Enhancement of Cross-section Feedback Module for Temperature Coefficient in STREAM/RAST-K

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1. Introduction

This paper introduces an enhancement process of STREAM/RAST-K in order to produce more accurate temperature coefficients. STREAM/RAST-K is a 2-step approach code system for neutron transport/diffusion analysis aiming to reactor core simulation. Verification and validation (V&V) of the code system have been ongoing [1]. In particular, the case matrix for group constants and cross-section feedback module work well for the steady-state simulation: RAST-K follows STREAM reference solution less than 30 pcm in hot states. However, it is found that STREAM/RAST-K needs some improvements to get accurate reactivity coefficients in cold states; thus, both STREAM and RAST-K make up for the weak points.

An interpolation method of a cross-section for temperatures in STREAM partially changes to consider thermal scattering cross-section characteristics of H in H_2O, which is as known as s(α,β). The full case matrix including the cold state, which needs generating few-group constants required for RAST-K, restructures densely. RAST-K also changes the existing 2D/1D cross-section interpolation to the 3D/2D cross-section interpolation. This paper presents improved results of moderator temperature coefficients (MTC) regarding temperature from the cold zero power (CZP) to the hot zero power (HZP) in an entire cycle by these enhanced methods.

2. Cross-section Interpolation in STREAM

2.1. H in H_2O neutron thermal scattering cross-section

The multi-group cross-section library used in STREAM reduces ENDF raw data to 72 groups through NJOY code and produces them on average seven temperature points for all isotopes. Equations for temperature, such as Doppler Broadening, can express most types of cross-sections; thus, it is easy to produce cross-sections for a specific temperature. On the other hand, H in H_2O thermal scattering cross-section is challenging to express in a specific equation according to temperature, so it relies on experimental data only. Therefore, STREAM uses the H in H_2O thermal scattering data from specific temperature points provided by the ENDF. Among the nine temperature point libraries provided in ENDF/B-VII.1, seven temperature

point libraries, which are at 293.6, 400, 500, 550, 600, 650, and 800K, were used.

2.2. Change of cross-section interpolation in STREAM

Cross-sections of most isotopes are linear according to the square root of temperature (Fig. 1), whereas thermal scattering cross-section of H in H_2O tends to be nonlinear, as shown in Fig. 2.
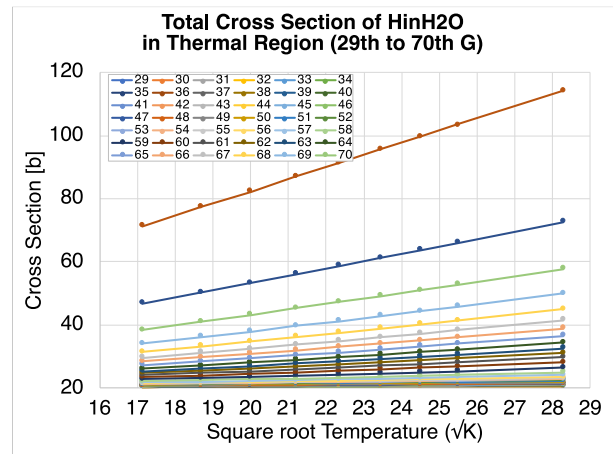

Fig. 1. Total cross-section of H in H_2O as a function of $\sqrt{temperature}$ in thermal region. 72th group is the lowest energy group.
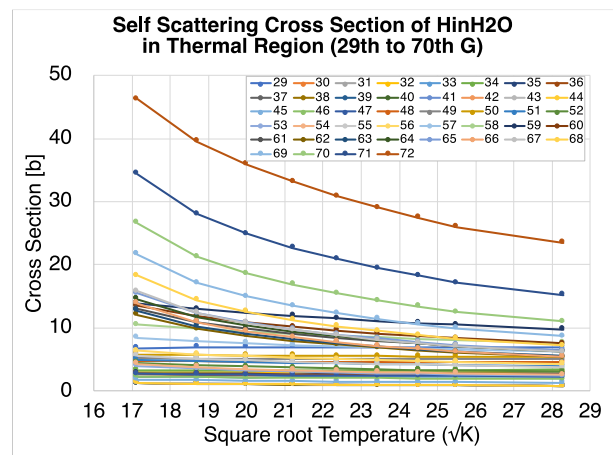

Fig. 2. Self-scattering cross-section of H in H_2O as a function of $\sqrt{temperature}$ in thermal region. 72th group is the lowest energy group.

