Preliminary Study on the Effect of Control Rod Depletion for the Operation of SMR using STREAM/RAST-K

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- Effects of control rod inserted operation
- Control rod depletion module in RAST-K
- Depletion analysis of i-SMR fuel assembly
- Conclusion

Introduction

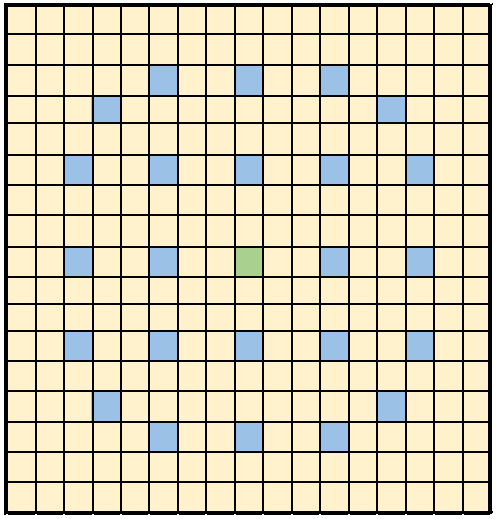
Control rod depletion for i-SMR analysis

- **innovative-Small Modular Reactor (i-SMR)**
  - **Soluble Boron Free (SBF) operation**
  - **Innovative Burnable Absorber (BA) design**
    - Control the excessive reactivity
    - CIMBA, CSBA, WABA, etc.
  - **Rod inserted operation**
    - To achieve criticality
  - **Control rod inserted operation analysis**
    - Should consider effects on fuel and control rod

Effects of control rod inserted operation

Test case

- **Test FA model**
  - **17x17 WH Fuel Assembly**
  - **No burnable poison**
  - **Boron concentration: 0 PPM**
  - **Moderator Temperature: 600 K**
  - **Fuel Temperature: 900 K**

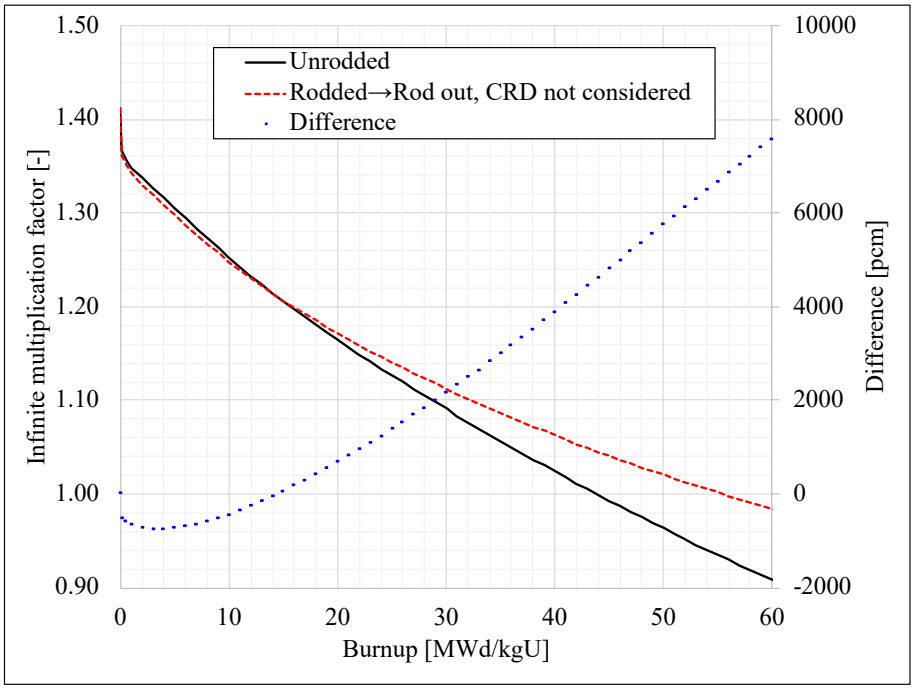


- **Test description**

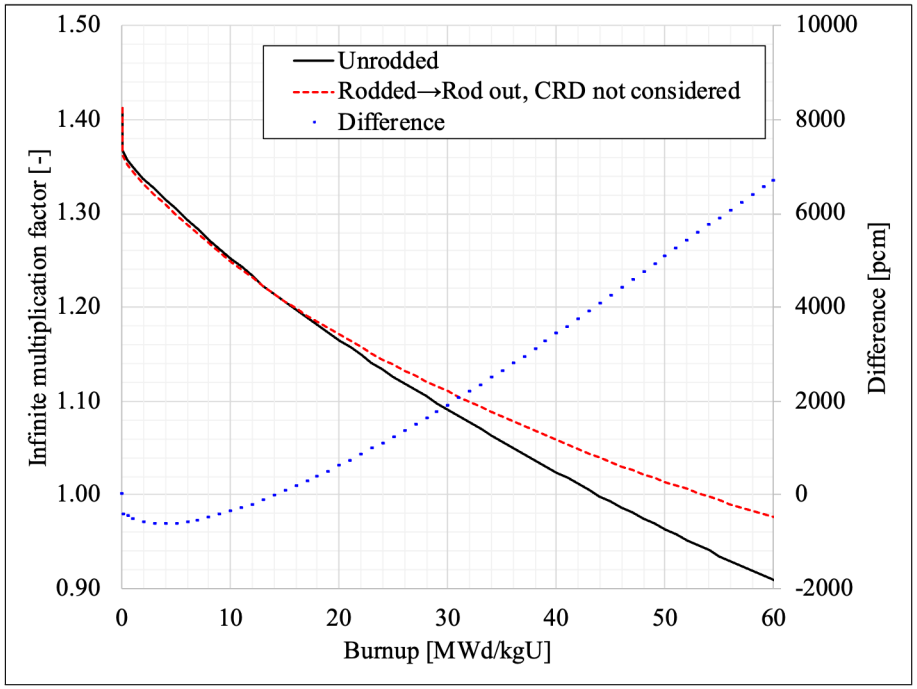
Index	Description
Test 1	Depletion of fuel under rodded/unrodded condition
Test 2	Depletion of fuel under rodded condition (considering control rod depletion or not)

Test 1: Depletion of fuel under rodded/unrodded condition

- **Case1: Depletion under unrodded condition**
- **Case2: Depletion under rodded condition → Rod withdrawn**
  - **Restart calculation (Snapshot at rod withdrawn state)**
- **Not considering depletion of control rod material**
- **Effect of depletion history**



