Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Modelling and Preliminary Analysis of the SPERT III E-core with nTRACER

Junsu Kang, Seungug Jae and Han Gyu Joo*
Department of Nuclear Engineering, Seoul National University, 1 Gwanak-gu, Seoul, Korea 08826
**Corresponding author: joohan@snu.ac.kr*

1. Introduction

nTRACER, which is developed by Seoul National University (SNU), is direct whole core calculation code with 2D/1D approach [1]. nTRACER has been validated by analyzing commercial PWRs like OPR1000, AP1000 and APR1400 and realistic benchmark problems such as BEAVRS and VERA. However, validation for core with complex structures and highly heterogeneous geometry was not sufficient. Also nTRACER is capable of transient calculation, but it has not been verified thoroughly.

The Special Power Excursion Reactor Test (SPERT), which was conducted by Phillips Petroleum Company, is a series of experiments to obtain data for the reactivity accident [2]. Among various core configurations of this program, the SPERT III E-core resembles commercial pressurized-water reactor (PWR) in terms of fuel assembly structure and thermal hydraulics properties. Several power excursion tests were performed with the SPERT III E-core and the experimental data has been used as the benchmarks for the validation of reactor dynamic calculation systems.

Though there have been many attempts to analyze SPERT III E-core, most of the attempts are based on two-step methods with spatial homogenization [3]. These attempts succeed to generate well matched transient solutions but showed their limitations of accuracy in steady-state calculations [4]. Complex structures of the SPERT III E-core such as fuel can and cruciform transient rod at the center of the core could cause discrepancy from experimental data when dealt by homogenization. In recent years, full core modelling with high resolution becomes mainstream and SPERT III E-core models with explicit treatment of complex structures are proposed and show better accuracy in steady-state calculations [4, 5].

The goals of this work are to validate the simulation capability of nTRACER for complex geometry and to establish base of further assessment of dynamics features of nTRACER. The modelling procedure of SPERT III E-core, which treats complex geometry explicitly, and solutions with nTRACER are presented in this paper. Both model and solutions were validated by comparisons with experimental data.

2. nTRACER Model of the SPERT III E-core

The SPERT III E-core consisted of 60 fuel assemblies which are moderated with pressurized-water. The radial cross section of the E-core is shown in Fig. 1. 48 out of 60 assemblies are 5×5 rectangular array and the remaining 12 assemblies are 4×4 rectangular array. 4 of 4×4 assemblies surround the cruciform transient rod located at the center and remaining 4×4 assemblies are fuel follower of control rod assemblies (CA) which are shaded parts in Fig. 1. The values of core parameters are listed in Table 1.

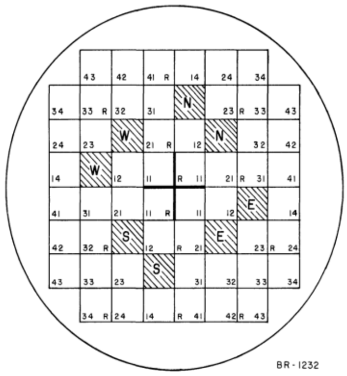

Fig. 1. Radial configuration of SPERT III E-core [6]

Table I: SPERT III E-core Parameters

Parameter	*Value*
Fuel	4.8 wt% UO_2
Fuel density	10.5 g/cm
Fuel pellet radius	0.5334 cm
Clad inner radius	0.5410 cm
Clad outer radius	0.5918 cm
Pin pitch	1.4859 cm
Core active height	97.282 cm

nTRACER is designed to use a uniform number of square unit cells, which usually represents one fuel pin, for all assemblies in the core. To modelling 3 types of fuel assembly in E-core that have different number of pins and dimensions, the unit cell was used as a quarter pin and 10×10 array of cell was set as an assembly. Also there was additional thinner layer of unit cell for each assembly to model complex structures such as fuel cans.

2.1 5×5 Fuel Assembly

The 5×5 Fuel assembly is contained in fuel can composed of type 348 stainless steel (SS348). It has overall dimension of 7.5565×7.5565 cm with thickness of 0.635 cm and contains water holes. Because explicit modelling of water hole is not possible with nTRACER, fuel can was modelled as a mixture of SS347 and water with 75% and 25% volume ratio. The volume ratio was computed from the total area of water holes 774.2 cm^2. The nTRACER model of 5×5 Fuel assembly is shown in Fig. 2. Fuel pins were modelled as 10×10 array of quarter pins and fuel can was modelled in additional cell layer.

