0.4782  -40.63  -182.85
 cylinder   108  1  0.4782  -20.32  -182.85
 cylinder   109  1  0.4782    0.00  -182.85
 cylinder   110  1  0.4782   21.32  -182.85
 cylinder   111  1  0.4782   40.63  -182.85
 cylinder   112  1  0.4782   60.95  -182.85
 cylinder   113  1  0.4782   81.27  -182.85
 cylinder   114  1  0.4782  101.58  -182.85
```

```
 cylinder   115  1  0.4782  121.90  -182.85
 cylinder   116  1  0.4782  142.22  -182.85
 cylinder   117  1  0.4782  162.53  -182.85
 cylinder   118  1  0.4782  182.85  -182.85
 cylinder   2    1   0.5588 182.85  -182.85
 cuboid     3    1 4p0.7366 182.85  -182.85
'
end geom
read bounds  all=reflect  end bounds
end data
end keno
end
```

9.3 Sample Problem 3

Sample problem 3, listed in Table 11, performs a burnup credit criticality safety calculation using the 238-group ENDF/B-V cross-section library for an array of Combustion Engineering (CE) 14 × 14 spent fuel assemblies in water. A subset of burnup credit actinides and fission products are included in the criticality calculation. A user-supplied 18-axial-region burnup profile of the assemblies is input. This profile was obtained from the axial burnup profile database[17] for Maine Yankee assembly N863. Note that the axial profile will be normalized by the code (sum to a value equal to the number of axial zones) using NPR=yes (default). The 3.3 wt % enriched UO_2 fuel is assumed to achieve a discharge burnup of 37626 MWd/t in three cycles of approximately 12.5 GWd/t per cycle and a downtime per cycle of 80 days, followed by a cooling time after irradiation of 5 years (1826 days). An average assembly power level of 32 MW/t is used for the depletion calculation. Two libraries per cycle are requested during the depletion. The nominal CE 14 × 14 assembly design specifications were obtained from Ref. 18. The assembly pitch in the criticality calculations is 22.78 cm. A cross-section view of the assembly geometry, a 2 × 8 array of water reflected assemblies, is illustrated in Figure 4.

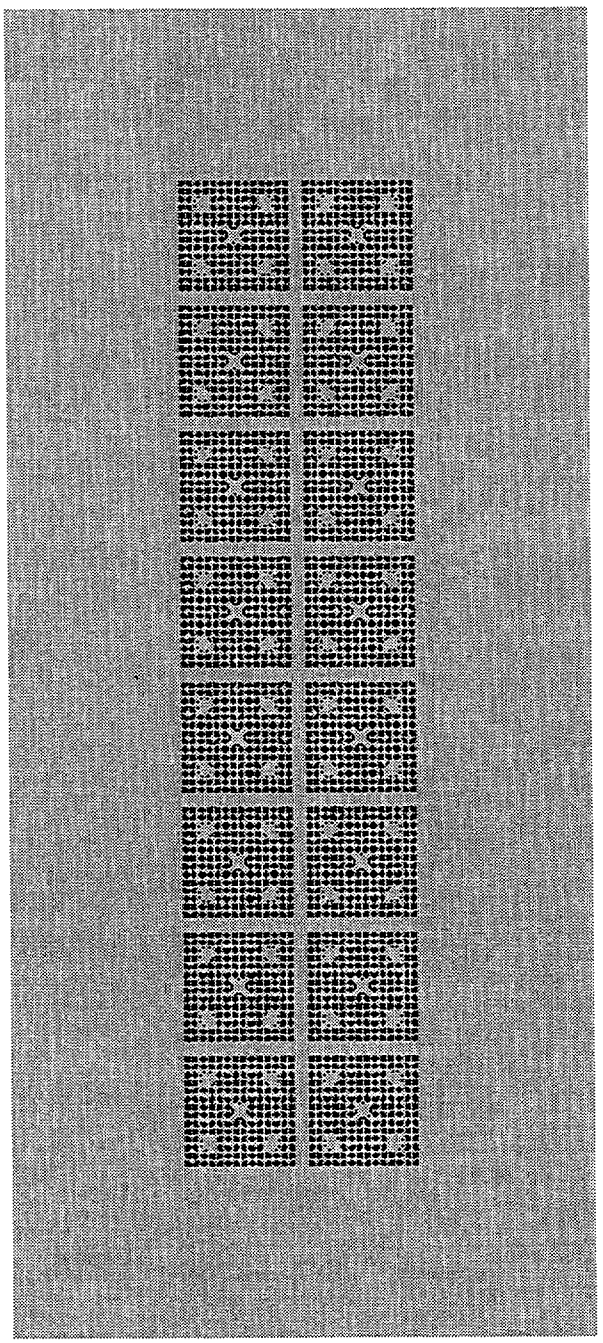

Figure 4 Plot of the CE 14 × 14 assembly array geometry in sample problem 3

Table 11 STARBUCS input listing for sample problem 3

