Demonstration of Approach for Developing BUC Loading Curve(s)

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OVERVIEW

- Introduction
- Procedures for Criticality Safety Evaluations
- BUC Loading Curve(s)
- BUC Analysis Process
  - STARBUCS
  - REBUCS
- Examples
- Concluding Remarks

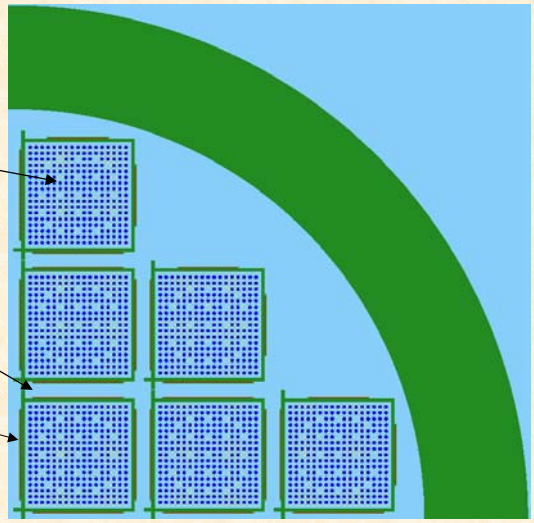
SCOPE

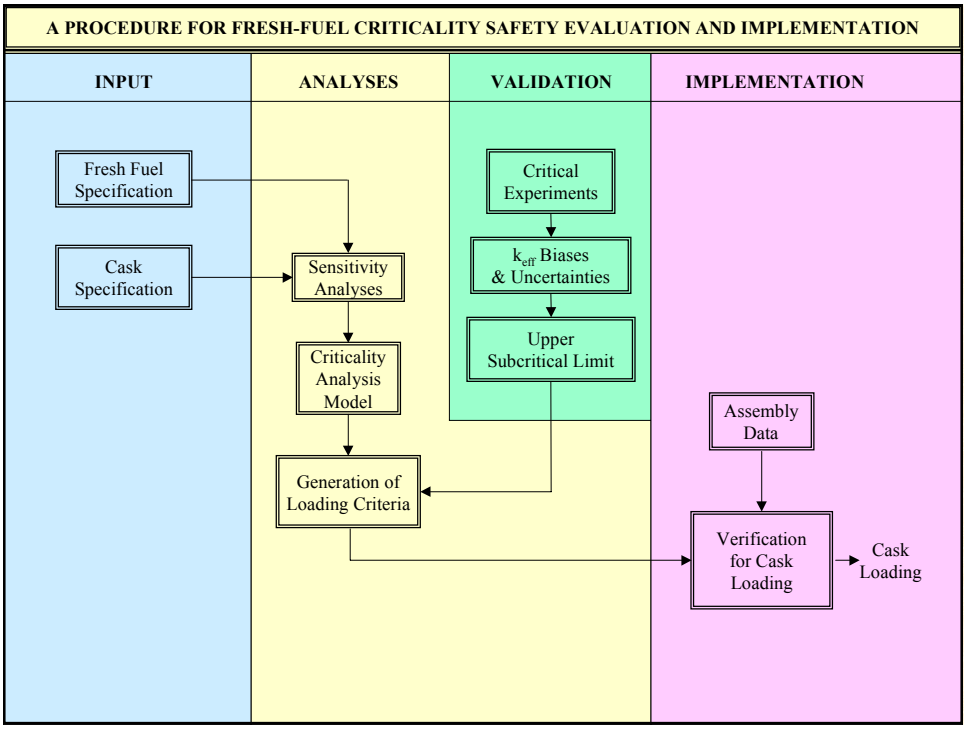
- This talk will be focused on storage and transportation of commercial PWR spent fuel
- There are numerous approaches to BUC - I will be describing <u>an</u> approach

