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nTRACER Whole Core Transport Solutions to C5G7-TD Benchmark

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Abstract – *The C5G7-TD benchmark problems are solved by the nTRACER direct whole calculation code employing faithful models of the core configuration and transient control parameters. In the cases of TD1-1 through TD1-3, nTRACER results are compared with those of the SUHAM-TD code of the benchmark originator to confirm the soundness of the solutions. For selected 2-D cases, the nTRACER results are compared with the McCARD Monte Carlo transient simulation results. For the 3-D TD4 problems involving control rod insertions and withdrawals, a fine axial plane model is used first to generate the reference solutions without significant control rod cusping effect. Then coarser axial plane models are used in which the modified approximate flux weighting method is employed as a decusping approach. The results consisting of transient power behaviors and dynamic reactivity changes are presented.*

I. INTRODUCTION

The C5G7-TD benchmark (Deterministic Time Dependent Neutron Transport Benchmark without Spatial Homogenization) [1] consisting of six series of transient problems was proposed by the Expert Group on Radiation Transport and Shielding (EGRTS) of the Working Party on Scientific Issues of Reactor Systems (WPRS) in OECD/NEA. Each problem set consists of several sub-problems defined with different core control parameters. The core configuration and cross section (XS) data such as the radial core geometry and the seven-group macroscopic XS were taken basically from the well-known C5G7-MOX benchmark problem [2]. The axial geometry, however, was changed for modeling control rod insertion from the top. For transient simulation, the kinetic parameters for the 8-group delayed neutron precursor groups such as delayed neutron fractions and emission spectra, and precursor decay constants as well as the neuron velocities are provided in the benchmark specification. Exercises 0 (TD0) through 3 (TD3) are two-dimensional (2-D) transient problems with various types of XS changes simulating control rod motions or moderator density changes. Among the three-dimensional (3-D) cases, Exercise 4 (TD4) set requires an actual modeling the control rod insertion and withdrawal movements and Exercise 5 (TD5) set involves moderator density changes.

The transient calculation capability in the direct whole core calculation codes involving the planner MOC based method was initially developed and demonstrated for the DeCART [3] code. The nTRACER [4] direct whole core calculation code which adopts essentially the same direct whole core calculation methods as those of DeCART is being developed at Seoul National University (SNU) for practical applications of the high-fidelity direct whole core calculation models. Previously, nTRACER was applied to the C5G7-MOX benchmark problems [5]. However, the transient calculation features of nTRACER [6] have not been examined with a common benchmark.

In the work here, all the C5G7-TD problem sets are solved by nTRACER employing the models that incorporate the specification faithfully. A few problems in TD1 will be compared with the SUHAM-TD [7] results which were produced by the benchmark originator. For this comparison, however, the old 8G delayed neutron group data are used temporarily because the SUHAM-TD results were generated with those. In the case of selected 2-D cases (TD0-1, TD0-5, TD1-1, TD2-1 and all sub-problems in TD3), the McCARD [8] Monte Carlo transient simulation results are available which was generated by using the Dynamic Monte Carlo (DMC) method [9]. For the 3-D problems involving control rod movements, the solutions were generated with a decusping method that mitigates the control rod cusping effect [10] by employing the Approximate Flux Weighting (AFW) method [11]. Section IV details the effect of decusping. The results for the 3-D cases could not be compared with the other solutions since this benchmark is still ongoing. The nTRACER solutions being presented here might be used as the independent solutions for other participants to compare with.

II. CORE MODELING AND OPTIONS

The 2-D radial geometry of the C5G7-TD core is exactly the same as that of the C5G7-MOX benchmark core while the axial geometry is slightly modified as shown in Fig. 1 [1]. For the radial two-region pin-cell modeling, a sufficient number of flat source regions (FSRs) were used, namely 5 and 4 annular regions for the fuel and moderator regions, respectively, with 8 azimuthal sectors. For the square pin-cells in the reflector, 7x7 lattice FSRs were used.

In the axial modeling, three different axial models were made for analyzing TD4. Since the TD4 is for 3-D control rod insertions/withdrawals which induce the control rod cusping effect, the first model was generated with fine equal height planes to nullify this cusping effect (120 planes for the active fuel and 5 planes each for the top and bottom reflectors). The second model was made with coarser equal height planes (24 planes for active fuel and 4 planes for top and bottom reflector each). The third model doubles the plane thickness of the second model. In the second and third models, the AFW based decusping method was applied. For the TD5 analysis, the second axial model was chosen. For axial 1-D nodal calculation, the P1 SENM of nTRACER solver was used.

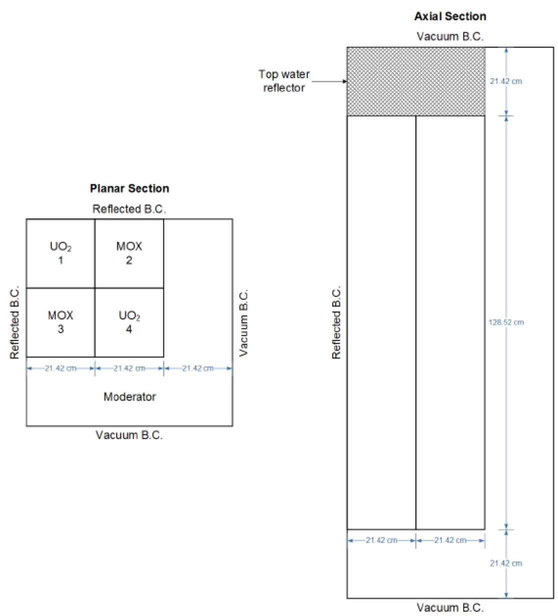

Fig. 1. Modified C5G7 3-D configuration [1]

The ray spacing was set to 0.05cm and the numbers of azimuthal angles and optimum polar angles per octant of the solid angle sphere were set to 16 and 4, respectively. In nTRACER, three temporal discretization schemes are available which are the Crank-Nicolson (CN) method, the CN with exponential transformation (CNET) [4,12] and the Backward Differentiation Formula (BDF) upto 5th order [13] with the isotropic angular flux time derivative assumption [3]. In this C5G7-TD analysis, however, the simplest CN method was used since there are no significant differences between the results of the three methods for these slow transient problems. For the 2-D cases, 2.5 ms time step size was used while 50 and 25 ms time steps were used for the TD4 and TD5 problems, respectively.