```
=starbucs
ce 14x14 asmby
238groupndf5  latticecell
'initial fuel
uo2  1 den=10.045 1 273 92234 0.0294 92235 3.3 92236 0.0152 92238 96.6554 end
'zircalloy
arbmzirc 6.44 4 0 0 1 40000 97.91 26000 0.5 50116 0.86 50120 0.73 2 1 620  end
'water
 h2o    3  1  end
end comp
'
' --- fuel-pin-cell geometry:
squarepitch  1.4732 0.9563 1  3  1.1176  2  0.9855   0  end
'
read control
arp=14x14 nax=18
axp=
  0.67053 0.93322 1.02433 1.05329 1.06026 1.06185
  1.06215 1.06249 1.06312 1.06408 1.06541 1.06702
  1.06836 1.06760 1.05918 1.02515 0.92262 0.66935 end
nuc=
  u-234  u-235  u-236  u-238  pu-238 pu-239 pu-240
  pu-241 pu-242 am-241 np-237
  mo-95  tc-99  ru-101 rh-103 ag-109 cs-133 nd-143
  nd-145 sm-147 sm-149 sm-150 sm-151 eu-151 sm-152
  eu-153 gd-155 end
end control
read hist
  power=32.00  burn=391.937 nlib=2 down=80  end
  power=32.00  burn=391.937 nlib=2 down=80  end
  power=32.00  burn=391.937 nlib=2 down=1826 end
end hist
read keno
ce 14x14 assembly model, 2x8 array of assemblies
'
'****************************************
'* materials
'* 101 = uo2, lower axial region (0.67053)
'* 118 = uo2, upper axial region (0.66935)
'* 2 = Zircaloy
'* 3 = Water
'****************************************
read param
tme=10000 gen=510 nsk=10 npg=1000
lib=40
end parm
read geom
'  Fuel Pin
unit          1
 cylinder   101  1  0.4782 -162.53  -182.85
 cylinder   102  1  0.4782 -142.22  -182.85
 cylinder   103  1  0.4782 -121.90  -182.85
 cylinder   104  1  0.4782 -101.58  -182.85
 cylinder   105  1  0.4782  -81.27  -182.85
 cylinder   106  1  0.4782  -60.95  -182.85
```

```
 cylinder   107  1  0.4782  -40.63  -182.85
 cylinder   108  1  0.4782  -20.32  -182.85
 cylinder   109  1  0.4782    0.00  -182.85
 cylinder   110  1  0.4782   21.32  -182.85
 cylinder   111  1  0.4782   40.63  -182.85
 cylinder   112  1  0.4782   60.95  -182.85
 cylinder   113  1  0.4782   81.27  -182.85
 cylinder   114  1  0.4782  101.58  -182.85
 cylinder   115  1  0.4782  121.90  -182.85
 cylinder   116  1  0.4782  142.22  -182.85
 cylinder   117  1  0.4782  162.53  -182.85
 cylinder   118  1  0.4782  182.85  -182.85
 cylinder   2    1   0.5588 182.85  -182.85
 cuboid     3    1 4p0.7366 182.85  -182.85
'
'  2 x 2 Array of Fuel Pins
unit           2
 array 1 3*0
'
'  Large Water Hole
unit           3
 cylinder   3    1  1.3140  182.85  -182.85
 cylinder   2    1  1.4160  182.85  -182.85
 cuboid     3    1 4p1.4732 182.85  -182.85
'
'  Assembly Unit
unit           4
 array      2 -10.3124 -10.3124 -182.85
 cuboid     3    1 4p11.390  182.85  -182.85
'
'  Assembly Array (2x8)
global
unit           5
 array      3  3*0
 reflector  3  1 6r30.0  1
end geom
read array
ara=1  nux=2  nuy=2  nuz=1 fill
  1 1
  1 1  end fill
ara=2  nux=7  nuy=7  nuz=1 fill
  2 2 2 2 2 2 2
  2 3 2 2 2 3 2
  2 2 2 2 2 2 2
  2 2 2 3 2 2 2
  2 2 2 2 2 2 2
  2 3 2 2 2 3 2
  2 2 2 2 2 2 2  end fill
ara=3  nux=2  nuy=8  nuz=1 fill
  16r4  end fill
end array
read bounds  all=void  end bounds
end data
end keno
end
```

9.4 Sample Problem 4

Sample problem 4, listed in Table 12, illustrates the application of STARBUCS for a criticality safety analysis of a burnup credit cask. The cask geometry in this example is based on a 32-assembly generic burnup credit cask model and is illustrated in Figure 5.

The assemblies are assumed to be Westinghouse 17 × 17 OFA assemblies with an initial enrichment of 4.98 wt %. The standard composition description for this problem includes the fuel assembly and all cask structural material definitions. The analysis applies built-in 18-axial zone profiles, and actinide-only burnup credit (i.e., only a subset of actinides and no fission products). The assembly is irradiated to an average burnup of about 50 GWd/MTU. The axial burnup profile is automatically selected by the code based on the average assembly burnup. Isotopic correction factors are applied to the calculated actinide inventories. The correction factors were obtained from Ref. 19. An axial moderator density is also applied. Note that entries in the MOD= array are not realistic for a PWR and are only intended to illustrate the use of this feature. Since the ARP library applied in this calculation does not have variable moderator density, the values in the MOD= array have not effect on the calculation. The criticality evaluation of the cask is performed following a cooling time of 1826 days (5 years). The calculations apply the 44-group ENDF/B-V cross-section library.

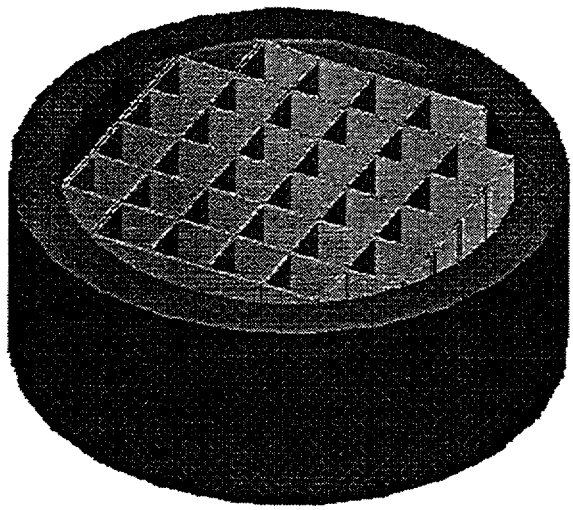

Figure 5 Plot of the generic 32-assembly burnup credit cask geometry

Table 12 STARBUCS input listing for sample problem 4