INTRODUCTION

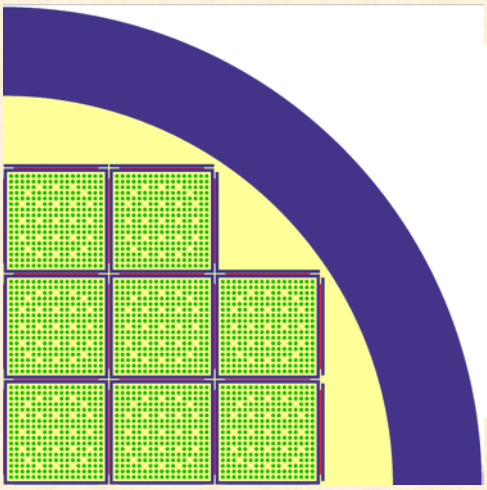
- Criticality Safety Evaluation
  - Prior to BUC
    - Assume fresh-fuel composition
    - Evaluations are relatively simple
    - Establish maximum enrichment limit(s)
  - BUC
    - Credit for fuel burnup
    - Significantly more complicated evaluations
    - Numerous approaches
    - Generate loading curve(s) for acceptance criteria
- Evaluation Procedures and Implementation

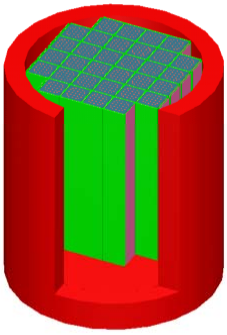
Non-burnup credit type cask



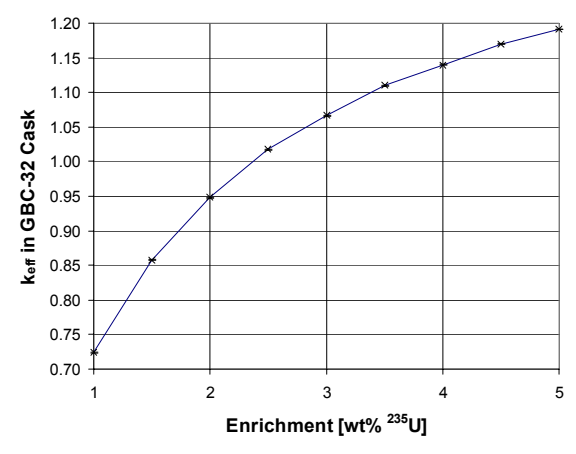


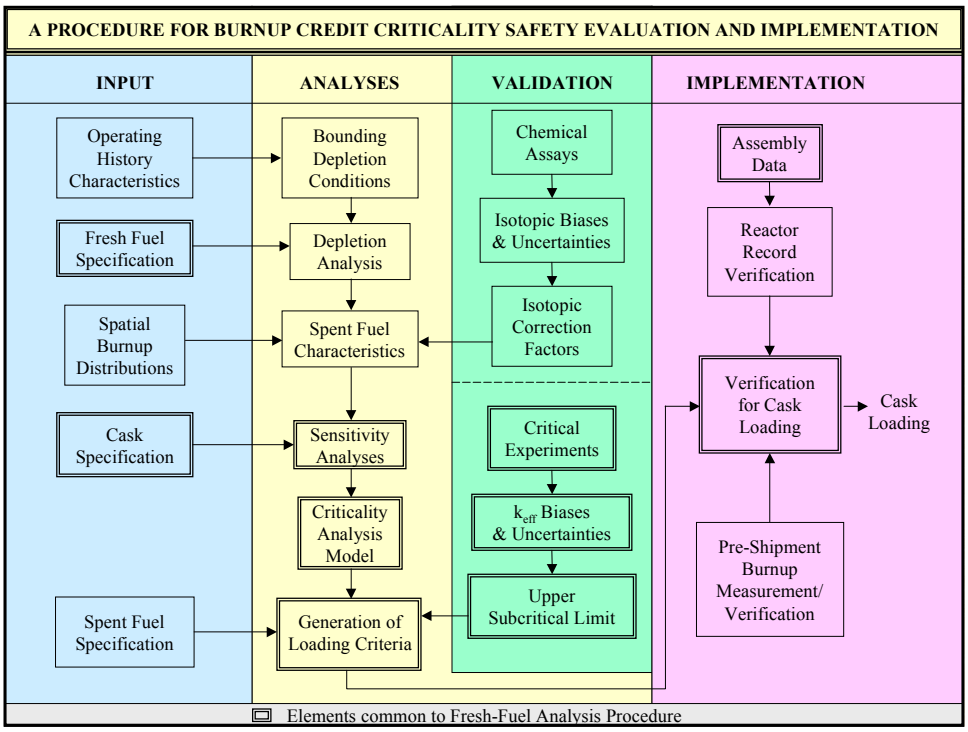
High-Density BUC Cask





K_{eff} versus Enrichment





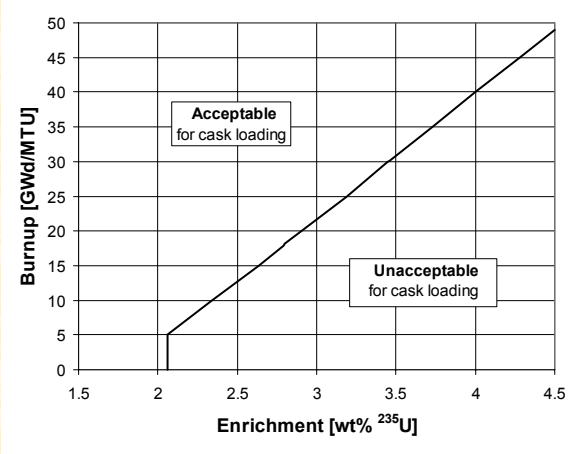
Issues for BUC Evaluations

- Depletion Conditions
- Nuclides - Isotopic Validation
- Criticality Validation for SNF
- Spatial Burnup Distributions
- Cooling Time
- Generation of Loading Curves
- Administrative Controls

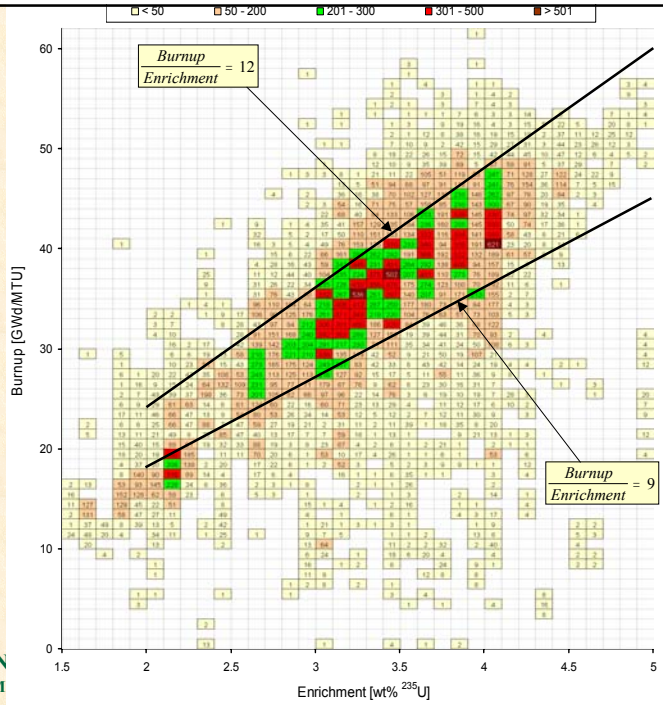
What is a Loading Curve ?

- A curve depicting initial enrichment and minimum burnup combinations that define the boundary for loading acceptability
- All points on the curve represent burnup and enrichment combinations that yield the same value for k_{eff} (the Upper Subcritical Limit, USL)
- The determination of these burnup-enrichment combinations requires a number of depletion and criticality calculations associated with an iterative search and/or interpolation capability

Illustrative Loading Curve



Note, the vertical portion of a loading curve (at low burnup) corresponds to a region in which the reduction in reactivity due to burnup is overwhelmed by the increase in reactivity associated with the conservatism in the burnup credit evaluation. Hence no credit is taken for burnup in that region.



BUC Analysis Process

- Determine k_{eff} for burned fuel
  - Depletion calculations to determine the isotopic compositions for each unique region (e.g., for 18 axial zones and 2 horizontal zones, 36 depletion calculations)
  - Extract isotopic compositions from depletion output for use in criticality model
  - Criticality calculation to determine k_{eff} value
- Generation of a loading curve requires a series of these calculations to determine burnup and enrichment combinations that correspond to the USL

BUC Analysis Process

- To simplify the BUC analysis process, analysis sequences have been developed to automate BUC analyses by coupling the depletion and criticality modules of SCALE
  - STARBUCS: Standardized Analysis of Reactivity for Burnup Credit using SCALE
  - REBUCS: A Prototypic Iterative Search Module for STARBUCS (Recycle STARBUCS)
- These sequences have been used extensively at ORNL for BUC-related studies