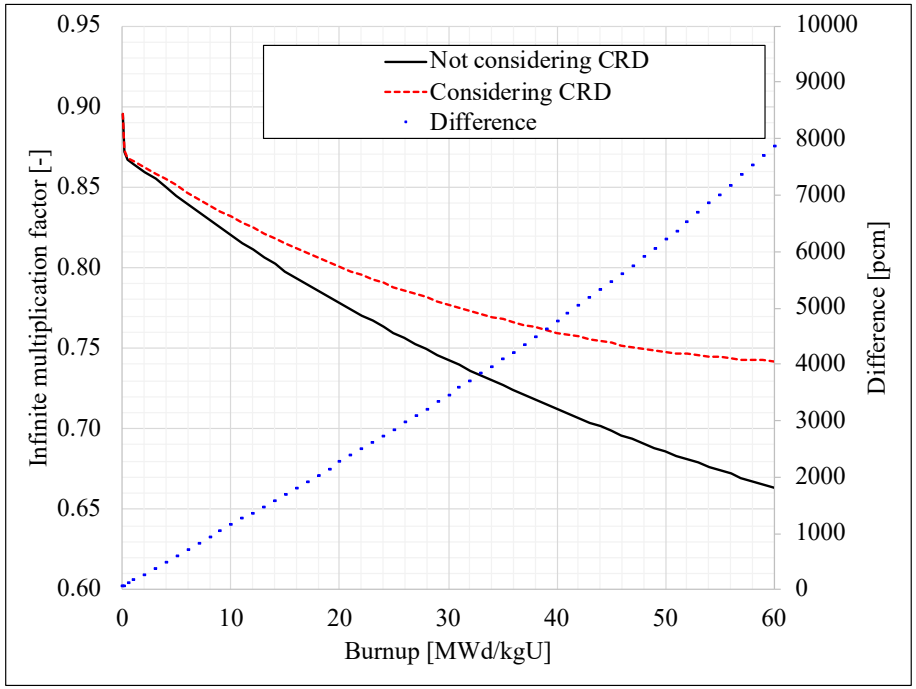
B4C Control rod



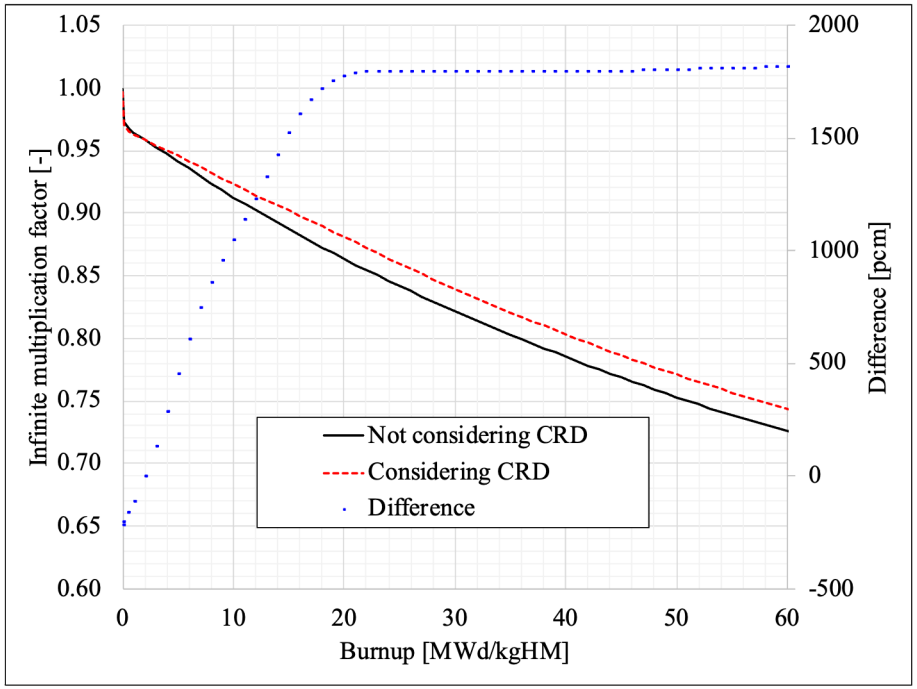
AIC control rod

Test 2: Depletion of fuel under rodded condition

- **Case1: Depletion under rodded condition (not considering CRD)**
- **Case2: Depletion under rodded condition (considering CRD)**
- **Effects of control rod depletion**
  - **Number density decrease of control rod materials**
  - **Rodded history effect for both cases**



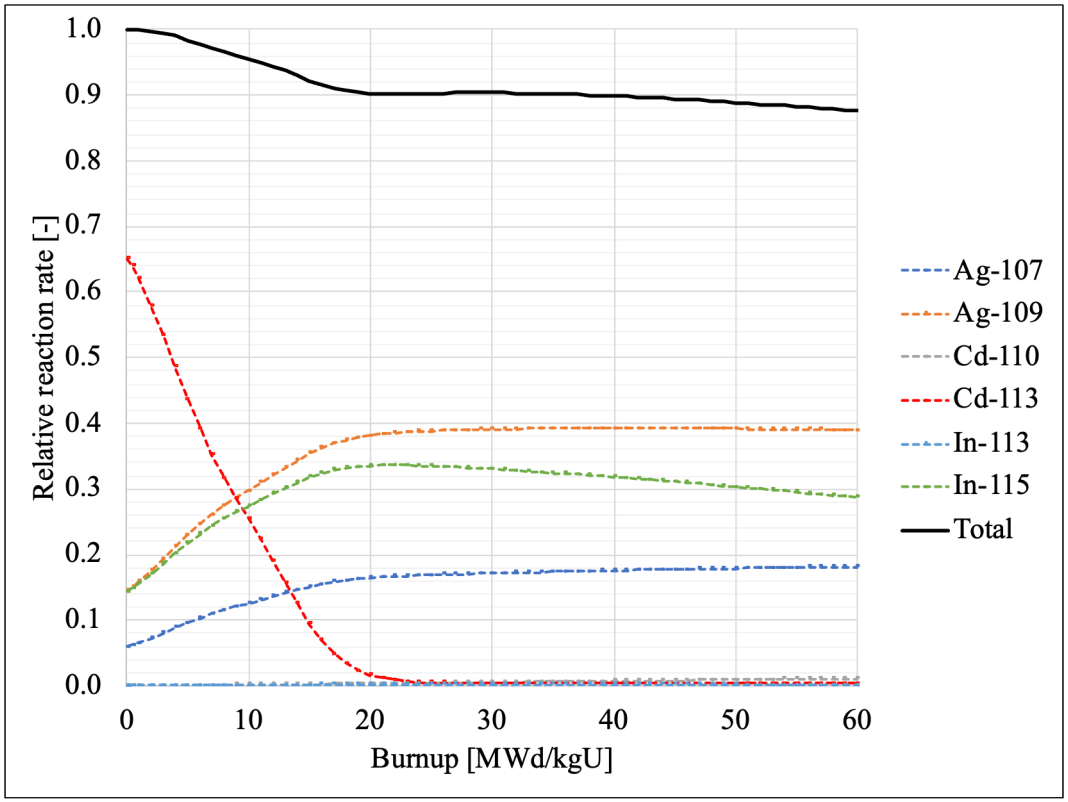
B4C Control rod



AIC control rod

Depletion of AIC

- **Absorption reaction rate of AIC materials**
  - **Rapid decrease of Cd-113's absorption reaction rate (~20 MWd/kgU)**
    - **Very high absorption cross section of Cd-113**
  - **Gentle slope of degradation after the depletion of Cd-113**