III. ANALYSES OF 2-D PROBLEMS

The 2-D problems consist of TD0 through 3 problems that contain their own sub-problems. The control rod motion is modeled by time-dependent change in the absorption XS which is either step or ramp change. The TD3 involves the ramp changes in moderator density.

1. TD0- Set with 5 sub-problems

In the TD0 Problems, control rod insertion/withdrawal motions are specified as a step change in the material composition, namely a sudden change from the guide tube cell to the control rod cell. Fig. 1 [1] shows detailed fractional control rod insertions during the transient as a stair-like XS change. Since there is a prompt jump or drop right after step reactivity change, the approximation below should be used in the CN method right after the step XS change:

$$\bar{\phi}^{n}_{g,m} \approx \bar{\phi}^{n-1}_{g,m} \tag{1}$$

$\phi^{n}_{g,m}$ = region m averaged group g flux at time step n.

The TD0 set consists of five sub-problems shown below:

- TD0-1: insertion/withdrawal of Bank 1
- TD0-2: insertion/withdrawal of Bank 3
- TD0-3: insertion/withdrawal of Bank 4
- TD0-4: insertion/withdrawal of Banks 1, 3, and 4
- TD0-5: insertion/withdrawal of Banks 1-4

The nTRACER results for core power behavior and reactivity change are shown in Figs. 3 and 4. The power behaviors of TD0-1 and TD0-5 are compared in Fig. 5 with those of McCARD Monte Carlo results [9] upto 3 seconds and the agreement between the two appears excellent.

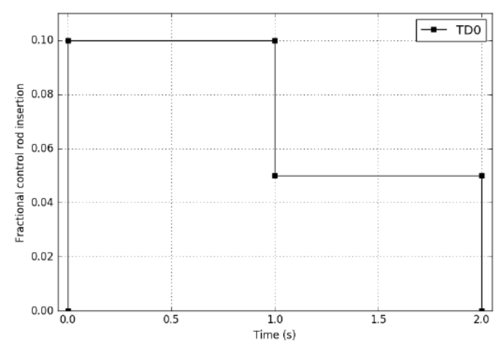

Fig. 2. Control rod movement in TD0

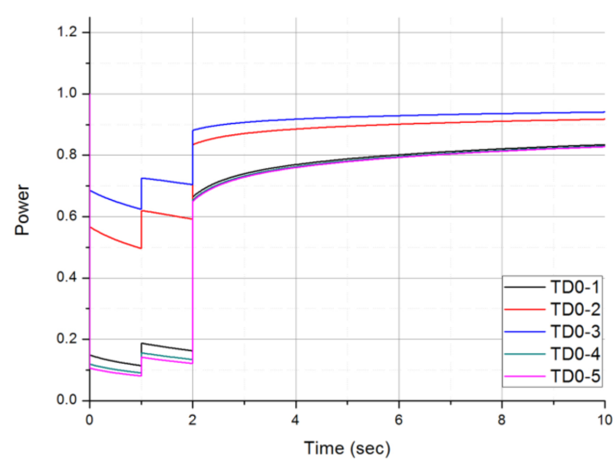

Fig. 3. nTRACER results for TD0 power behavior

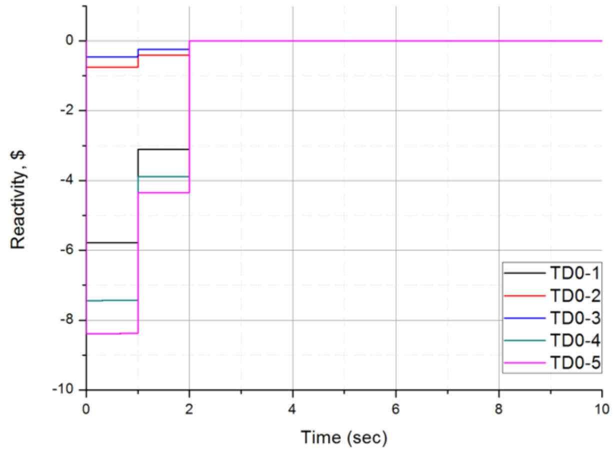

Fig. 4. nTRACER results for TD0 core reactivity change

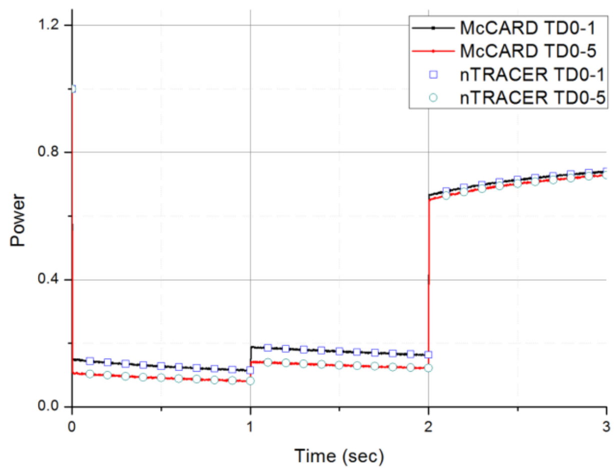

Fig. 5. TD0-1 and TD0-5 comparison between nTRACER and McCARD

2. TD1- Set with 5 sub-problems

The TD1 problems consist of control rod insertion and withdrawal cases with a ramp change in absorption XS reaching the maximum 1% change in control rod strength as shown in Fig. 6. [1]. TD1 set has also five sub-problems described below:

- TD1-1 : insertion/withdrawal of Bank 1
- TD1-2 : insertion/withdrawal of Bank 3
- TD1-3 : insertion/withdrawal of Bank 4
- TD1-4 : insertion/withdrawal of Banks 1, 3, and 4
- TD1-5 : insertion/withdrawal of Banks 1-4

For TD1-1 through TD1-3, there are solutions generated by the SUHAM-TD code [7]. However, those results cannot be compared with current nTRACER results since those results are generated with the old kinetic parameters. Therefore, additional nTRACER calculations were performed to compare the results of the two codes. The comparison reveals excellent agreement as shown in Fig. 7. Figs. 8 and 9 are for the cases with the new kinetic parameters. Fig. 10 shows TD1-1 comparison results with the McCARD code upto 3 seconds which reveals good agreement.