STARBUCS

- Integrated depletion analysis, cross-section processing and Monte Carlo criticality safety calculations for a 3-D system
- Uses existing, well-established modules in the SCALE system
- Creates input, executes codes, and performs all data transfer functions
- Capable of simulating important BUC phenomena, e.g.,
  - Axial and horizontal burnup variations
  - Analyses can be performed for nuclide subgroups, i.e., evaluation of fission product margin
  - Isotopic correction factors may be applied
- Sequence is *not* restricted to analysis of spent fuel casks, e.g., could be used for spent fuel pools

STARBUCS

- Depletion analysis methodology
  - Uses the ORIGEN-ARP sequence
  - Cross-sections for depletion in ORIGEN-S obtained by interpolation of an existing ARP library
  - Interpolation on enrichment, burnup, moderator density
  - The analysis is extremely fast and accurate
- Criticality safety analysis
  - KENO V.a, KENO VI (future)
  - Multigroup, 3-D capability

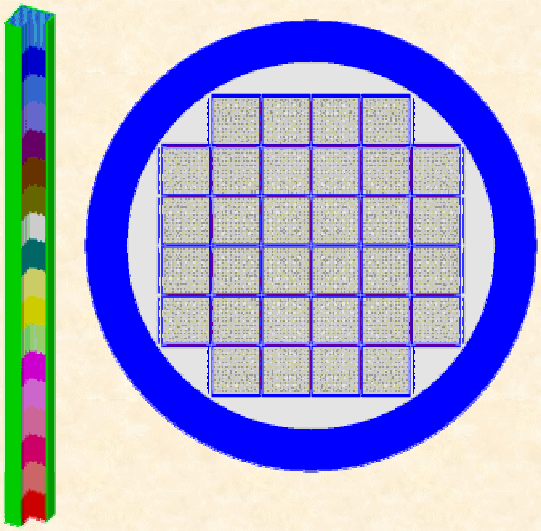
STARBUCS

- Flexible, easy-to-use sequence, uses input similar to existing SCALE modules
  - Standard composition data used to define all materials in the problem (depletion and non-fuel)
  - Depletion analysis input based on SAS2H-like input formats
  - Any existing KENO V.a input deck (e.g., fresh fuel) can be used with only minor changes to incorporate spatial variation of burnup regions

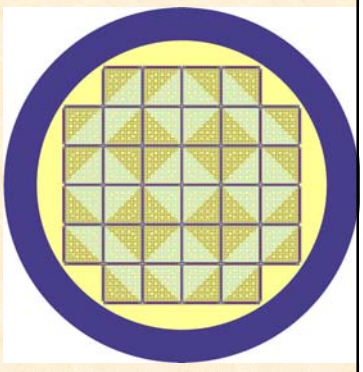
STARBUCS

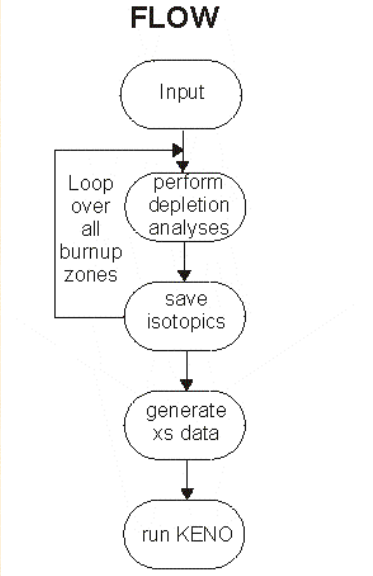
- Spent fuel compositions for each spatial region
  - separate burnup calculation for each region
  - composition interpolation unreliable
- Extract nuclides for analysis
- Apply correction factors (if applicable)
- Prepare compositions for resonance processing of cross sections (multigroup) and criticality analysis