```
=starbucs
w17x17 pwr 18-axial zones, gbc-32 cask model
44groupndf5  latticecell
 uo2     1 den=10.96 0.95 293.0 92235 4.98 92238 95.02 end
'zircalloy
 cr      2  0  7.5891E-05  end
 fe      2  0  1.4838E-04  end
 zr      2  0  4.2982E-02  end
'water
 h2o     3  1  end
'Stainless steel
 ss304   4  1  end
' boral center - b-10 loading of 0.0225 g/cm3
 b-10    5  0  6.5795E-03    293.0  end
 b-11    5  0  2.7260E-02    293.0  end
 c       5  0  8.4547E-03    293.0  end
 al      5  0  4.1795E-02    293.0  end
'Stainless steel
 ss304   6  1  end
' aluminum
 al      7  0  0.0602        293.0  end
end comp
'
' --- fuel-pin-cell geometry:
 squarepitch   1.25984  0.81920 1 3  0.83570 2 end
'
read control
 arp=17x17 nax=-18
 nuc= u-234 0.635
      u-235 1.085
      u-236 0.910
      u-238 0.992
     pu-238 0.856
     pu-239 1.076
     pu-240 0.945
     pu-241 1.087
     pu-242 0.848
     am-241 0.609
     am-243 0.804
     np-237 0.697 end
mod= 0.720 0.709 0.699 0.688 0.678 0.667 0.657
     0.646 0.635 0.625 0.614 0.604 0.593 0.583
     0.572 0.562 0.551 0.540 end
end control
read hist
 power=32.89 burn=100 end
 power=32.89 burn=200 end
 power=32.89 burn=900 nlib=3 end
 power=32.89 burn=320 down=-1826 end
end hist
read keno
keno model for Generic 32-Assembly Burnup Credit Cask (GBC-32)
'*************************************
```

```
'* Assembly Type: Westinghouse 17x17 OFA/V5
'* Materials
'* 101 - 118 = uo2, axial regions 1 through 18
'* 2 = Zircaloy
'* 3 = Water
'* 4 = Stainless Steel
'* 5 = Boral
'* 6 = Stainless Steel
'* 7 = Al
'*************************************
read param tme=10000 gen=510 nsk=10 npg=1000 end param
read geom
'           Fuel Pin
unit           1
 cylinder   101  1  0.40958 -162.53  -182.85
 cylinder   102  1  0.40958 -142.22  -182.85
 cylinder   103  1  0.40958 -121.90  -182.85
 cylinder   104  1  0.40958 -101.58  -182.85
 cylinder   105  1  0.40958  -81.27  -182.85
 cylinder   106  1  0.40958  -60.95  -182.85
 cylinder   107  1  0.40958  -40.63  -182.85
 cylinder   108  1  0.40958  -20.32  -182.85
 cylinder   109  1  0.40958    0.00  -182.85
 cylinder   110  1  0.40958   21.32  -182.85
 cylinder   111  1  0.40958   40.63  -182.85
 cylinder   112  1  0.40958   60.95  -182.85
 cylinder   113  1  0.40958   81.27  -182.85
 cylinder   114  1  0.40958  101.58  -182.85
 cylinder   115  1  0.40958  121.90  -182.85
 cylinder   116  1  0.40958  142.22  -182.85
 cylinder   117  1  0.40958  162.53  -182.85
 cylinder   118  1  0.40958  182.85  -182.85
 cylinder   0    1  0.41783  182.85  -182.85
 cylinder   2    1  0.47498  182.85  -182.85
 cuboid     3    1  2p0.6299  2p0.6299  182.88  -182.88
'
'           Guide Thimble/Instrument Tube  (assumed to be same)
unit           2
cylinder        3  1  0.5613                                      365.76   0.
cylinder        2  1  0.6020                                      365.76   0.
cuboid          3  1  0.6299   -0.6299    0.6299    -0.6299      365.76   0.
'
'           Top Half Horizontal Boral Panel
unit           4
cuboid          7  1  9.5250   -9.5250     0.02540   -0.0        365.76   0.
cuboid          5  1  9.5250   -9.5250     0.128270  -0.0        365.76   0.
'
'           Right-Hand Side Half Vertical Boral Panel
unit           5
cuboid          7  1  0.02540   -0.0       9.5250   -9.5250      365.76   0.
cuboid          5  1  0.128270  -0.0       9.5250   -9.5250      365.76   0.
'
'           Bottom Half Horizontal Boral Panel
unit           6
cuboid          7  1  9.5250   -9.5250     0.0      -0.02540     365.76   0.
cuboid          5  1  9.5250   -9.5250     0.0      -0.128270    365.76   0.
'
'           Left-Hand Side Half Vertical Boral Panel
unit           7
```