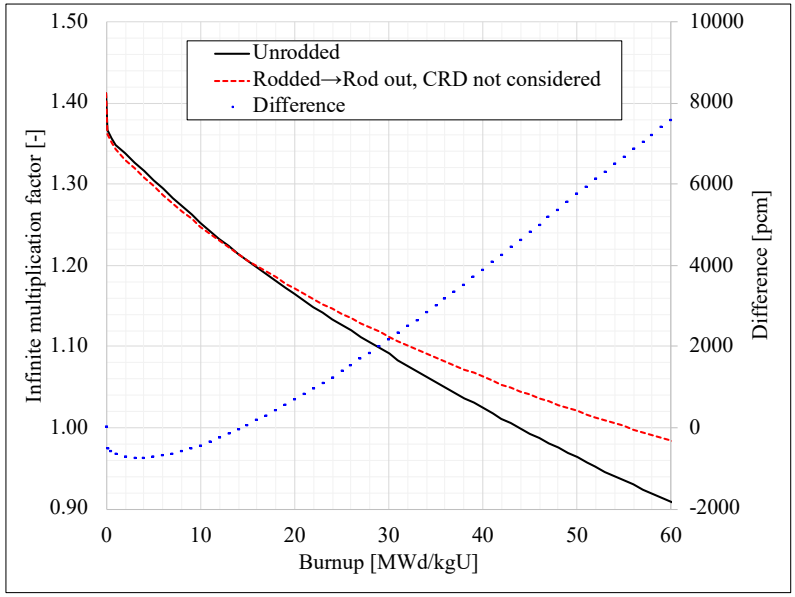


Isotope-wise relative absorption reaction rate

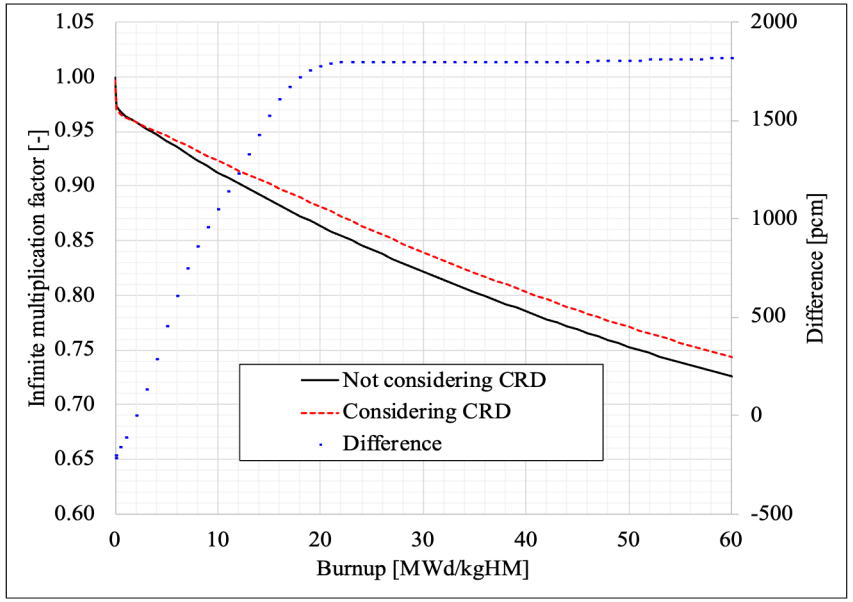
Summary: Effects of control rod inserted operation

- **Effects on fuel (Test 1)**
  - **Depletion behavior depends on the rodded history**
    - **Neutron spectrum hardening**

- **Effects on control rod (Test 2)**
  - **Absorption reaction rate degradation**
    - **Control rod depletion**