Illustrative Cask Model, 18-Axial Zone Assembly



Can also include horizontal variation in burnup





STARBUCS

Standardized Analysis of Reactivity for Burnup Credit using SCALE

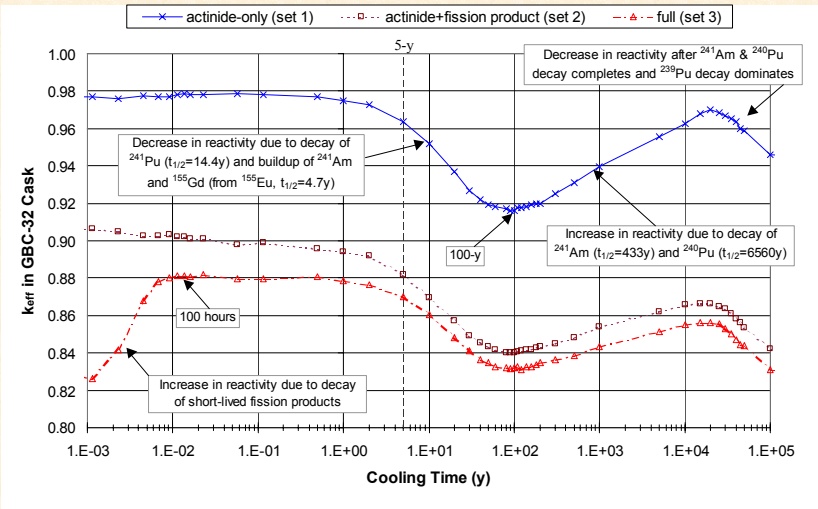
STARBUCS Input File

```
=Starbucs
  Title
  Cross-section Library          Unit Cell Type
  Standard Composition Data
  Unit Cell Data
READ CONT
  Control and Parameter Data
END CONT
READ HIST
  Irradiation History Data
END HIST
READ KENO
  KENO Input Data
END KENO
End
```

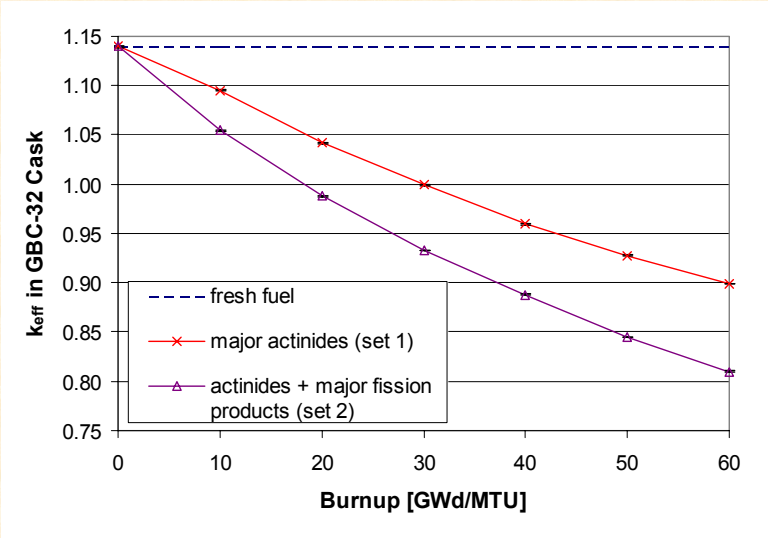
STARBUCS

- **Verification & Validation**
  - Components are independently validated
  - Comparisons against independent codes/data
- **Limitations**
  - Single fuel material allowed
  - Single ARP library allowed
  - Availability of ARP libraries
- **Availability**
  - Planned release in SCALE-5
- **Examples of studies performed with STARBUCS**