```
cuboid          7  1   0.0      -0.02540    9.5250    -9.5250       365.76    0.
cuboid          5  1   0.0      -0.128270   9.5250    -9.5250       365.76    0.
'
'
'           Assembly Basket Cell
unit         101
array           1  -10.7086     -10.7086        0.
cuboid          3  1  11.0000  -11.0000   11.0000  -11.0000      365.76    0.
cuboid          4  1  11.7500  -11.7500   11.7500  -11.7500      365.76    0.
cuboid          3  1  11.87827 -11.87827  11.87827 -11.87827     365.76    0.
hole            4    0.         11.75000    0.
hole            5   11.75000     0.         0.
hole            6  0.          -11.75000    0.
hole            7  -11.75000     0.         0.
'
'
'           Top Boral/Basket Plate
unit         110
cuboid          4  1  11.7500  -11.7500    0.0000   -0.7500      365.76    0.
cuboid          3  1  11.7500  -11.7500    0.0000   -0.8783      365.76    0.
hole            6    0.         -0.7500    0.
'
'           Bottom Boral/Basket Plate
unit         111
cuboid          4  1  11.7500  -11.7500    0.7500   -0.0000      365.76    0.
cuboid          3  1  11.7500  -11.7500    0.8783   -0.0000      365.76    0.
hole            4    0.          0.7500    0.
'
'           Left-Hand Side Boral/Basket Plate
unit         112
cuboid          4  1  0.0000   -0.7500    10.9999  -10.9999      365.76    0.
cuboid          3  1  0.0000   -0.8783    10.9999  -10.9999      365.76    0.
hole            7   -0.75000     0.         0.
'
'           Right-Hand Side Boral/Basket Plate
unit         113
cuboid          4  1  0.7500   -0.0000    10.9999  -10.9999      365.76    0.
cuboid          3  1  0.8783   -0.0000    10.9999  -10.9999      365.76    0.
hole            5    0.75000     0.         0.
'
'           Cask Inner Volume
global  unit   200
cylinder        3  1  87.500                                    395.76   -30.00
'           Assemblies
hole            101 -35.634840    59.391400     0.
hole            101 -11.878270    59.391400     0.
hole            101  11.878270    59.391400     0.
hole            101  35.634840    59.391400     0.
'
hole            101 -59.391400    35.634840     0.
hole            101 -35.634840    35.634840     0.
hole            101 -11.878270    35.634840     0.
hole            101  11.878270    35.634840     0.
hole            101  35.634840    35.634840     0.
hole            101  59.391400    35.634840     0.
'
hole            101 -59.391400    11.878270     0.
hole            101 -35.634840    11.878270     0.
```