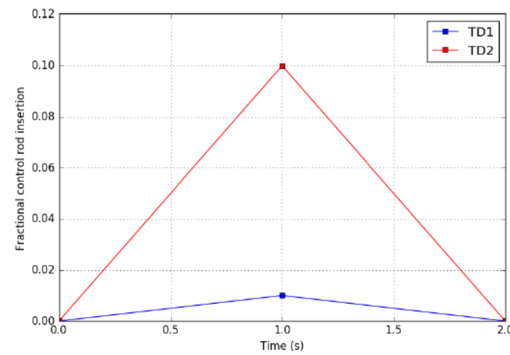

Fig. 6. Control rod movement in TD1 [1]

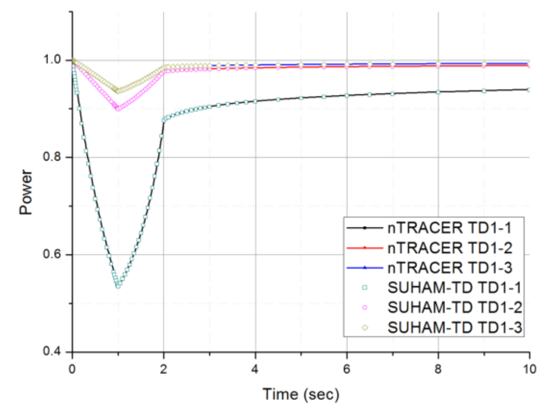

Fig. 7. TD1-1 through TD1-3 comparison between nTRACER and SUHAM-TD using old kinetic parameters

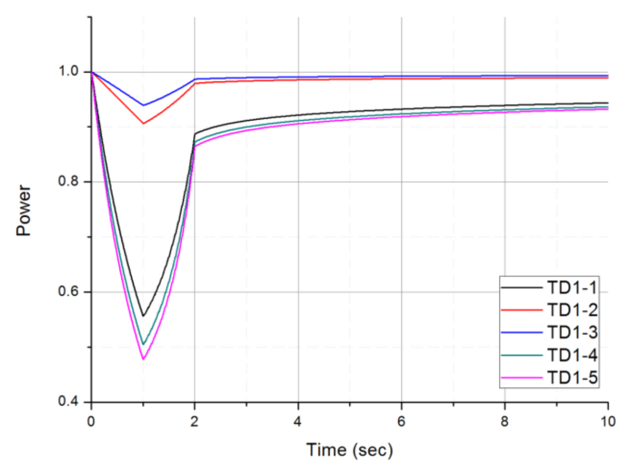

Fig. 8. nTRACER results for TD1 power behavior

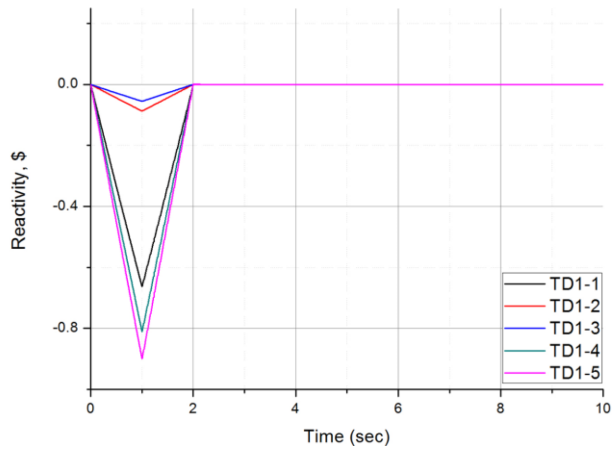

Fig. 9. nTRACER results for TD1 reactivity change

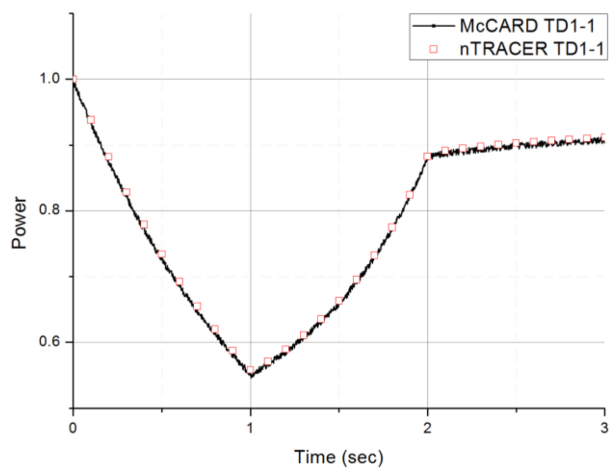

Fig. 10. TD1-1 comparison between nTRACER and McCARD

3. TD2- Set with 3 sub-problems

The TD2 problems are very similar to the TD1 except the maximum control rod strength of 10% as shown in Fig. 6 [1]. The TD2 consists of three sub-problems shown below:

- TD2-1 : insertion/withdrawal of Bank 1
- TD2-2 : insertion/withdrawal of Bank 3
- TD2-3 : insertion/withdrawal of Bank 4

Figs. 11 and 12 show the nTRACER results and Fig 13 shows the TD2-1 comparison with McCARD upto 3 seconds. The two solutions again agree very well.