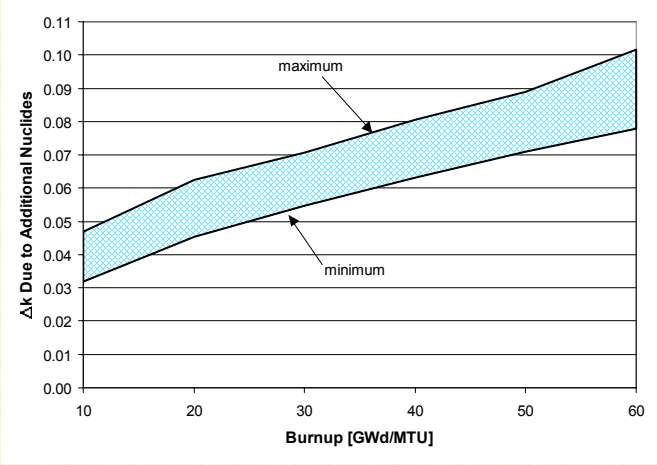
Reactivity Effect of Cooling Time



Reactivity Effect of Nuclide Sets



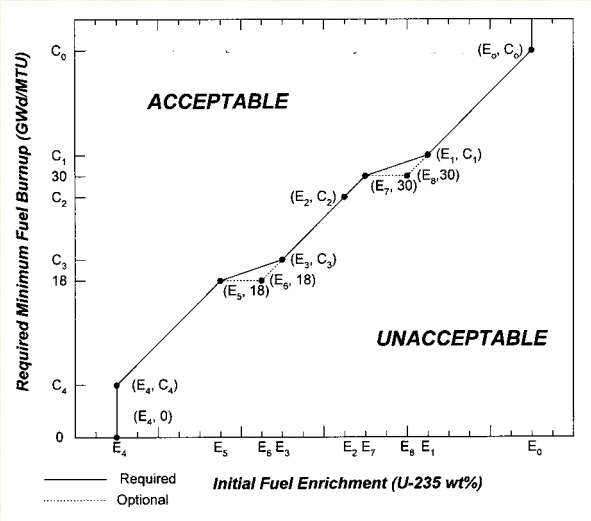
Reactivity Margin Associated with Major Fission Products and Minor Actinides



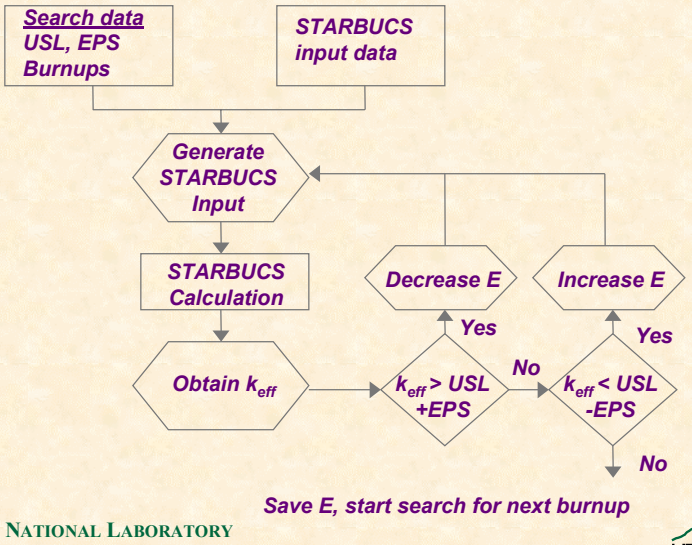
REBUCS

- REBUCS: Recycle STARBUCS
- Designed to automatically generate a loading curve using repeated STARBUCS calculations
- Adjusts fuel *enrichment* to achieve the desired k_{eff} (USL) for a given range of burnups (avoids discontinuity with burnup due to profiles)
- A search algorithm is used to "guess" the next value that will yield desired k_{eff}
- Determines acceptable enrichment and burnup combinations for loading

Loading Curve Generation



REBUCS Flow Chart



REBUCS

- Technique requires ~ 3-6 iterations per burnup point
- Initial calculation performed using Standard Composition enrichment
- User-specified enrichment search range
- User-specified USL
- User-specified tolerance band
- REBUCS input is identical to STARBUCS, except HISTORY data block is replaced with a SEARCH data block