```
hole          101 -11.878270    11.878270     0.
hole          101  11.878270    11.878270     0.
hole          101  35.634840    11.878270     0.
hole          101  59.391400    11.878270     0.
'
hole          101 -59.391400   -11.878270     0.
hole          101 -35.634840   -11.878270     0.
hole          101 -11.878270   -11.878270     0.
hole          101  11.878270   -11.878270     0.
hole          101  35.634840   -11.878270     0.
hole          101  59.391400   -11.878270     0.
'
hole          101 -59.391400   -35.634840     0.
hole          101 -35.634840   -35.634840     0.
hole          101 -11.878270   -35.634840     0.
hole          101  11.878270   -35.634840     0.
hole          101  35.634840   -35.634840     0.
hole          101  59.391400   -35.634840     0.
'
hole          101 -35.634840   -59.391400     0.
hole          101 -11.878270   -59.391400     0.
hole          101  11.878270   -59.391400     0.
hole          101  35.634840   -59.391400     0.
'
'
'           Exterior Half Boral Panels
'       Top Plates
hole          110 -35.634840    72.147980     0.
hole          110 -11.878270    72.147980     0.
hole          110  11.878270    72.147980     0.
hole          110  35.634840    72.147980     0.
hole          110  59.391400    48.391420     0.
hole          110 -59.391400    48.391420     0.
'       Bottom Plates
hole          111 -35.634840   -72.147980     0.
hole          111 -11.878270   -72.147980     0.
hole          111  11.878270   -72.147980     0.
hole          111  35.634840   -72.147980     0.
hole          111  59.391400   -48.391420     0.
hole          111 -59.391400   -48.391420     0.
'       Left-Hand Side Plates
hole          113 -48.391420    59.391400     0.
hole          113 -72.147980    35.634840     0.
hole          113 -72.147980    11.878270     0.
hole          113 -72.147980   -11.878270     0.
hole          113 -72.147980   -35.634840     0.
hole          113 -48.391420   -59.391400     0.
'       Right-Hand Side Plates
hole          112  48.391420    59.391400     0.
hole          112  72.147980    35.634840     0.
hole          112  72.147980    11.878270     0.
hole          112  72.147980   -11.878270     0.
hole          112  72.147980   -35.634840     0.
hole          112  48.391420   -59.391400     0.
'
'           Steel Cask/Overpack
cylinder        6  1  107.5                   415.76    -60.
'
'           Cube of Water Surrounding Cask
```

```
cuboid          0  1  108  -108   108   -108    415.76   -60.
end geom
'
'
'      Assembly Type: Westinghouse 17x17 OFA/V5
read array
ara=1  nux=17  nuy=17  nuz=1
fill
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 2 1 1 2 1 1 2 1 1 1 1 1
 1 1 1 2 1 1 1 1 1 1 1 1 1 2 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 2 1 1 2 1 1 2 1 1 2 1 1 2 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 2 1 1 1 1 1 1 1 1 1 2 1 1 1
 1 1 1 1 1 2 1 1 2 1 1 2 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
end fill
end array
read bounds  xyf=specular   end bounds
end data
end keno
end
```

9.5 Sample Problem 5

Sample problem 5, listed in Table 13, uses the CE 14 × 14 assembly design from problem 3, and performs a burnup credit calculation using the horizontal burnup profile option. The assembly configuration is taken to be a simple 2 × 2 assembly array with water reflection. This problem is only designed to illustrate the basic features of the horizontal profile option. In this example, it is assumed that there is a burnup gradient across the assemblies, such that half the fuel pins have a burnup exceeding the average assembly burnup by 10% and half the pins have a burnup of 10% less than the average, with the two burnup regions separated by the assembly diagonal. The input card required to simulate the two horizontal burnup regions in an assembly is

```
hzp= 0.9 1.1 end
```

STARBUCS applies these factors to calculate compositions for each of the horizontally-varying burnup regions in each zone of the problem. It is important to note that the option inherently assumes that there is an equal volume/mass of fuel in each of the horizontal (an axial) zones since the code weights all regions equally when determining the average assembly burnup. To illustrate this, consider modeling an assembly with **only one quadrant** having a burnup that is 10% higher than the other three quadrants. The user would enter data for each of the four horizontal assembly quadrants or zones, e.g.,

```
hzp= 0.9766 0.9766 0.9766 1.0700 end
```

such that the average of the HZP array entries is unity. This ensures that the average assembly burnup will be that specified in the power history data block. Note that this array is automatically normalized in NPR=yes (default). However, the user could substantially reduce the computational time involved by specifying only two fuel regions, e.g.,

```
hzp= 0.9766 1.0700 end
```

and turning off the normalization option (e.g., NPR=no). The normalization option must be turned off to prevent the profile from being altered (since the sum is not equal to 2). This allows the user to account for the fact that, in this scenario, there are three quadrants having a lower burnup (and consequently three times the mass) and just one quadrant having an elevated burnup compared to the average. However, it is the responsibility of the user to ensure that the profiles and the KENO V.a problem description produce the desired average burnup.

In this sample problem the four assemblies are aligned so the lower burnup regions of the assemblies are adjacent to one another to maximize the system reactivity. The assembly geometry showing the different burnup regions of the assemblies is illustrated in Figure 6. The criticality calculation is performed using the 238-group ENDF/B-V cross-section library.

Table 13 STARBUCS input listing for sample problem 5