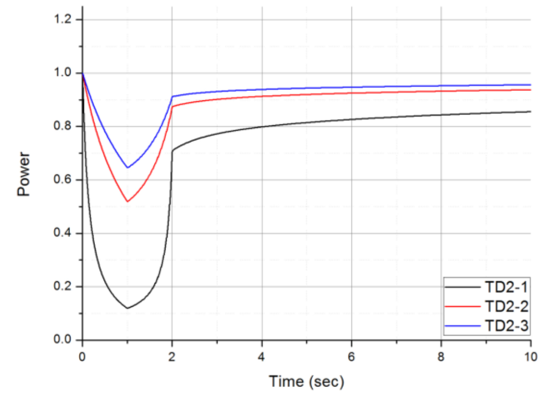

Fig. 11. nTRACER results for TD2 power behavior

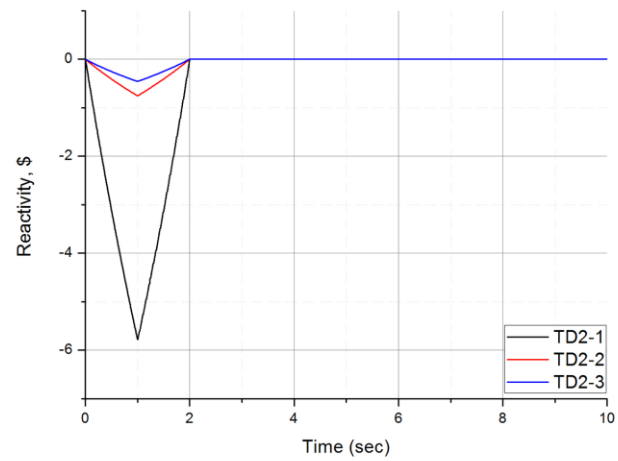

Fig. 12. nTRACER results for TD2 reactivity change

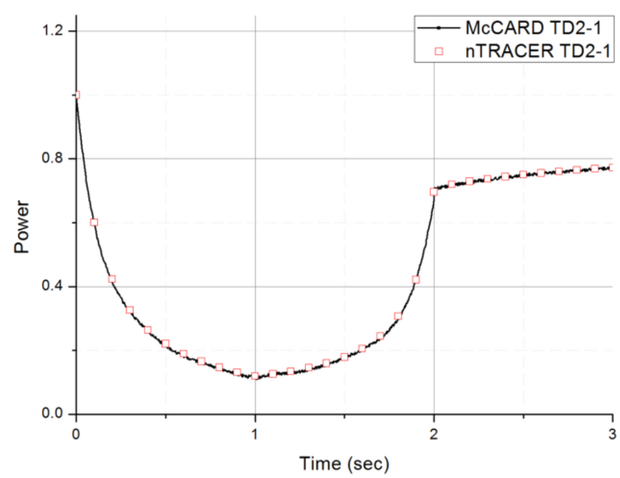

Fig 13. TD2-1 comparison between nTRACER and McCARD

4. TD3- Set with 4 sub-problems

In the TD3 problems, overall core-wise moderator density should be changed as shown in Fig. 14 [1]. There are four sub-problems with their own weighting factors. Figs. 15 and 16 show the nTRACER results and for the TD3 problems, McCARD results could be compared for all the sub-problems upto 3 seconds. As shown in Fig. 17, excellent agreements between the two codes are observed.

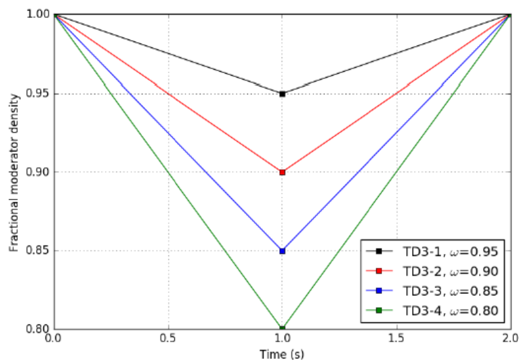

Fig. 14. Cove average moderator density changes in TD3 exercise [1]