Illustration of Iteration Process

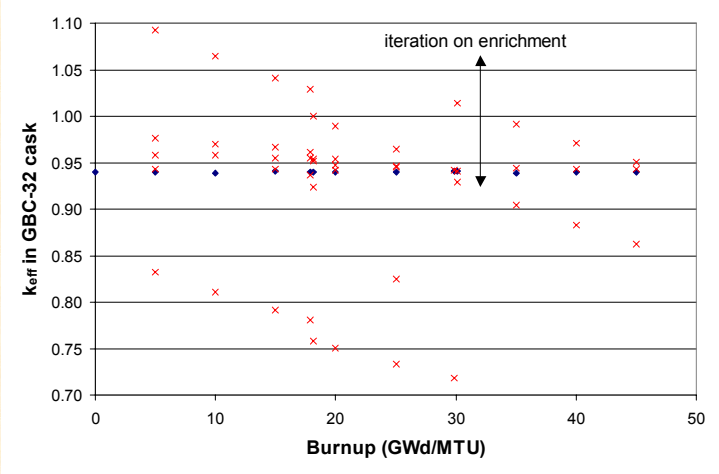
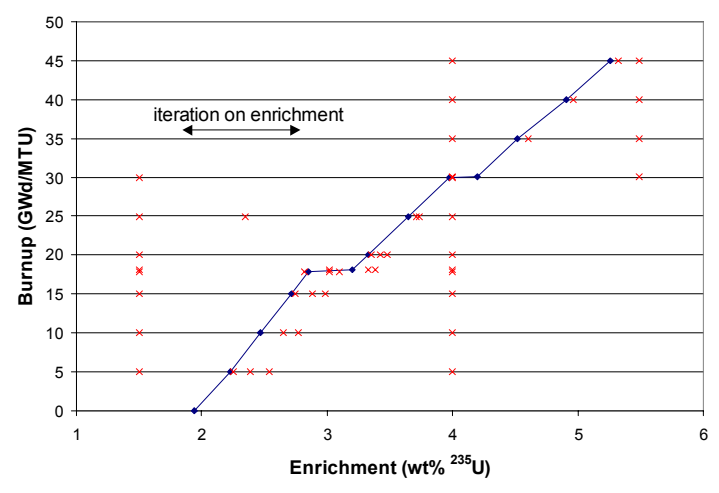
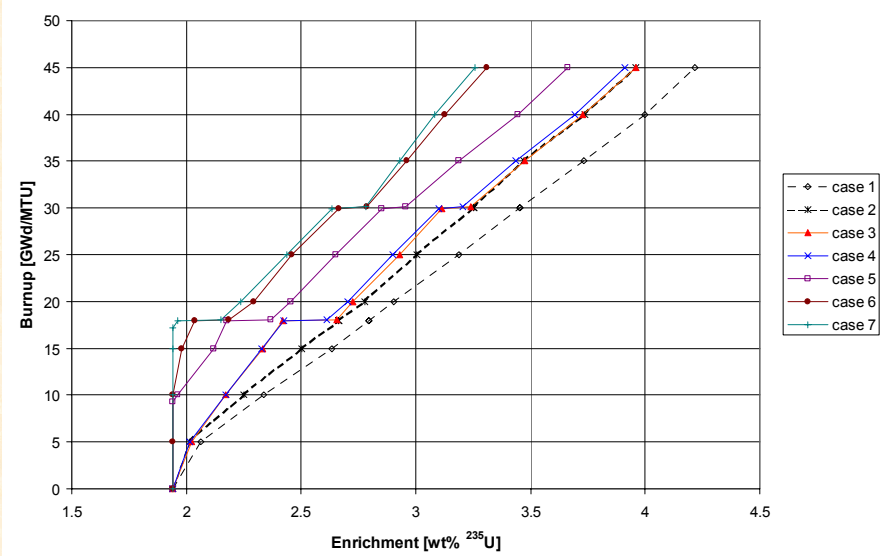