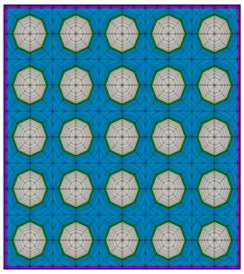

Fig. 2. nTRACER model for 5x5 fuel assembly

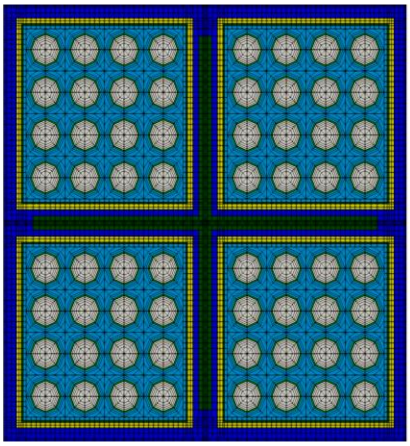

Fig. 3. nTRACER model for center region of the E-core

2.2 4×4 Fuel Assembly and Transient Rod

In the 4×4 fuel assembly, 16 fuel pins are surrounded by stainless wall. The overall dimension is 6.2890×6.2890 cm. The thickness of the wall, 0.635 cm, was computed from 20 cm^2 of flow area [2]. There is also guide tube made of Zircaloy-2 that protects fuel assemblies from transient rod [2]. However detailed information of guide tube is not known. In nTRACER model, the thickness of guide tube is assumed as 0.198976 cm to guarantee the space for bushing pad whose thickness is 0.2286 cm.

The cruciform transient rod has thickness of 0.47625 cm and its overall width is 6.50875 cm. It is divided into upper section made of 18-8 stainless and lower poison section made of 1.35 wt% borated stainless steel. The nTRACER model for center region is shown in Fig. 3. Fuel pins were modelled in 8×8 array of unit cells at the center of assembly and the transient rod was modelled by rectangular sub-cells in peripheral cells and additional cell layer.

2.3 Control Rod Assembly

The control rod assembly is composed of an upper section of poison and a lower section of a fuel follower. The square shaped 18-8 stainless steel with 1.35 wt% boron is used as the poison. The outer dimension of poison box is reported as 6.3398 cm [2], but it includes 0.0254 cm for rubbing pad. Therefore explicit outer dimension for poison box is 6.2890 cm. The thickness of poison box is 0.47244 cm. The fuel follower consist of 4×4 fuel pins surrounded by stainless wall. The thickness of the wall, 0.1727 cm, was computed from 18 cm^2 of flow area [2]. The control rod assemblies are surrounded by guide tube made of Zircaloy-2.

In the intermediate region between poison section and fuel section, compression springs for fuel rods exist and also another poison called flux suppressor exists. The height of this intermediate region is known as 11.938 cm. The flux suppressor is composed of 1.35 wt% borated stainless steel plates. In nTRACER, flux suppressor was modelled with the outermost rings in the unit cell and the spring was modelled as stainless steel smeared in water in cylindrical region. Fig. 4 shows radial cut of nTRACER model for three sections of control rod assembly.

2.4 Auxiliary Structures and Whole Core Model

The cylindrical core skirt is occupied by filler pieces. It has the thickness of 0.3175 cm. Whole area outside the core skirt was modeled as stainless steel type 304. Fig. 5 shows the whole core model of nTRACER.

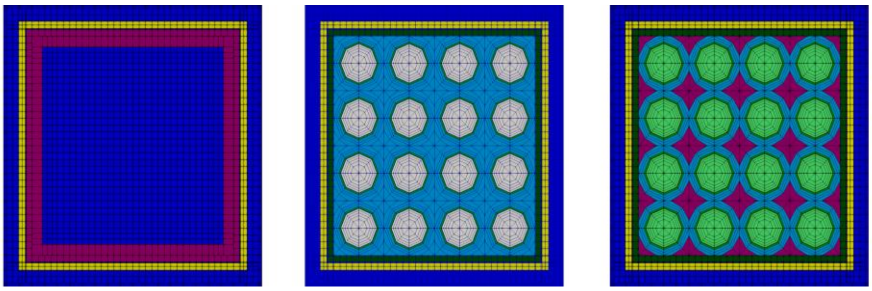

Fig. 4. nTRACER model for poison section (left), fuel section (middle), and intermediate section (right) of control rod assembly