For every type for all isotopes, cross-section interpolation for a given temperature in STREAM was used by linear interpolation with the square root of temperature using nearby two temperature points.

Figs. 3 and 4 show the k_{eff} and MTC obtained from the conventional cross-section interpolation for a typical 2D fuel assembly (FA) model used in a pressurized water reactor (PWR). The fuel temperature increases from 300K to 15K units and the moderator temperature is given as ± 3K of the fuel temperature. That is, in the case of MTC at 400K, the fuel temperature is fixed at 400K, and the moderator temperature is changed to 397K and 403K. Then, the k_{eff} is calculated. MTC is calculated for seven different boron concentrations (from 0 ppm to 2400 ppm), from 300K to 570K.

k_{eff} result, as shown in Fig. 3, by cross-sections obtained by the conventional interpolation looks smooth, but MTC depicted in Fig. 4 result is discontinuous in certain points.
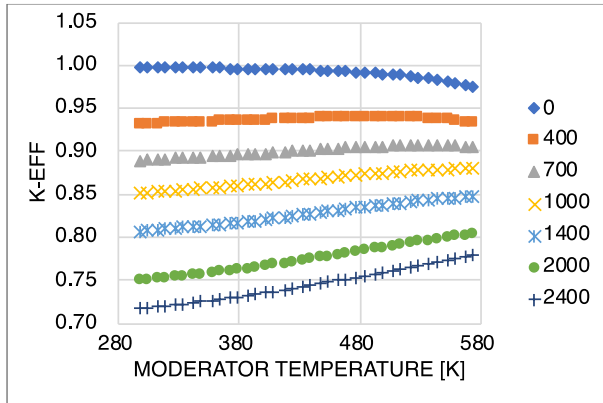

Fig. 3. k_{eff} of STREAM as a function of moderator temperature in seven different boron concentration. Temperatures of H in H₂O libraries at 293.6, 400, 500, 550 K. Linear interpolation is adopted for cross-section interpolation. The TH1D correlation is used as the function of water temperature and density.
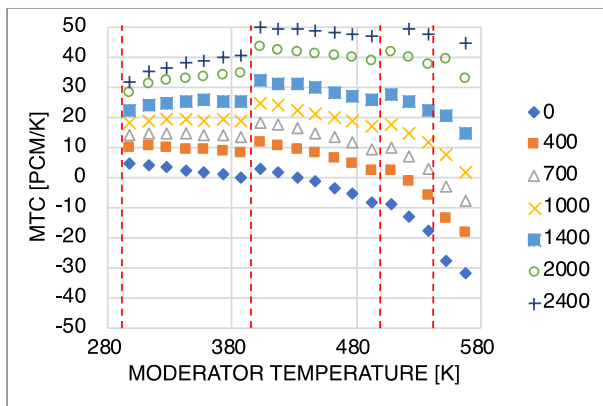

Fig. 4. MTC of STREAM as a function of moderator temperature in seven different boron concentration. Temperatures of H in H₂O libraries at 293.6, 400, 500, 550 K. Linear interpolation is adopted for cross-section interpolation.

The TH1D correlation is used as the function of water temperature and density.