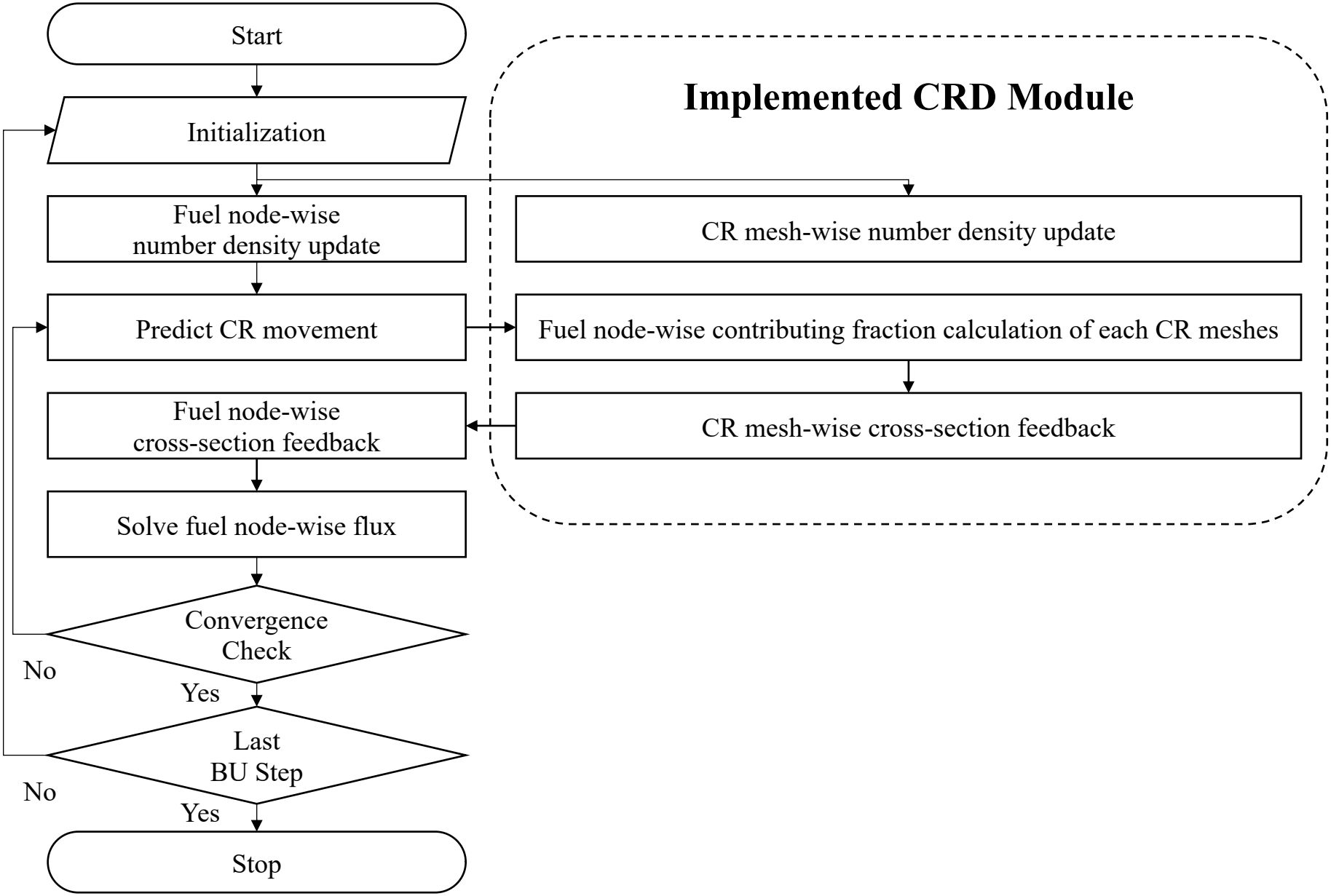
Test 1



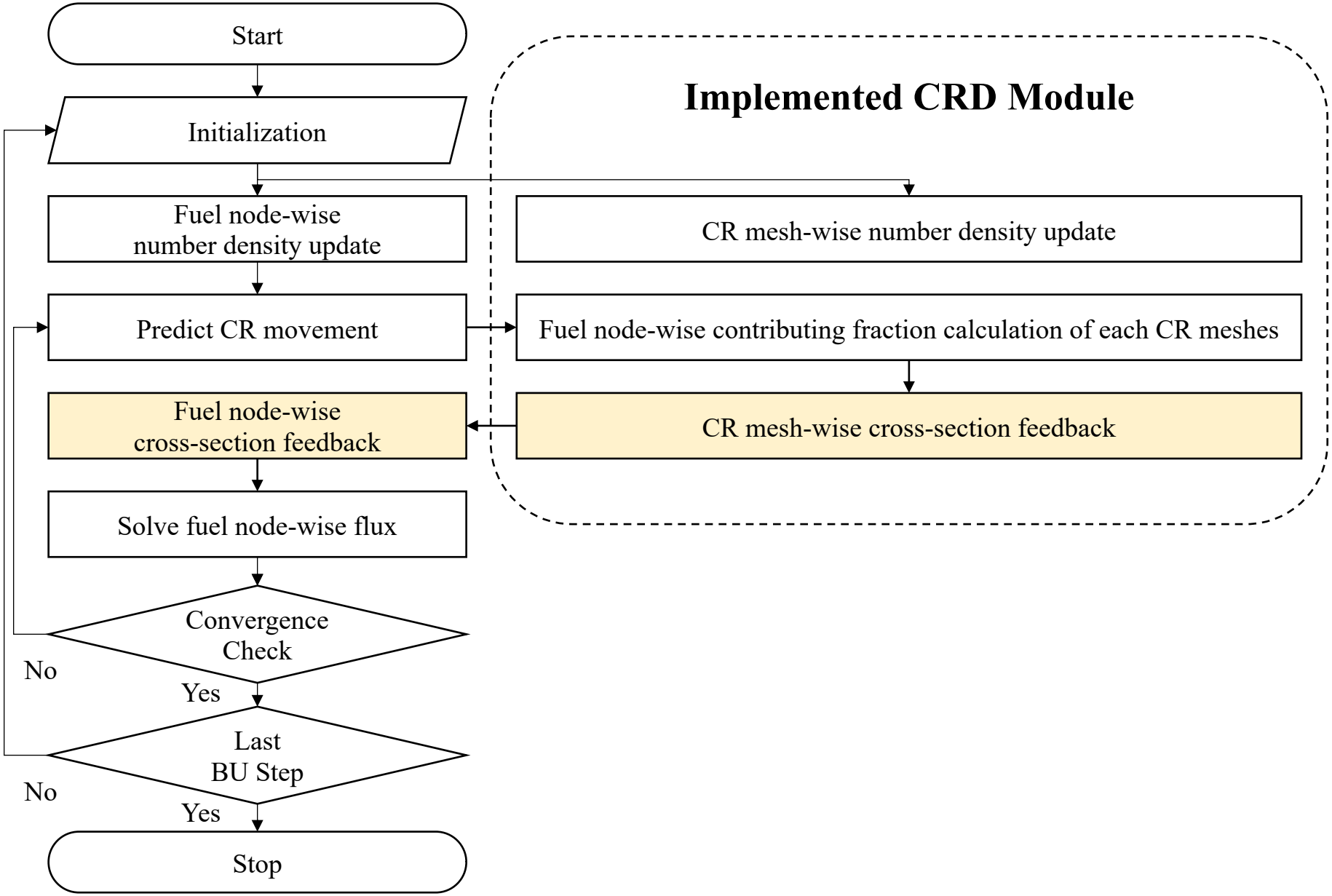
Test 2

Control Rod Depletion Module

Flowchart of RAST-K



Flowchart of RAST-K



Cross section feedback

- **Functionalized cross section model**

$$\sigma = f\left(BU, PPM, \sqrt{T_{fuel}}, T_{mod}, CR\right) \longrightarrow \sigma = f\left(BU, \sqrt{T_{fuel}}, T_{mod}, CR, CRDEP\right)$$

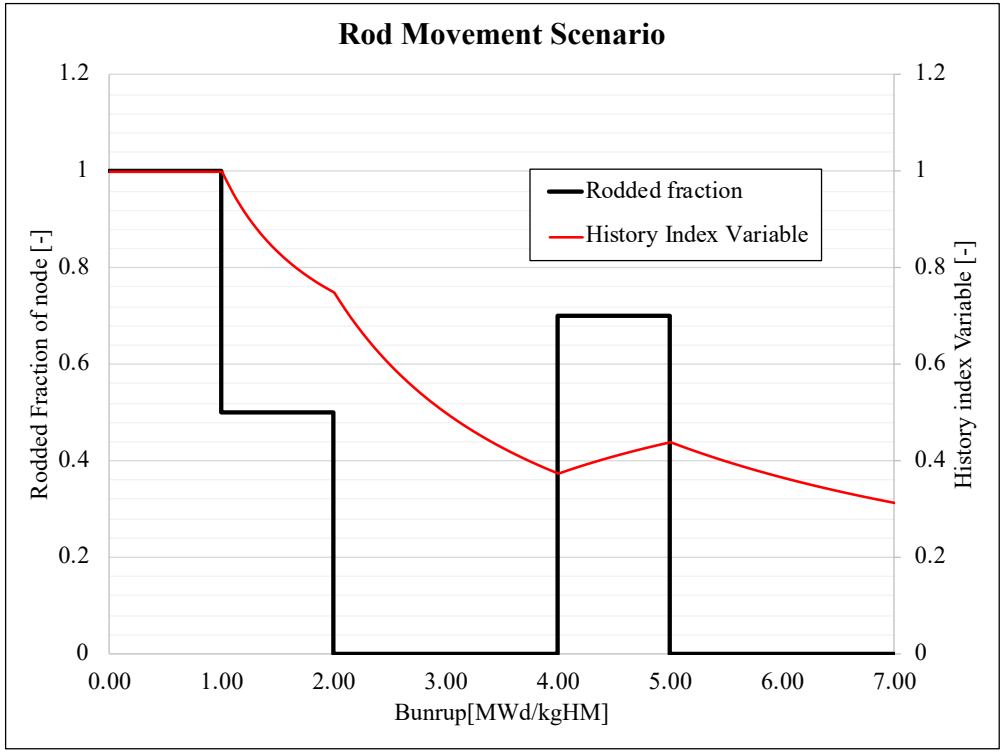
  - BU : Burnup
  - PPM : Boron concentration
  - T_{fuel} : Fuel temperature
  - T_{mod} : Moderator temperature
  - CR : Control rod
  - $CRDEP$: Depleted fraction of control rod material
    - Fresh, 1% burnt, 5% burnt, ...