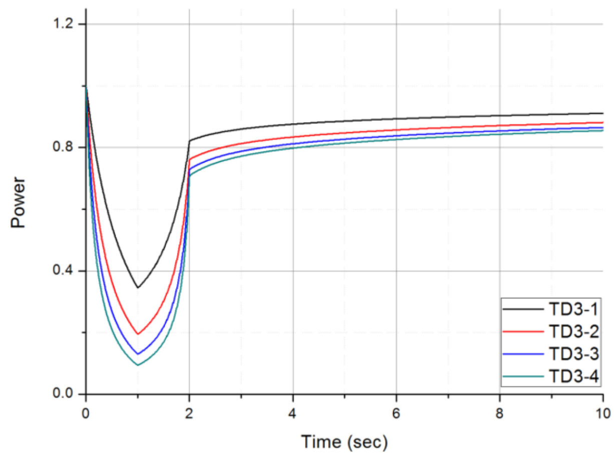

Fig. 15. nTRACER results for TD3 power behavior

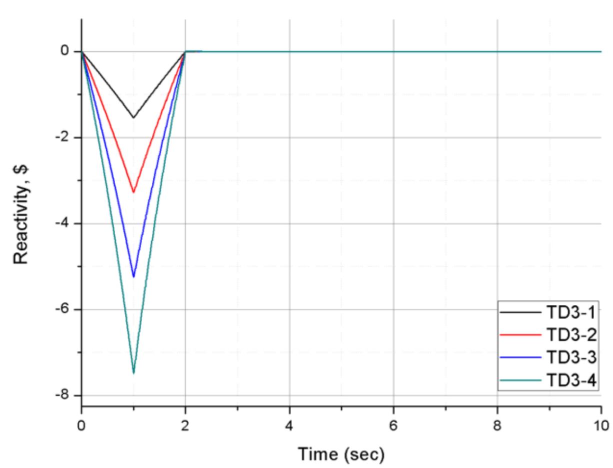

Fig. 16. nTRACER results for TD3 reactivity change

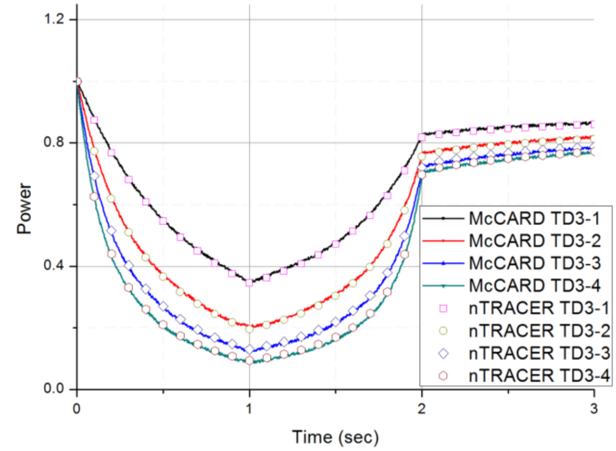

Fig 17. TD3 comparison between nTRACER and McCARD

IV. ANALYSES OF 3-D PROBLEMS

The 3-D problem involves control rod movements which induce partial insertion of a control rod in a thick axial plane. Thus a proper treatment of the axially homogenized XS should be implemented to avoid the control rod cusping effect. In the following the AFW [11] based decusping method of nTRACER is described and the solutions are assessed by comparing the decusped solutions with the reference solutions generated with very fine axial meshes (Model 1).

1. TD4- Set with 5 sub-problems

In the TD4 problems, there are five control rod insertion and withdrawal cases as follows:

- TD4-1 : Bank 1 insertion/withdrawal
- TD4-2 : Bank 3 insertion/withdrawal
- TD4-3 : Bank 1 and 3 insertions/withdrawals
- TD4-4 : Bank 3 and 4 insertions/withdrawals
- TD4-5 : Bank 1 and 3 insertions/withdrawals

In each sub-problem, one or two control rod banks move simultaneously with a constant speed as shown in Fig. 18 [1]. Fig. 19 and 20 shows nTRACER results with 120 fuel planes which were employed to avoid the control rod cusping effect.

Since such a fine axial geometry model is not suitable for the actual large PWR cores and requires tremendous computational resources, a proper control rod de-cusping treatment should be implemented. In nTRACER, a unique treatment was established [14]. However, this treatment requires pre-calculation and tabulated parameters. To avoid such pre-calculations, the AFW [11] method and Neighboring Spectral Index [15] method which was originally from the Inverse of Spectral Index (ISI) [16] method were applied for the TD4 analysis.

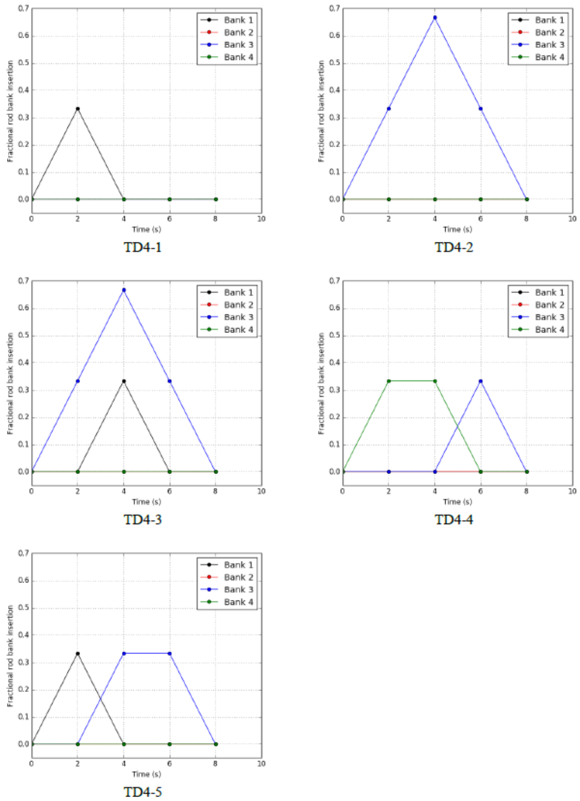

Fig. 18. Relative position of control banks in TD4 [1]

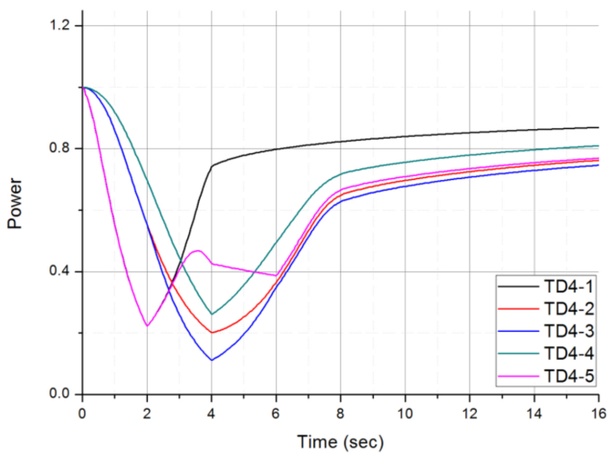

Fig. 19. nTRACER results for TD4 power behavior

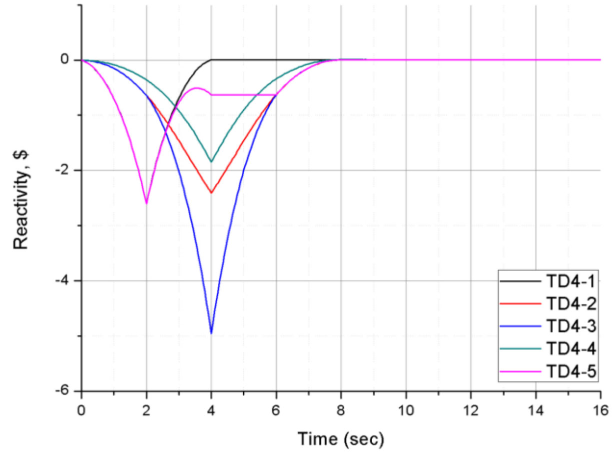

Fig. 20. nTRACER results for TD4 reactivity change

With simple C5G7 3x3 pin cell transient test, the AFW method shows slightly better performance than the NSI method , thus the AFW method was chosen to mitigate cusping effects. Fig. 21 shows a partially rodded node (PRN) at certain FSR.