To compensate for MTC discontinuity issue, only thermal scattering cross-section of H in H_2O adopts Lagrange polynomial interpolation using nearby three temperature points. Weighting factors for cross-section interpolation, F, is calculated as follows:

$$F = \begin{bmatrix} f1 \\ f2 \\ f3 \end{bmatrix} = \begin{bmatrix} \dfrac{(\sqrt{T}-\sqrt{T2})(\sqrt{T}-\sqrt{T3})}{(\sqrt{T1}-\sqrt{T2})(\sqrt{T1}-\sqrt{T3})} \\ \dfrac{(\sqrt{T}-\sqrt{T1})(\sqrt{T}-\sqrt{T3})}{(\sqrt{T2}-\sqrt{T1})(\sqrt{T2}-\sqrt{T3})} \\ \dfrac{(\sqrt{T}-\sqrt{T1})(\sqrt{T}-\sqrt{T2})}{(\sqrt{T3}-\sqrt{T1})(\sqrt{T3}-\sqrt{T2})} \end{bmatrix} \quad (1)$$

where T is a given temperature, $T1$ is a nearby lower temperature, $T2$ and $T3$ are nearby higher temperatures.

Furthermore, the number of temperature points increases from seven to all nine points: 293.6, 350, 400, 450, 500, 550, 600, 650, and 800K.

2.3. Additional updates in STREAM

In STREAM 2D, the water density function for the temperature at 155 bar used TH1D correlation at a temperature of 280°C or higher, and correlation obtained from a steam table in the CTF at 280°C or lower. In order to solve the discontinuity occurring at 280°C (553.15K) boundary, the steam table (IAPWS-IF97 [2]) is used in all temperature and pressure ranges.

Figs. 5 and 6 show the k_{eff} and MTC calculated by the updated STREAM for a typical 2D FA model used in a PWR. Not only k_{eff} but also MTC tends to be smooth and continuous.
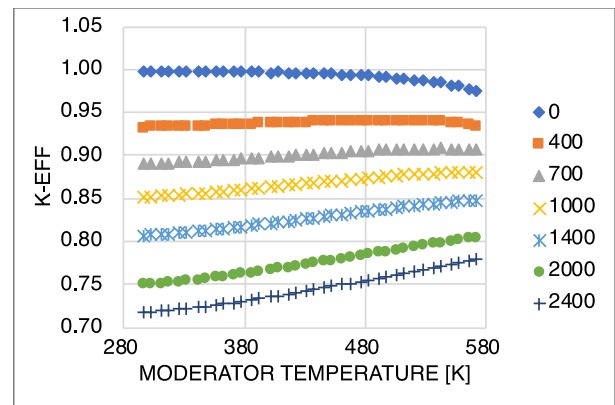

Fig. 5. k_{eff} of STREAM as a function of moderator temperature in seven different boron concentration. Six temperatures of H in H₂O libraries at 293.6, 350, 400, 450, 500, 550 K. Lagrange interpolation is adopted for cross-section interpolation. The steam table is used as the function of water temperature and density.
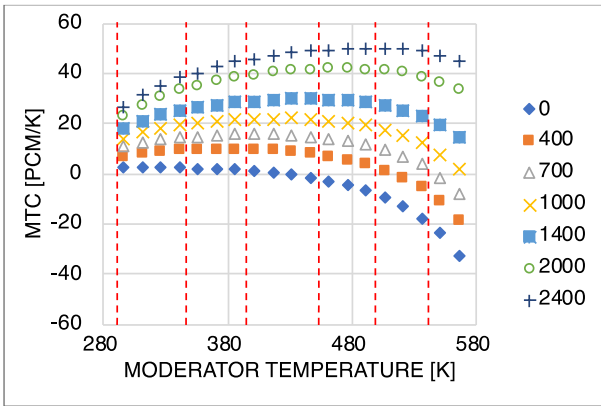
Fig. 6. MTC of STREAM as a function of moderator temperature in seven different boron concentration. Six temperatures of H in H_2O libraries at 293.6, 350, 400, 450, 500, 550 K. Lagrange interpolation is adopted for cross-section interpolation. The steam table is used as the function of water temperature and density.