- **History dependent cross section feedback**
  - **Feedback cross sections having rodded/unrodded histories**
    - Σ_{Rodded} : Cross section following rodded history
    - $\Sigma_{Unrodded}$: Cross section following unrodded history

History index variable

- **Burnup weighted Rodded/Unrodded depletion fraction**
  - **Saves node-wise history**

$$h = \frac{\sum_i^k (f_{Rodded}^i \cdot \Delta BU_i)}{\sum_i^k (\Delta BU_i)}$$

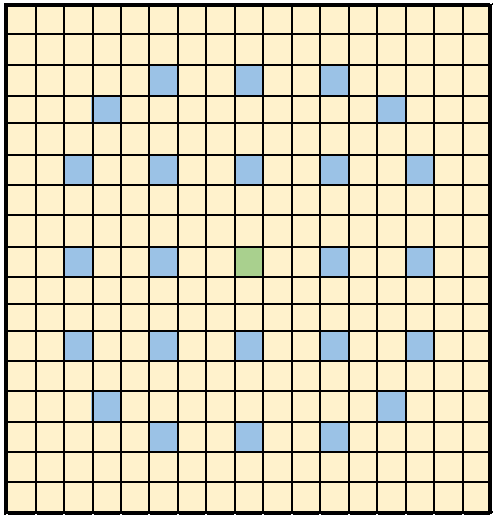


- **Cross section feedback using the history index variable**

$$\Sigma_{Node}^k = h \cdot \Sigma_{Rodded}^k + (1 - h) \cdot \Sigma_{Unrodded}^k$$

Test Case

- **Test FA model**
  - **17x17 WH Fuel Assembly**
  - **No burnable poison**
  - **Boron concentration: 0 PPM**
  - **Moderator Temperature: 600 K**
  - **Fuel Temperature: 900 K**
  - **Control rod material: AIC**

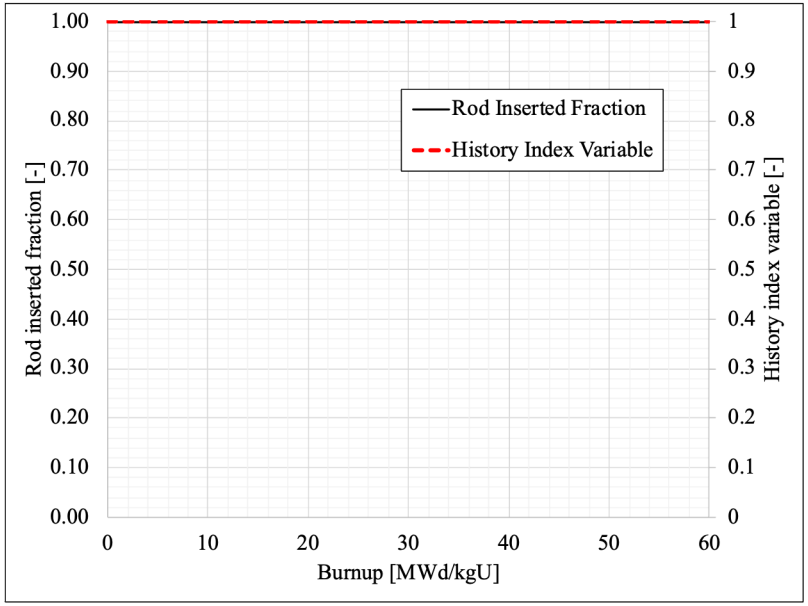


- **Test description**

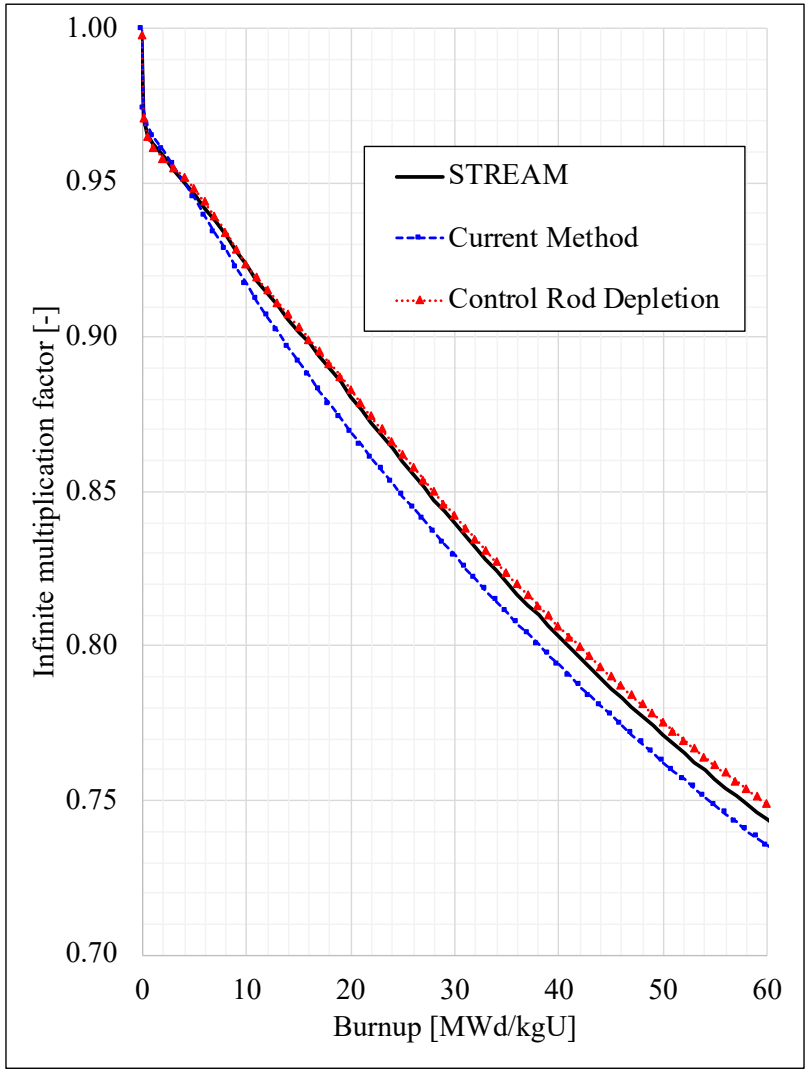
Index	Description
Test 3	Depletion under rodded condition
Test 4	Depletion under unrodded condition → rod insertion
Test 5	Depletion under rodded condition → rod withdrawal