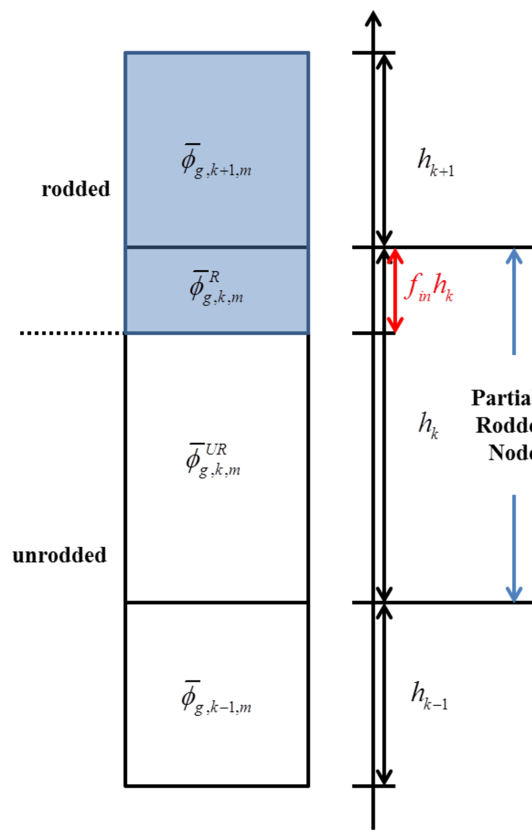

Fig. 21. Axial plane for partially rodded node

To apply the AFW method in nTRACER, nodal mesh-wise spatial resolution should be applied to each FSR wise meshes as follows:

$$\bar{\phi}^{R}_{g,k,m} = \frac{f_{in} h_k \bar{\phi}_{g,k,m} + h_{k+1} \bar{\phi}_{g,k+1,m}}{f_{in} h_k + h_{k+1}} \quad (2)$$

$$\bar{\phi}^{UR}_{g,k,m} = \frac{(1-f_{in}) h_k \bar{\phi}_{g,k,m} + h_{k-1} \bar{\phi}_{g,k-1,m}}{(1-f_{in}) h_k + h_{k-1}} \quad (3)$$

where

$\bar{\phi}^{UR}_{g,k,m}$ = unrodded region average flux at k plane,

$\bar{\phi}^{R}_{g,k,m}$ = rodded region average flux in k plane,

$\bar{\phi}_{g,k-1,m}$, $\bar{\phi}_{g,k,m}$, $\bar{\phi}_{g,k+1,m}$ = node average flux,

h_{k-1}, h_k, h_{k+1} = node height,

f_{in} = fraction of rodded region in k plane.

Then the homogenized XS for FSR in a PRN is obtained as follows:

$$\bar{\Sigma}_{g,k,m} = \frac{\Sigma^{R}_{g,k,m} f_{in} \bar{\phi}^{R}_{g,k,m} + \Sigma^{UR}_{g,k,m} (1-f_{in}) \bar{\phi}^{UR}_{g,k,m}}{f_{in} \bar{\phi}^{R}_{g,k,m} + (1-f_{in}) \bar{\phi}^{UR}_{g,k,m}} . \quad (4)$$

To examine the effectiveness of the AFW method, the TD4-1 and the TD4-5 were selected and the two coarse axial models were examined. Fig. 22 shows the TD4-1 results obtained with the mere volume weighting (VW) and with the AFW method upto 2 seconds. Fig. 23 show the TD4-5 results from 2 to 4 seconds. Figs. 24 and 25 show the relative power errors of TD4-1 and TD4-5 upto 16 seconds. As shown in these figures, the AFW treatment removes the cusping effect drastically. However, about 1% error is noted for the asymptotic power level and this would be due to the difference in the transport solution accuracy between the thin and coarse plane models.

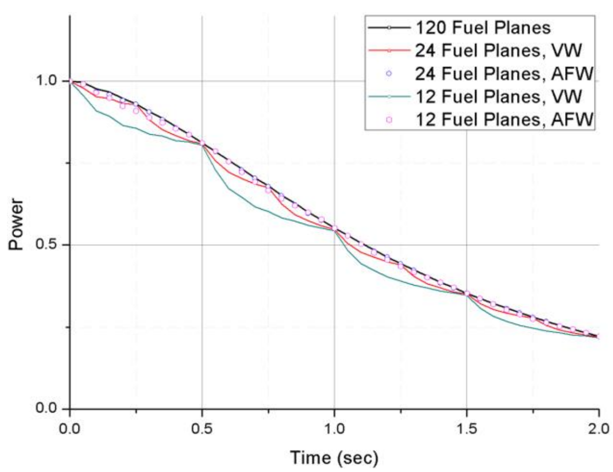

Fig. 22. TD4-1 power behavior results upto 4 seconds with VW and AFW

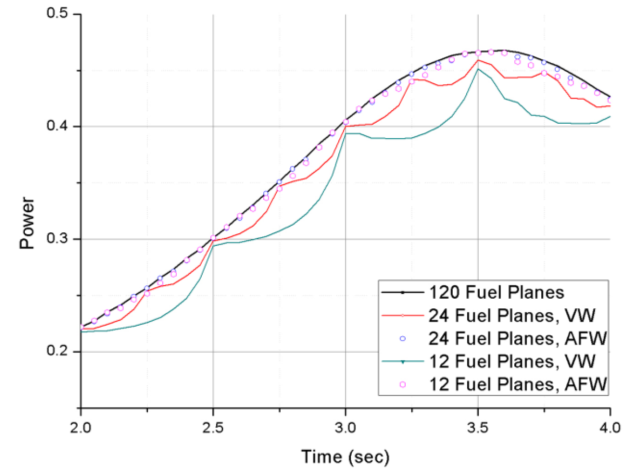

Fig. 23. TD4-5 power behavior results from 2 seconds to 4 seconds with VW and AFW