3. Full Case Matrix and Cross-section Feedback Module in RAST-K

When performing 2D/1D cross-section interpolation with the cold state case matrix, the difference with the STREAM reference is irregular and shows up to ±60pcm, as shown in Fig. 7.
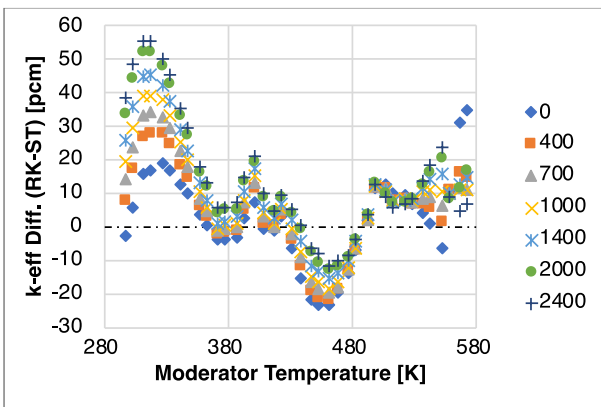

Fig. 7. k_{eff} difference between RAST-K and STREAM as a function of moderator temperature in seven different boron concentration. Current 2D/1D cross-section interpolation is used in the cross-section feedback module of RAST-K.

To compensate for this, the number of 83 branches, including fuel temperature, water temperature, boron concentration, and control rod insertion expands to 173 branches. The branch points used in the full case matrix are:
- branches for fuel temperature:
  293.6, R_{TM}-25, R_{TF}, 1500 K
- branches for moderator temperature:
  293.6, 330, 350, 400, 425, 450, 500, 500, 525, R_{TM}-25, R_{TM}, R_{TM}+25 K
- branches for boron concentration:
  0.1, R_{BOR}, 2×R_{BOR}, 2400 ppm.

The cross-section interpolation in RAST-K is also densely changed to a 3D/2D interpolation, an example of a 3D/2D case matrix is described in Fig. 8.
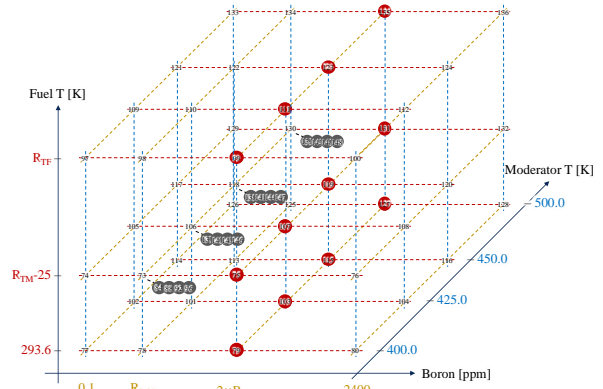

Fig. 8. Example of 3D/2D case matrix for the cold state at one burnup point. The matrix is a function of fuel temperature, moderator temperature and boron concentration.

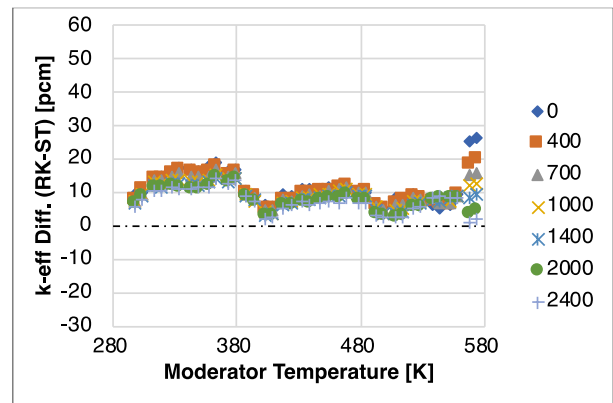It is confirmed that the RAST-K fits the STREAM reference within keff of 15 pcm, and MTC of 0.7 pcm/K.

Fig. 9. k_{eff} difference between RAST-K and STREAM as a function of moderator temperature in seven different boron concentration. Updated 3D/2D cross-section interpolation is used in the cross-section feedback module of RAST-K.