Test 3: Prediction of depletion under rodded condition

- **Rodded condition (~ 60 MWd/kgU)**
  - **Current method**
    - Not considering control rod depletion
    - Unrodded history based
  - **Control rod depletion**
    - Considering control rod depletion
    - History follow calculation



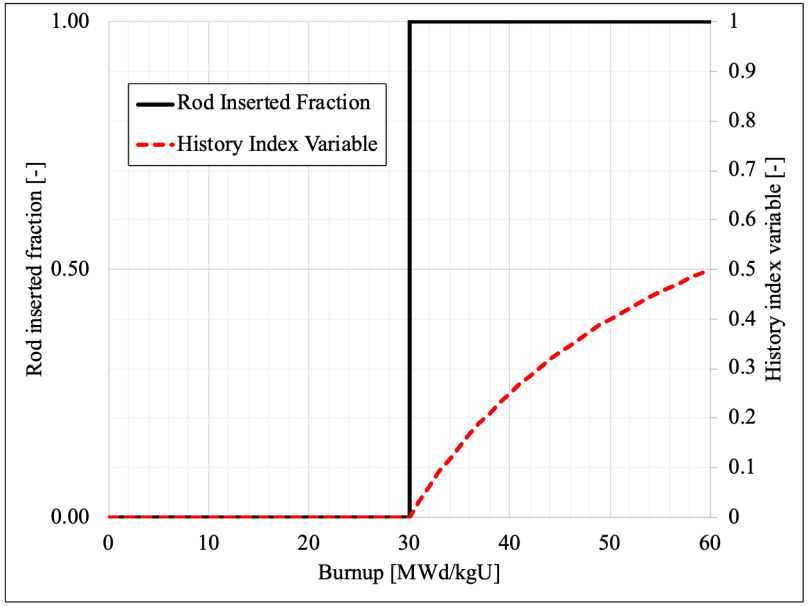
Rod insertion history



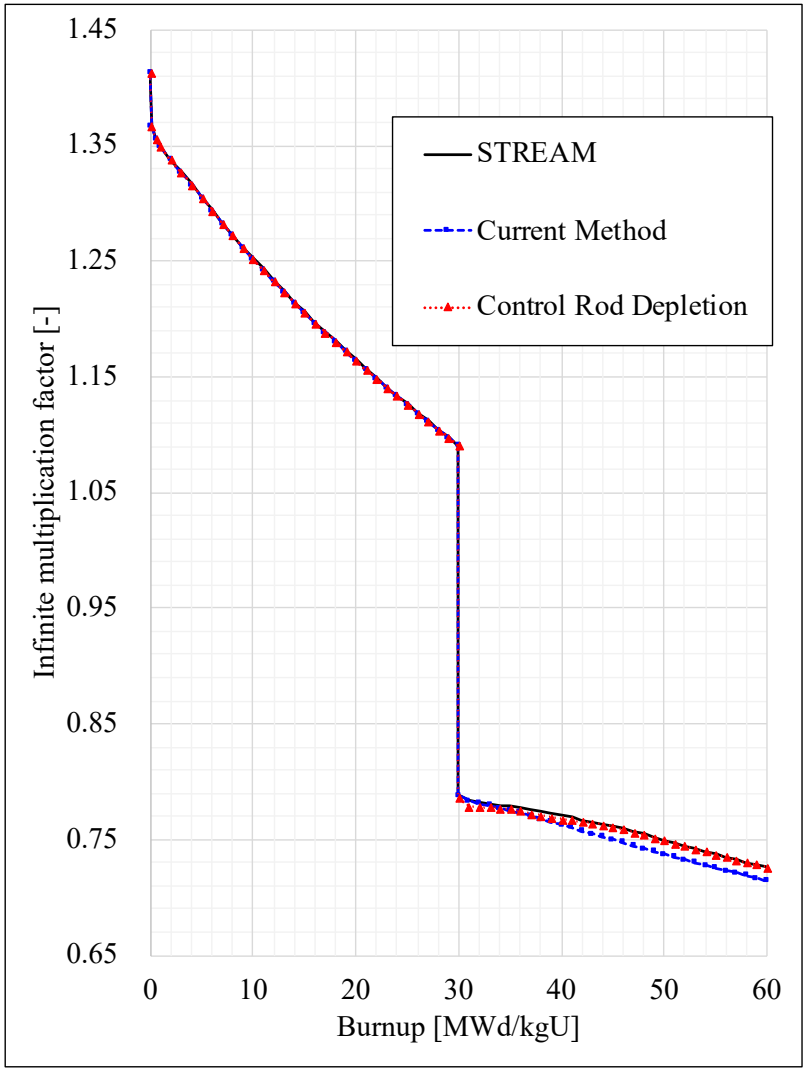
Infinite multiplication factor

Test 4: Depletion under unrodded condition → rod insertion

- **Withdrawn → Rod insertion at 30 MWd/kgU**
  - **Depletion until 30 MWd/kgU**
    - No difference between two cases
  - **Rod insertion at 30 MWd/kgU**
    - Gradually increasing history index variable
    - Current method: accumulation of error