```
=starbucs
ce 14x14 asmby
238groupndf5  latticecell
'initial fuel
uo2  1 den=10.045  1  273
   92234 0.027 92235 3.038 92236 0.014 92238 96.921   end
'zircalloy
arbmzirc 6.44 4 0 0 1 40000 97.91 26000 0.5 50116 0.86 50120 0.73 2 1 620  end
'water
 h2o    3  1  end
end comp
'
' --- fuel-pin-cell geometry:
squarepitch  1.4732 0.9563 1  3  1.1176  2  0.9855   0  end
'
read control
arp=14x14
nax=18
axp=
  0.67053 0.93322 1.02433 1.05329 1.06026 1.06185
  1.06215 1.06249 1.06312 1.06408 1.06541 1.06702
  1.06836 1.06760 1.05918 1.02515 0.92262 0.66935 end
nhz= 2
hzp= 0.9 1.1  end
nuc=
  u-234  u-235  u-236  u-238  pu-238 pu-239 pu-240
  pu-241 pu-242 am-241 np-237
  mo-95  tc-99  ru-101 rh-103 ag-109 cs-133 nd-143
  nd-145 sm-147 sm-149 sm-150 sm-151 eu-151 sm-152
  eu-153 gd-155 end
end control
read hist
  power=28.00  burn=520.833 nlib=2 down=80  end
  power=28.00  burn=520.833 nlib=2 down=80  end
  power=28.00  burn=520.833 nlib=2 down=-1865 end
end hist
read keno
ce 14x14 assembly model, 2x8 array of assemblies
'************************************************************
'* materials
'* 101 = uo2, lower axial region, low burnup region
'* 118 = uo2, upper axial region, low burnup region
'* 201 = uo2, lower axial region, high burnup region
'* 218 = uo2, upper axial region, high burnup region
'* 2 = Zircaloy
'* 3 = Water
'************************************************************
read param
tme=10000 gen=510 nsk=10 npg=1000
lib=40
end parm
read geom
'  Fuel Pin, Low Burnup Region
unit          1
```

```
 cylinder   101  1  0.4782 -162.53  -182.85
 cylinder   102  1  0.4782 -142.22  -182.85
 cylinder   103  1  0.4782 -121.90  -182.85
 cylinder   104  1  0.4782 -101.58  -182.85
 cylinder   105  1  0.4782  -81.27  -182.85
 cylinder   106  1  0.4782  -60.95  -182.85
 cylinder   107  1  0.4782  -40.63  -182.85
 cylinder   108  1  0.4782  -20.32  -182.85
 cylinder   109  1  0.4782    0.00  -182.85
 cylinder   110  1  0.4782   21.32  -182.85
 cylinder   111  1  0.4782   40.63  -182.85
 cylinder   112  1  0.4782   60.95  -182.85
 cylinder   113  1  0.4782   81.27  -182.85
 cylinder   114  1  0.4782  101.58  -182.85
 cylinder   115  1  0.4782  121.90  -182.85
 cylinder   116  1  0.4782  142.22  -182.85
 cylinder   117  1  0.4782  162.53  -182.85
 cylinder   118  1  0.4782  182.85  -182.85
 cylinder   2    1   0.5588 182.85  -182.85
 cuboid     3    1 4p0.7366 182.85  -182.85
'
'  Fuel Pin, High Burnup Region
unit           2
 cylinder   201  1  0.4782 -162.53  -182.85
 cylinder   202  1  0.4782 -142.22  -182.85
 cylinder   203  1  0.4782 -121.90  -182.85
 cylinder   204  1  0.4782 -101.58  -182.85
 cylinder   205  1  0.4782  -81.27  -182.85
 cylinder   206  1  0.4782  -60.95  -182.85
 cylinder   207  1  0.4782  -40.63  -182.85
 cylinder   208  1  0.4782  -20.32  -182.85
 cylinder   209  1  0.4782    0.00  -182.85
 cylinder   210  1  0.4782   21.32  -182.85
 cylinder   211  1  0.4782   40.63  -182.85
 cylinder   212  1  0.4782   60.95  -182.85
 cylinder   213  1  0.4782   81.27  -182.85
 cylinder   214  1  0.4782  101.58  -182.85
 cylinder   215  1  0.4782  121.90  -182.85
 cylinder   216  1  0.4782  142.22  -182.85
 cylinder   217  1  0.4782  162.53  -182.85
 cylinder   218  1  0.4782  182.85  -182.85
 cylinder   2    1   0.5588 182.85  -182.85
 cuboid     3    1 4p0.7366 182.85  -182.85
'
'  2 x 2 Array of Lower Burnup Fuel Pins
unit           3
 array 1 3*0
'
'  2 x 2 Array of Higher Burnup Fuel Pins
unit           4
 array 2 3*0
'
'  Large Water Hole
unit           5
 cylinder   3    1  1.3140  182.85  -182.85
 cylinder   2    1  1.4160  182.85  -182.85
 cuboid     3    1 4p1.4732 182.85  -182.85
'
'  Assembly 1 Unit
```