4. MTC results from CZP to HZP

MTC calculation from CZP to HZP is conducted for the first cycled of OPR-1000. Figs. 10 to 12 depict MTC change according to the temperature in BOC, MOC and EOC, respectively. The curve, which was abnormal under 200℃, changes acceptable, and the error due to the correlation of water temperature and density that occurred near 280℃, is also eliminated.
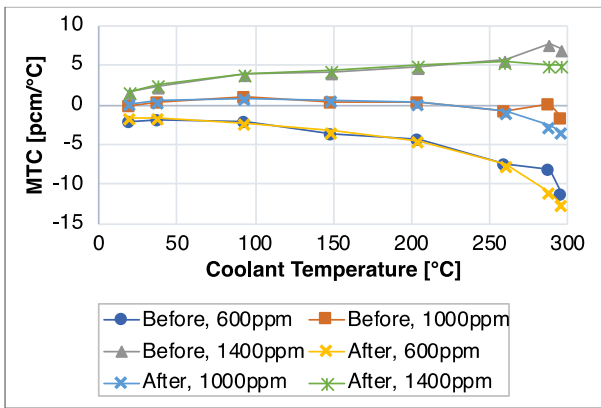
Fig. 10. MTC vs. moderator temperature at the beginning of cycle (BOC) from cold zero power (CZP) to hot zero power (HZP), all rods out (ARO), no xenon. "After" cases are the final results.
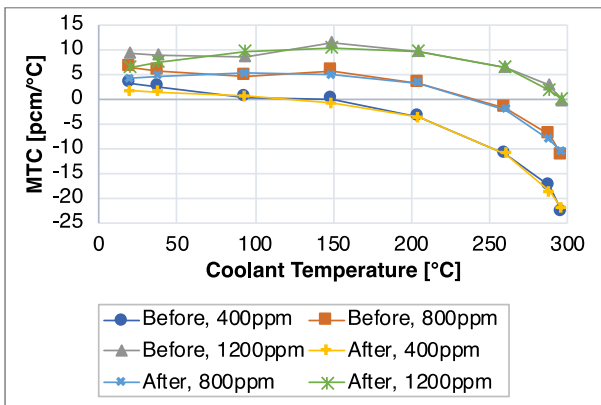

Fig. 11. MTC vs. moderator temperature at the middle of cycle (MOC) from cold zero power (CZP) to hot zero power (HZP), all rods out (ARO), no xenon. "After" cases are the final results.
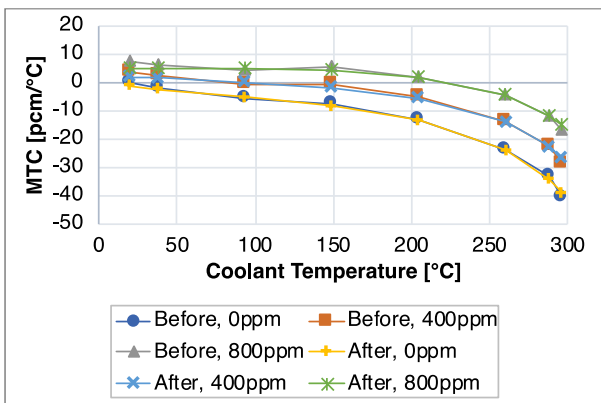

Fig. 12. MTC vs. moderator temperature at the end of cycle (EOC) from cold zero power (CZP) to hot zero power (HZP), all rods out (ARO), no xenon. "After" cases are the final results.

5. Conclusions

STREAM/RAST-K is enhanced to produce more accurate temperature coefficients. STREAM adopts Lagrange polynomial interpolation of a cross-section for temperatures to reflect thermal scattering cross-section characteristics of H in H_2O. The number of branches expands to 173 for denser case matrix. RAST-K also changes the cross-section feedback module as the 3D/2D cross-section interpolation. Both STREAM and RAST-K use the steam table for water property, not correlations at a fixed pressure. These changes lead to generating better temperature coefficients. RAST-K follows STREAM reference solution within 15 pcm and MTC in whole core shows good agreement.

ACKNOWLEDGEMENT

REFERENCES

[1] J. Choe, S. Choi, P. Zhang, J. Park, W. Kim, H.C. Shin, H.S. Lee, J.E. Jung, D. Lee, "Verification and Validation of STREAM/RAST-K for PWR Analysis," Nucl. Eng. Tech., 51(2): 356-368, 2019.
[2] R.K. Salko, M.N. Avramova, "CTF Theory Manual," Oak Ridge National Laboratory, CASL-U-2016-1110-000, 2016