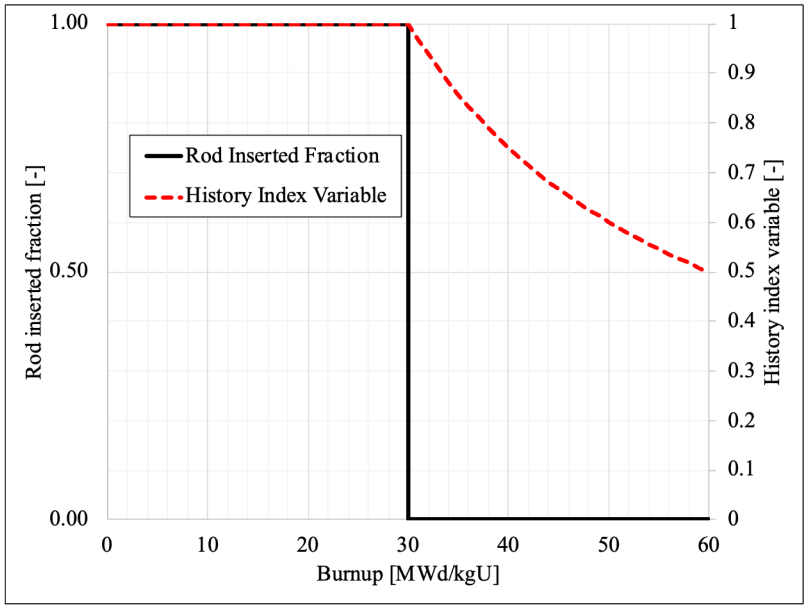
Rod insertion history



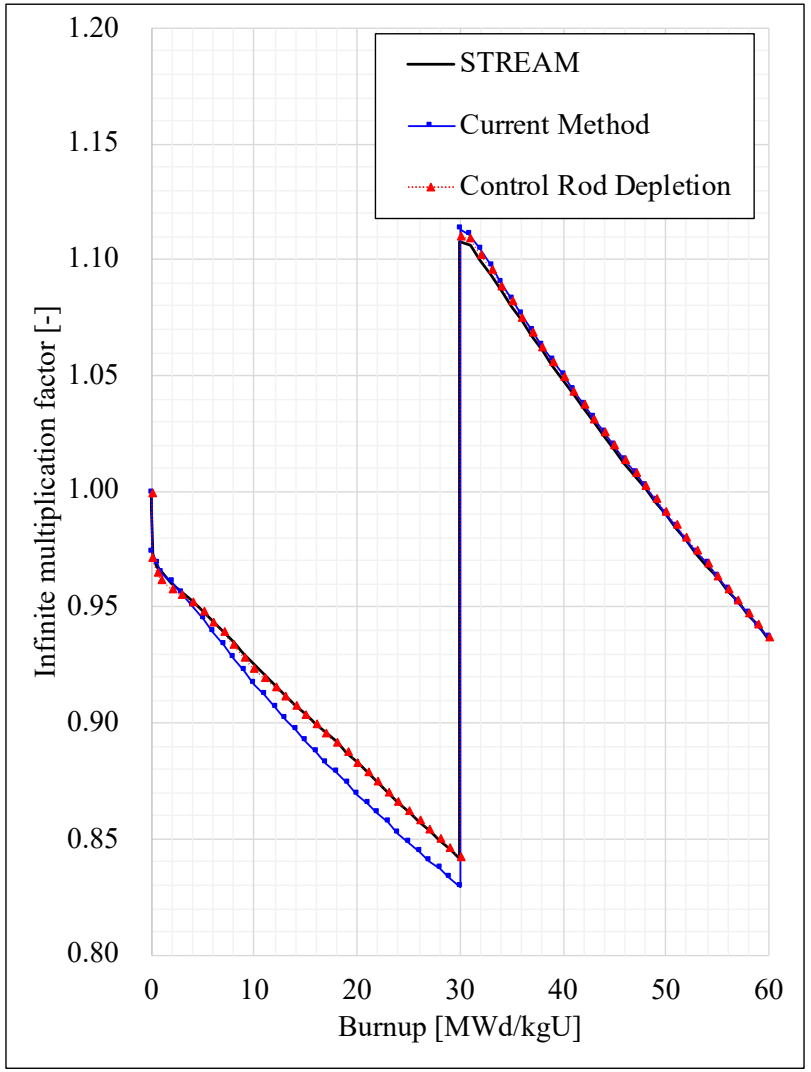
Infinite multiplication factor

Test 5: Depletion under rodded condition → rod withdrawal

- **Inserted → Rod withdrawal at 30 MWd/kgU**
  - **Depletion until 30 MWd/kgU**
    - Depletion under rodded condition
    - Current method: error accumulation
  - **Rod insertion at 30 MWd/kgU**
    - Gradually decreasing history index variable



Rod insertion history



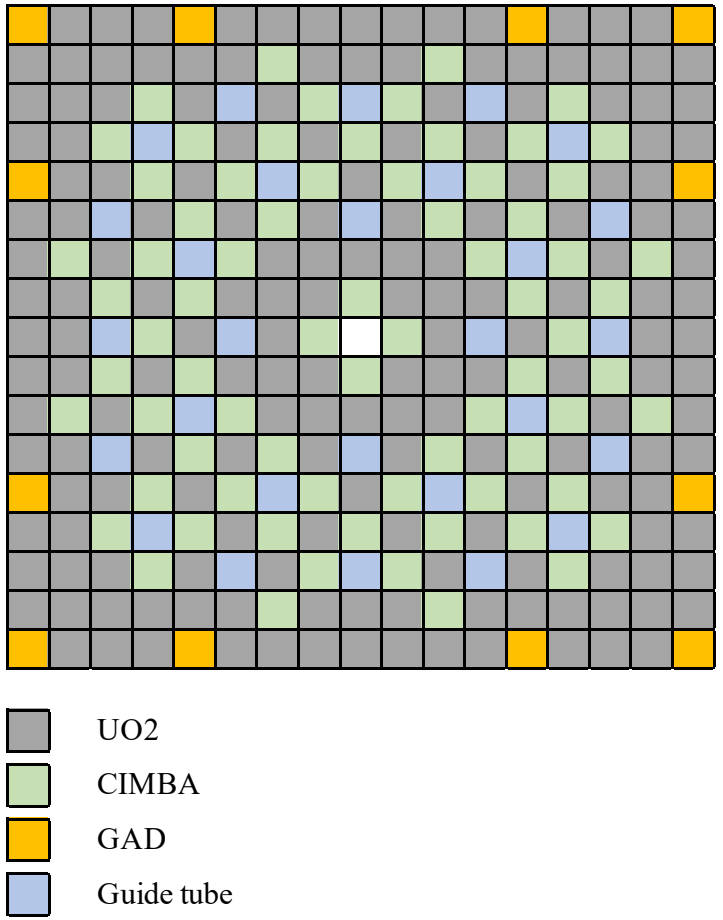
Infinite multiplication factor

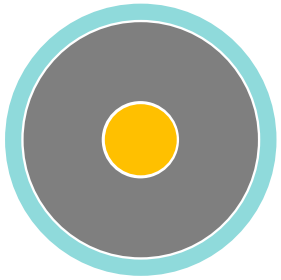
Depletion Analysis

CIMBA-based i-SMR Fuel Assembly

Test Case

- **Test FA model**
  - **17x17 CIMBA Fuel Assembly**
  - **Total number of fuel pin: 260**
    - **UO2 (Annular): 176**
    - **CIMBA pin: 72**
    - **GAD pin: 12**
  - **Number of guide tubes: 28**
  - **Boron concentration: 0 PPM**
  - **Fuel Temperature: 850 K**
  - **Moderator Temperature: 584 K**