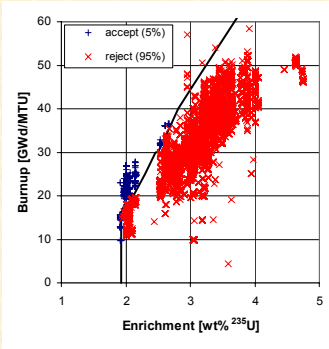
Illustration of Iteration Process



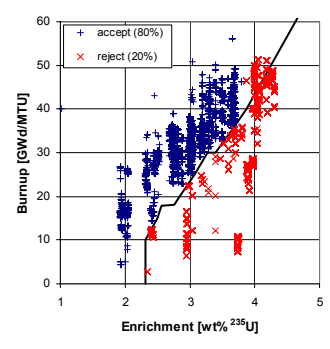
REBUCS

- REBUCS being considered for release in SCALE-5
- Examples of Loading Curves

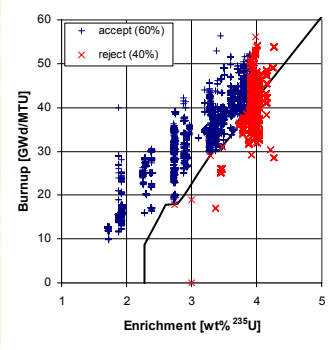




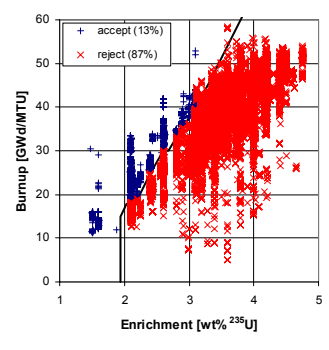
B&W 15x15



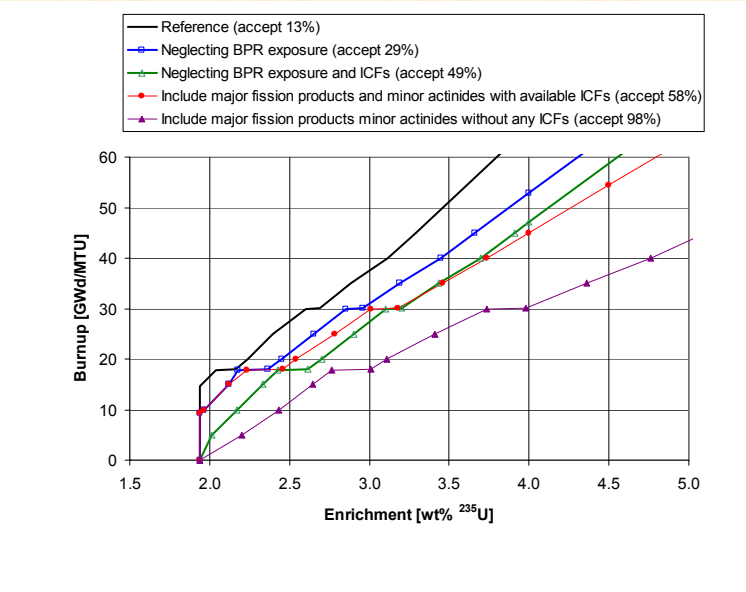
CE 14x14

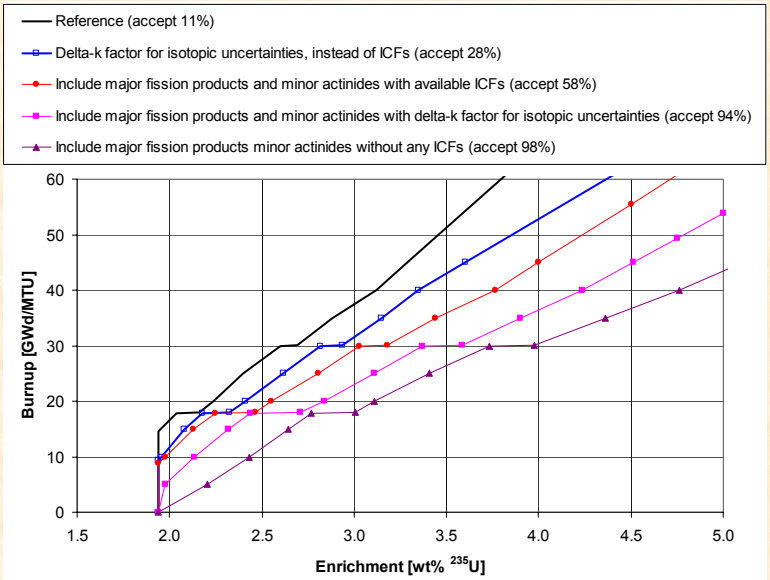


CE 16x16



WE 17x17


Reference (accept 13%)
Neglecting BPR exposure (accept 29%)
Neglecting BPR exposure and ICFs (accept 49%)
Include major fission products and minor actinides with available ICFs (accept 58%)
Include major fission products minor actinides without any ICFs (accept 98%)
Burnup [GWd/MTU]
0
10
20
30
40
50
60
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Enrichment [wt% 235U]


Reference (accept 11%)
Delta-k factor for isotopic uncertainties, instead of ICFs (accept 28%)
Include major fission products and minor actinides with available ICFs (accept 58%)
Include major fission products and minor actinides with delta-k factor for isotopic uncertainties (accept 94%)
Include major fission products minor actinides without any ICFs (accept 98%)
Burnup [GWd/MTU]
0
10
20
30
40
50
60
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Enrichment [wt% 235U]

CONCLUDING REMARKS

- The added complexities of BUC necessitate new computational tools for code integration/interface and data handling
  - Reduce user effort
  - Reduce likelihood of user error
  - Facilitate studies to increasing understanding
- STARBUCS / REBUCS developed, tested, and utilized for a large number of studies at ORNL
- While computationally intensive, REBUCs automates the generation of BUC loading curves