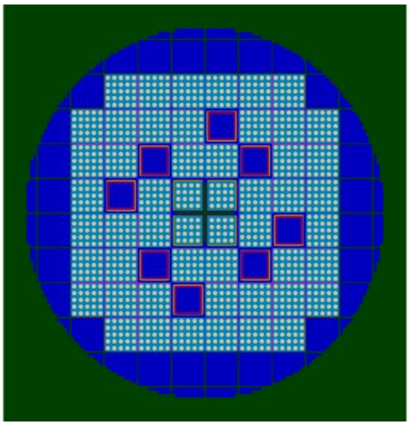

Fig. 5. nTRACER whole core model

3. Calculation Results

The 47 group nTRACER library generated from ENDF/B-VII.1 data was used for SPERT III E-core analysis. The method of characteristics calculation in nTRACER was carried out with 0.05 cm ray spacing, 16 azimuthal angles and 4 polar angles in the octant of the solid angle sphere, and P2 scattering source. All calculations were performed in GPU cluster in SNU equipped with commercial GPUs (NVIDIA GeForce RTX 2080 Ti). The core was discretized into 20 axial planes and 20 GPUs were used for the calculations reported in here. The computing time for steady-state calculation was approximately 7 minutes.

2.1 Cold Zero Power Condition Results

Table II: Nuclear properties at Cold Zero Power

Nuclear properties	*nTRACER*	*experimental*
k_{eff} at critical CA position	0.99870	1.00000
Calculated critical CA position	37.25 cm	36.96 cm
Effective delayed neutron fraction, β_{eff}	744 pcm	N/A
Prompt neutron generation time, Λ	17.3 μs	N/A
Reduced prompt neutron generation time, Λ / β_{eff}	2.32 ms	2.15 ms
Total excess reactivity	13.4 $	14.2 $
Differential CA worth near critical	0.69 $/cm	0.61 $/cm

The nuclear properties of the E-core at 21.11 °C and 1 atmosphere pressure were measured and reported [8, 9]. Reported properties were computed with nTRACER and compared with experimental data as shown in Table II. There was good agreement for eigenvalue and CA position. The difference of eigenvalue at critical CA position was less than 130 pcm. The reduced prompt neutron generation time shows the relative error of 7.9 %. The total excess reactivity was initially reported as 14.2 $ [7], but the control rod worth measurement is refined [8]. The comparison of the refined experimental rod worth to nTRACER rod worth are shown in Fig. 6 and great agreement was observed.

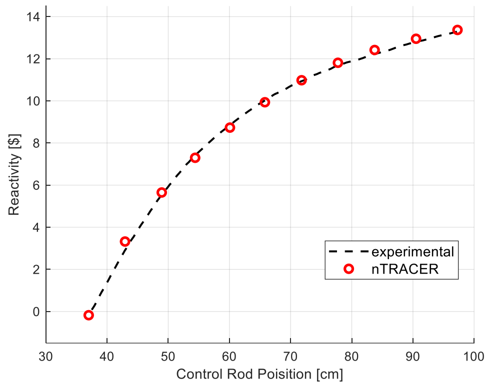

Fig. 6. Control rod reactivity worth curve at Cold Zero Power

2.2 Hot Zero Power Condition Results

Table III: Nuclear properties at Hot Zero Power

Nuclear properties	*nTRACER*	*experimental*
k_{eff} at critical CA position	1.00118	1.00000
Calculated critical CA position	70.79 cm	71.76 cm
Effective delayed neutron fraction, β_{eff}	740 pcm	N/A
Prompt neutron generation time, Λ	17.2 μs	N/A
Total excess reactivity	3.3 $	2.5 $
Differential CA worth near critical	0.16 $/cm	0.16 $/cm

The nuclear properties at 287.78 °C and 1740 psig were measured and reported [7]. Both reported experimental data and the properties calculated with nTRACER are listed in Table III. Agreement between nTRACER and experiment was good for both eigenvalue and CA position. The eigenvalue error at critical CA position was less than 118 pcm. The difference between nTRACER and experimental data for total excess reactivity was 0.8 $, but the uncertainty of measurement was not provided. The total excess reactivity was also computed with Tripoli-4® [5] and the calculated value was 3.1 $ which shows reasonable agreement with nTRACER.

2.3 Transient Rod Worth Results

The worth of transient rod was measured at both CZP (21.11 °C) and HZP condition (260.00 °C). For normalized reactivity, β_{eff} = 744 pcm was used for CZP and β_{eff} = 739 pcm was used for HZP condition. Reasonable agreement was observed for both condition as shown in Fig. 7.