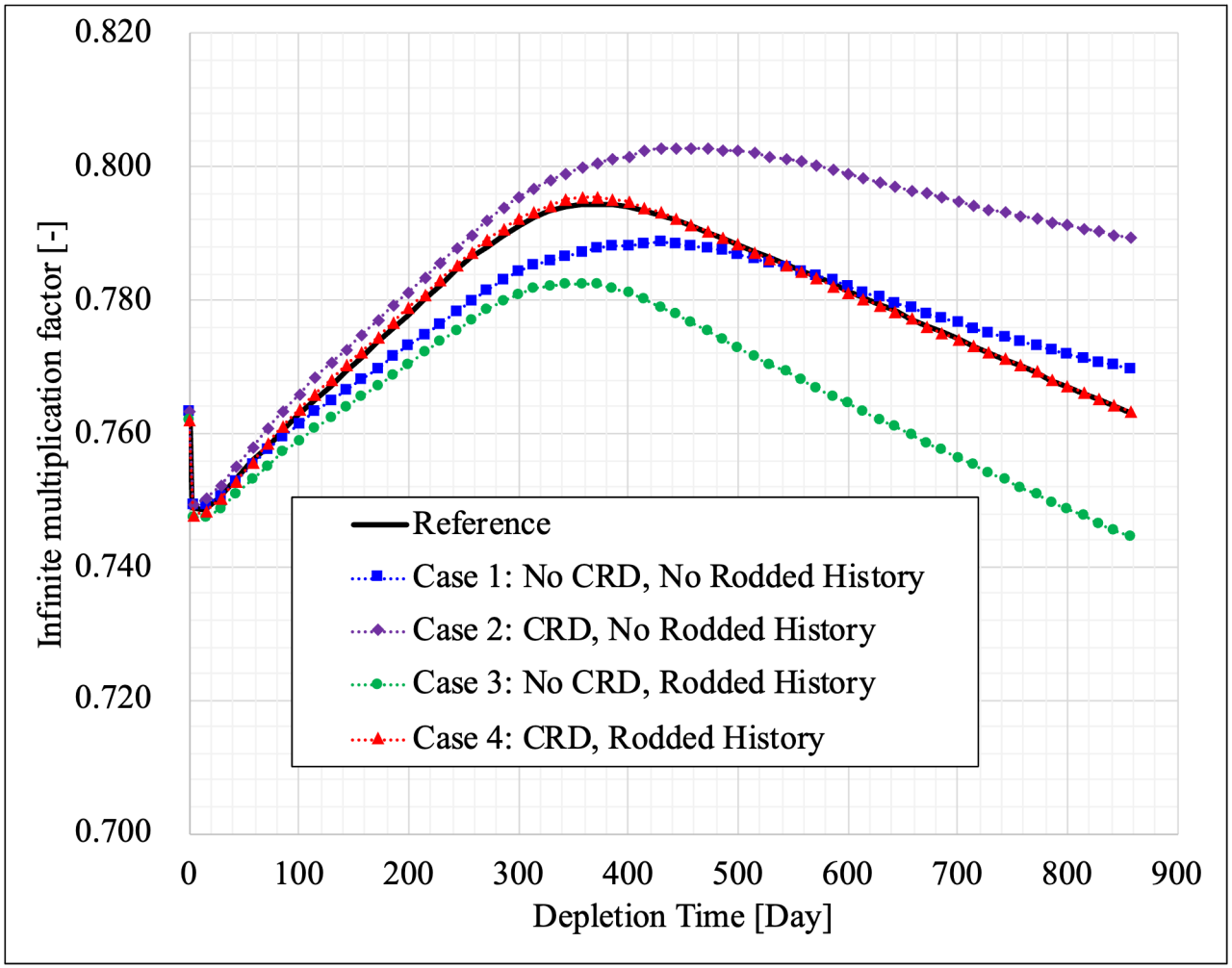




CIMBA pin: Annular UO2 pin + Cylindrical BA

Depletion calculation of the i-SMR Fuel assembly

- **Calculated k_∞ of the rodded FA against burnup**
  - **Maximum error of Case 4: 109 pcm**



Conclusion

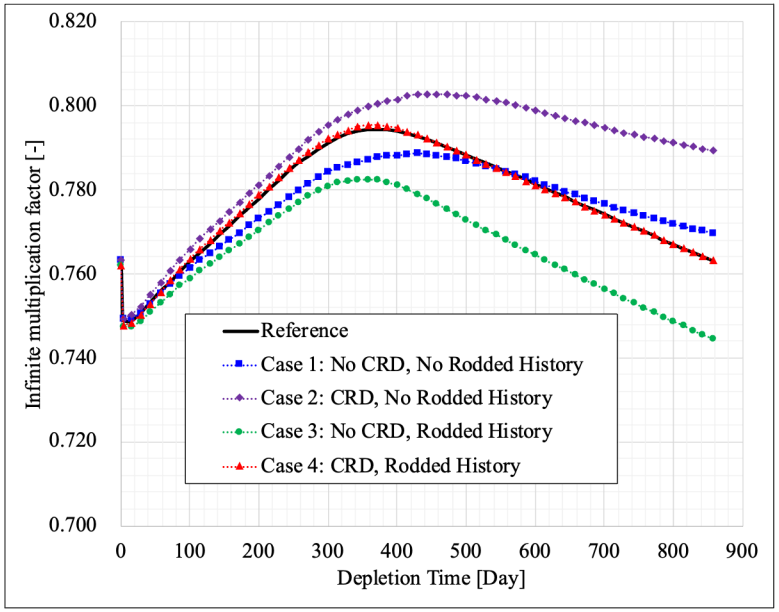
Conclusion

- **Effects of control rod insertion**
  - **Depletion behavior under rodded condition**
    - Due to spectrum hardening
  - **Degradation of absorption strength**
    - Control rod depletion
- **Control rod depletion module in RAST-K**
  - **Cross section feedback**
    - considering control rod depletion
  - **History following**
    - History index variable, *h* and cross section feedback

$$h = \frac{\sum_i^k (f_{Rodded}^i \cdot \Delta BU_i)}{\sum_i^k (\Delta BU_i)} \qquad \Sigma_{Node}^k = h \cdot \Sigma_{Rodded}^k + (1-h) \cdot \Sigma_{Unrodded}^k$$

Conclusion

- **i-SMR fuel assembly depletion analysis**
  - **Accurate infinite multiplication factor prediction**
    - Less than 109 pcm error
- **Ongoing works**
  - **Detailed depletion history**
    - Depleted CR insertion
  - **Axially heterogeneous cases**

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