```
unit            6
 array       3 -10.3124 -10.3124 -182.85
 cuboid      3    1 4p11.390  182.85  -182.85
'
'  Assembly 2 Unit
unit            7
 array       4 -10.3124 -10.3124 -182.85
 cuboid      3    1 4p11.390  182.85  -182.85
'
'  Assembly 3 Unit
unit            8
 array       5 -10.3124 -10.3124 -182.85
 cuboid      3    1 4p11.390  182.85  -182.85
'
'  Assembly 4 Unit
unit            9
 array       6 -10.3124 -10.3124 -182.85
 cuboid      3    1 4p11.390  182.85  -182.85
'
'  Assembly Array (2 x 2)
global
unit            10
 array       7  3*0
 reflector   3  1 6r30.0  1
end geom
read array
ara=1  nux=2  nuy=2  nuz=1 fill
  1 1
  1 1  end fill
ara=2  nux=2  nuy=2  nuz=1 fill
  2 2
  2 2  end fill
ara=3  nux=7  nuy=7  nuz=1 fill
  3 3 3 3 3 3 3
  3 5 3 3 3 5 4
  3 3 3 3 4 4 4
  3 3 3 5 4 4 4
  3 3 3 4 4 4 4
  3 5 4 4 4 5 4
  4 4 4 4 4 4 4  end fill
ara=4  nux=7  nuy=7  nuz=1 fill
  3 3 3 3 3 3 3
  4 5 3 3 3 5 3
  4 4 4 3 3 3 3
  4 4 4 5 3 3 3
  4 4 4 4 3 3 3
  4 5 4 4 4 5 3
  4 4 4 4 4 4 4  end fill
ara=5  nux=7  nuy=7  nuz=1 fill
  4 4 4 4 4 4 3
  4 5 4 4 4 5 3
  4 4 4 4 4 3 3
  4 4 4 5 3 3 3
  4 4 3 3 3 3 3
  4 5 3 3 3 5 3
  4 3 3 3 3 3 3  end fill
ara=6  nux=7  nuy=7  nuz=1 fill
  3 4 4 4 4 4 4
```