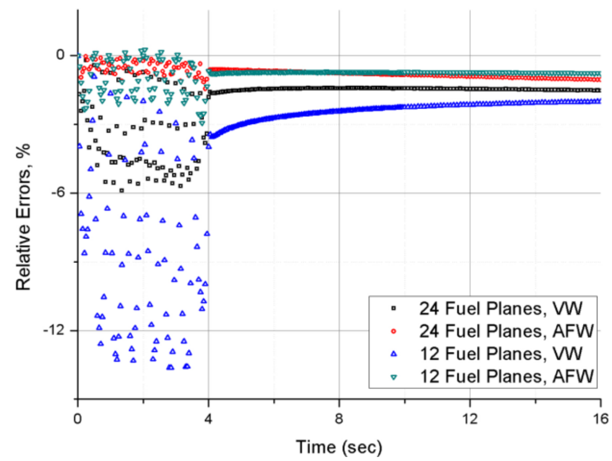

Fig. 24. TD4-1 relative errors in power behavior with VW and AFW

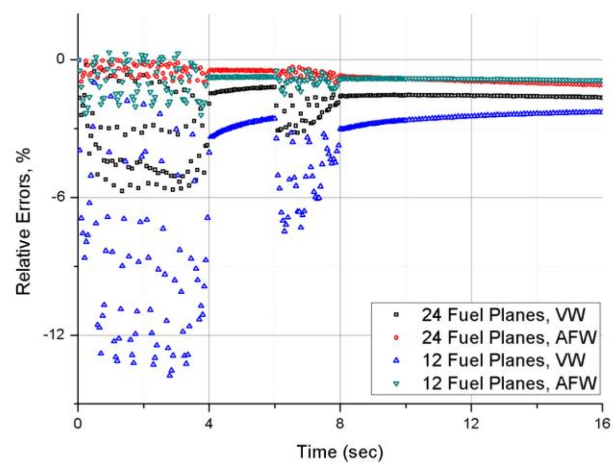

Fig. 25. TD4-5 relative errors in power behavior with VW and AFW

2. TD5- Set with 4 sub-problems

The TD5 problem set consists the following four series of moderator density changes:

- TD5-1 : Assembly No 1 and 3
- TD5-2 : Assembly No 1, 2 and 3
- TD5-3 : Assembly No 1, 3, and 4
- TD5-4 : Assembly No 2, 3, and 4

Fig. 26 [1] shows relative moderator density changes in the TD5 exercise. Figs. 27 and 28 show power and reactivity results of nTRACER.

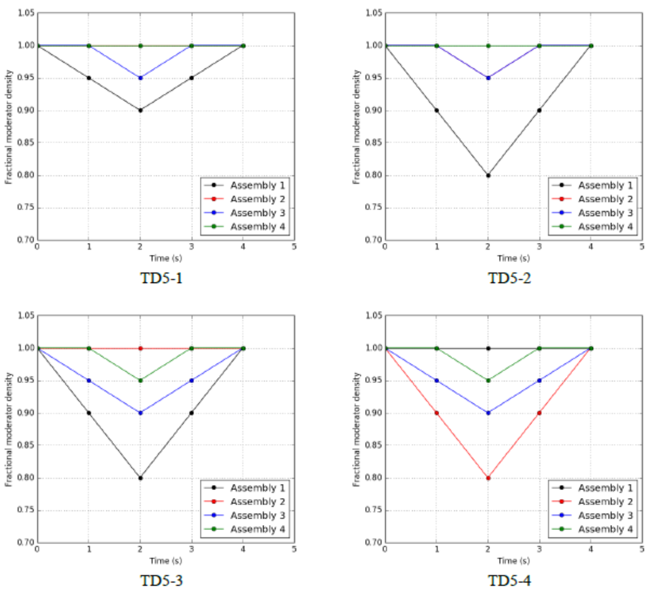

Fig. 26. Relative moderator density in TD5 exercise [1]