```
  3 5 4 4 4 5 4
  3 3 4 4 4 4 4
  3 3 3 5 4 4 4
  3 3 3 3 3 4 4
  3 5 3 3 3 5 4
  3 3 3 3 3 3 4  end   fill
'
ara=7  nux=2  nuy=2  nuz=1 fill
  6 7
  8 9  end fill
end array
read bounds  all=void  end bounds
end data
end keno
end
```

Following the STARBUCS calculation, the KENO V.a geometry model could be readily altered to simulate other assembly configurations (e.g., shuffle the fuel assembly locations). The KENO V.a case could subsequently be executed as a standalone case since all of the material cross sections have already been created during the initial STARBUCS run and are available on logical unit 40. This facilitates the rapid evaluation of different fuel configuration without the need to regenerate the material cross sections using STARBUCS.

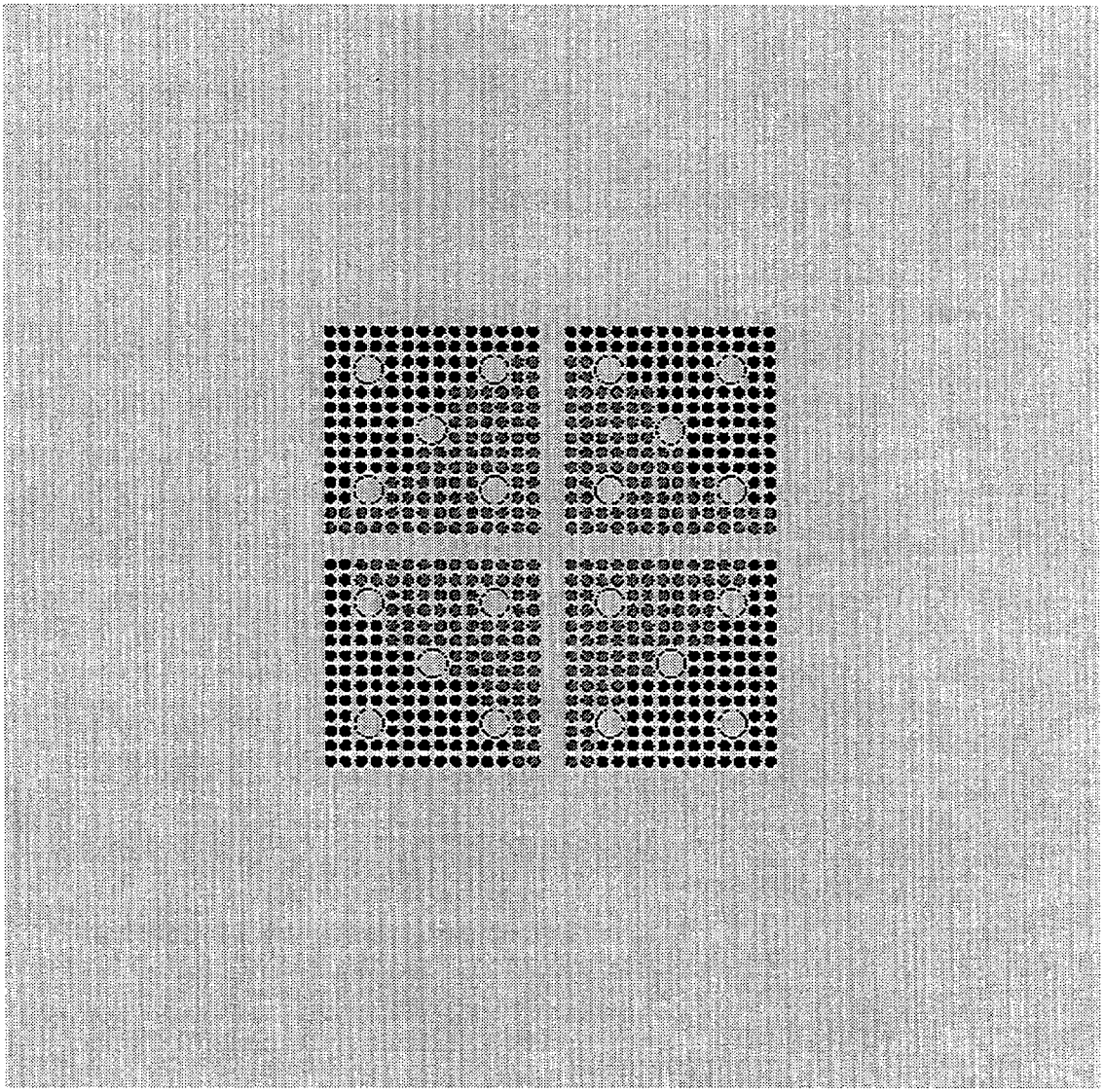

Figure 6 Plot of the 2 × 2 array of CE 14 × 14 assemblies with burnup gradient

10 FUTURE DEVELOPMENTS

The STARBUCS prototype described in this report represents the initial implementation of an automated burnup credit computational methodology in SCALE. The burnup credit sequence uses existing, well-established modules of the SCALE code system. It is anticipated that the sequence will be further developed to provide additional enhancements, and remove some of the present limitations and restrictions of the program. Some of the potential future STARBUCS development areas are listed below.

1. Provide greater integration of the STARBUCS program within SCALE. This involves incorporating routines in the CSAS control module that are used to generate input for the resonance cross-section processing codes directly into STARBUCS. This would allow STARBUCS to execute each of the function modules (e.g., BONAMI and NITAWL) via the SCALE driver directly, instead of calling the CSAS control module as is performed in the current version of the code. This capability would allow STARBUCS to function in a way that is very similar to CSAS and would allow a search capability to be incorporated within STARBUCS. Such a capability could be used to automatically generate a loading curve by searching on enrichment and burnup combinations that meet a specified subcritical safety criterion.

2. Upgrade STARBUCS to run within the SCALE-5 system. This would allow STARBUCS to use the standard SCALE-5 versions of the ARP and ORIGEN-S codes (i.e., special versions would no longer be required).

3. Modify the format of the criticality cross-section library generated by the sequence to a Monte Carlo format instead of the AMPX working format library currently used. This would remove the need to have STARBUCS generate a MIXTURE data block for the KENO V.a input.

4. Upgrade STARBUCS to directly access the SCALE Standard Composition Library to map nuclide identifiers to their alphanumeric names. This would expand the number of standard compositions that could be used in the burnup credit sequence.

5. Provide enhanced error checking and diagnosis of input data, and monitoring of program execution for successful completion.

6. Extend STARBUCS to use either KENO V.a or KENO-VI as the criticality module.

7. Develop additional standard ARP cross-section libraries for a wide range of assembly classes and design characteristics that can be used with the STARBUCS burnup credit sequence.

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10. SUPPLEMENTARY NOTES
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11. ABSTRACT *(200 words or less)*

STARBUCS is a new prototypic analysis sequence for performing automated criticality safety analyses of spent fuel systems employing burnup credit. A depletion analysis calculation for each of the burnup-dependent regions of a spent fuel assembly, or other system containing spent fuel, is performed using the ORIGEN-ARP sequence of SCALE. The spent fuel compositions are then used to generate resonance self-shielded cross sections for each region of the problem, which are applied in a three-dimensional criticality safety calculation using the KENO V.a code. This prototypic burnup credit analysis sequence allows the user to simulate the axial and horizontal burnup gradients in a spent fuel assembly, select the specific actinides and/or fission products that are to be included in the criticality analysis, and apply isotopic correction factors to the predicted spent fuel nuclide inventory to account for calculational bias and uncertainties. Although STARBUCS was developed to address the burnup credit analysis needs for spent fuel transport and storage applications, it provides sufficient flexibility to allow criticality safety assessments involving many different potential configurations of spent nuclear fuel to be simulated.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*
criticality safety, burnup credit, depletion, STARBUCS, SCALE

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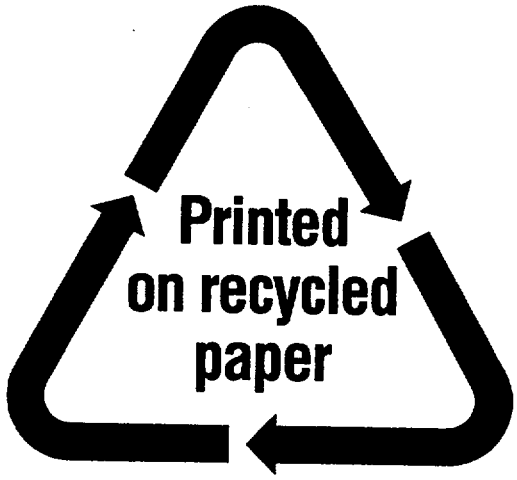

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