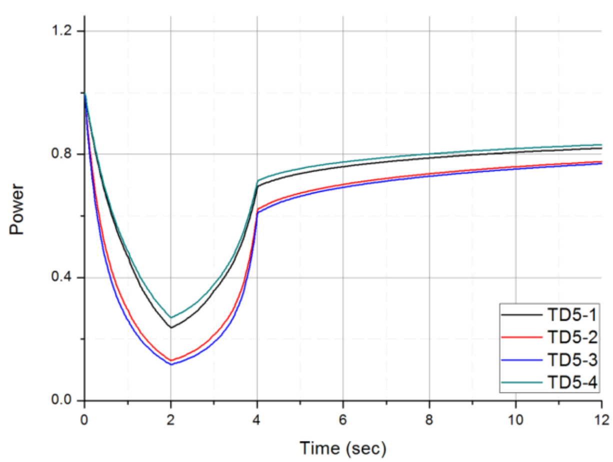

Fig. 27. nTRACER results for TD5 power behavior

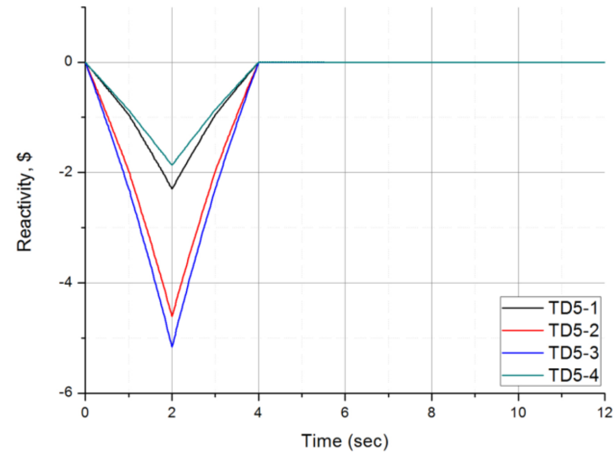

Fig. 28. nTRACER results for TD5 reactivity change

V. CONCLUSION

All the problems of the C5G7-TD benchmark were analyzed by the nTRACER direct whole core calculation code employing faithful models. The results of nTRACER agree very with those of SUHAM-TD in the cases of TD1-1 through 1-3 and also with those of the McCARD Monte Carlo transient simulations in the cases of selected 2-D problems. These comparison results demonstrate the soundness of the nTRACER direct whole core transient transport solutions. For the 3-D problem, a proper decusping method is essential and it was demonstrated that the approximate flux weighting method works very well even for the applications to the subpin level heterogeneous cases.

ACKNOWLEDGMENTS

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REFERENCES

1. V. F. BOYARINOV, P. A. FOMICHENKO, J. HOU and K. IVANOV, "Deterministic Time-Dependent Neutron Transport Benchmark without Spatial Homogenization," NEA/NSC/DC (2016).
2. E. E. LEWIS, M. A. SMITH, N. TSOULFANIDIS, G. PALMIOTTI, T. A. TAIWO and R. N. BLOMQUIST, "Benchmark Specification for Deterministic 2-D/3-D MOX fuel assembly Transport Calculations without Spatial Homogenization (C5G7MOX),: NEA/NSC/DOC (2001).

3. J. Y. CHO, K. S. Kim, C. C. LEE, H. G. JOO, W. S. YANG, T. A. TAIWO and J. THOMAS, "Transient Capability for a MOC-Based Whole Core Transport Code DeCART," *Trans. Am. Nucl. Soc.*, Vol. **92**, 721 (2005).
4. Y. S. JUNG, C. B. SHIM, C. H. LIM and H. G. JOO, "Practical Numerical Reactor Employing Direct Whole Core Neutron Transport and Subchannel thermal/hydraulic solvers," *Ann. Nuc. Energy*, Vol. **62**, 357 (2013).
5. M. J. LEE, Y. S. JUNG and H. G. JOO, "Assembly Based Modular Ray Tracing for Rectangular and Hexagonal Lattices," *Trans. Korean Nuclear Society Autumn Meeting*, Pyeong Chang, Korea, Oct. 25-16 (2007).
6. Y. S. JUNG and H. G. JOO, "Investigation of Conditional Transport Update in Method of Characteristics Based Coarse Mesh Finite Difference Transient Calculation," *Proc. PHYSOR2014*, Kyoto, Sep. 28 – Oct. 03, American Nuclear Society (2014) (CD-ROM).
7. V. F. BOYARINOV, A. E. KONDRUSHIN and P. A. FOMICHENKO, "Benchmark on Deterministic Time-Dependent Transport Calculation without Spatial Homogenization," *Proc. PHYSOR201*4, Kyoto, Japan, Sep. 28 – Oct. 03, 2014, American Nuclear Society (2014) (CD-ROM).
8. H. J SHIM, B. S. HAN, J. S. JUNG, H. J. PARK and C. H. KIM, "McCARD: Monte Carlo Code for Advanced Reactor Design and Analysis," *Nucl. Eng. Technol.*, Vol **44**(2), 161 (2012).
9. N. SHAUKAT, M. RYU and H. J. SHIM, "Dynamic Monte Carlo Transient Analysis for the OECD/NEA C5G7-TD Benchmark," *Nucl. Eng. Technol.*, Submitted, Manuscript number: NETJOURNAL_2017_57.
10. H. S. JOO, "Resolution of the Control Rod Cusping Problem for Nodal Methods," Ph.D. thesis, Massachusetts Institute of Technology (1984).
11. J. C. GEHIN, "A Quasi Static Polynomial Nodal Method for Nuclear Reactor Analysis," Ph.D. thesis, Massachusetts Institute of Technology (1992).
12. H. G. JOO, D. BARBER, G. JIANG and T. DOWNAR, "PARCS: A Multi-Dimensional Two-Group Reactor Kinetics Code Based on the Nonlinear Analytic Nodal Method," PUNE-98-26, Purdue University (1998).
13. C. B. SHIM, et al., "Application of Backward Differentiation Formula to Spatial Reactor Kinetics Calculation with Adaptive Time Step Control," *Nuclear Engineering and Technology*, Vol. **43**, 531 (2011).
14. Y. S. JUNG, Y. S. BAN and H. G. JOO, "Control Rod Decusping Treatment based on Local 3-D CMFD Calculation for Direct Whole Core Transport Solvers," *Proc. ICAPP 2014*, Charlotte, NC, USA, Apr. 6-9,2014, American Nuclear Society (2014) (CD-ROM).
15. B. CHO and N. Z. CHO, "A Nonoverlapping Local/Global Iterative Method with 2-D/1-D Fusion Transport Kernel and p-CMFD Wrapper for Transient Reactor Analysis," *Ann. Nucl. Energy*, Vol. **85**, 937 (2015)
16. A. YAMAMOTO, "A Simple and Efficient Control Rod Cusping Model for Three-Dimensional Pin-by-Pin Core Calculations," *Nucl. Technol.*, Vol. **145**, 11 (2004).