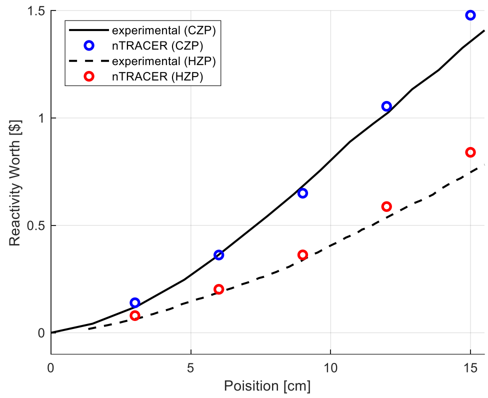

Fig. 7. Transient rod reactivity worth curves

2.4 Preliminary Transient Calculation Results

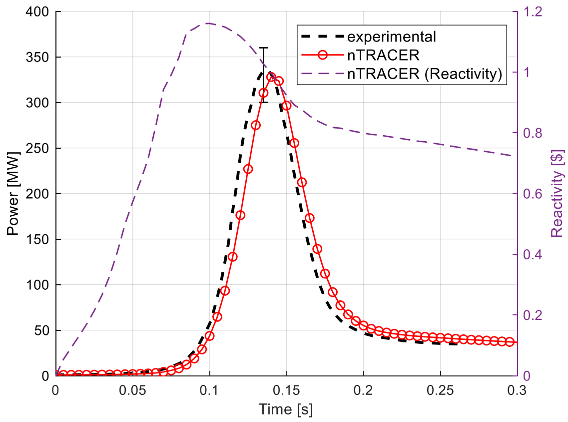

Fig. 8. Test81 power behavior

Power excursion tests with various inserted reactivity and initial conditions had been performed in SPERT III E-core. As a preliminary calculation, test81 was simulated with nTRACER. The test81 is power excursion test at hot-standby condition with 0.9 ± 0.1 MW and initial inlet temperature of 261.7 ± 0.1 °C. The inserted reactivity is 1.17 ± 0.04 $ [2]. The specific heat and thermal conductivity of fuel were computed based on the model used in FRAPCON-4.0 [9] and 2.6% of the energy was assumed to be transferred directly from a conductor to moderator. The transient rod was ejected with acceleration of 50.8 m/s^2 in calculation. The time step size was 5 ms and the solution is corrected with PKE solution with 0.01 ms time-steps based on quasi-static method. The computing time to simulate from 0.0 s to 0.3 s was about 3 hours.

Good agreement was observed for core power behavior as shown in Fig. 8. The calculated peak power was 327.9 MW at 0.140 s and experimental peak power was 330 ± 30 MW at 0.135 ± 0.002 s.

5. Conclusions

The nTRACER model of SPERT III E-core was generated successfully. The complex core structures including cruciform transient rod, guide tubes, and stainless fillers were explicitly modelled. The nTRACER model is validated through the comparisons with the experimental results. The results calculated with nTRACER showed good agreement with the experimental results at both cold zero power and hot zero power conditions. The reactivity discrepancies at critical CA position were within 131 pcm. Good agreement was also observed in transient calculation results. nTRACER yielded core power behavior similar to experimental data in test81 calculation. The peak power difference was smaller than the measurement uncertainty and the peak time difference was 0.005 s. The model generated here could be the base for further transient analysis of the SPERT III E-core and assessment of the dynamics calculation capabilities of nTRACER.

ACKNOWLEDGEMENTS

This research is supported by National Research Foundation of Korea Grant No. 2018M2A8A1091081 (Improvement of nTRACER for Advanced Reactor Applications)

REFERENCES

[1] 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. Nucl. Energy*, 2013.

[2] J. Dugone, “SPERT III reactor facility: E-core revision,” Phillips Petroleum Co., Idaho Falls, Idaho. Atomic Energy Div., 1965.

[3] T. Fujita and T. Sakai, “Analysis of the SPERT-III E-Core experiment using CASMO5/TRACE/PARCS based on JENDL-4.0 and ENDF/B-VII. 1,” *J. Nucl. Sci. Technol.*, vol. 56, no. 6, pp. 553–571, 2019.

[4] L. Cao, A. Gerlach, Y. Xu, T. Downar, and J. C. Lee, “Neutronics modeling of the SPERT III E-Core critical experiments with MPACT and KENO,” *Ann. Nucl. Energy*, vol. 80, pp. 207–218, 2015.

[5] A. Zoia and E. Brun, “Reactor physics analysis of the SPERT III E-core with Tripoli-4®,” *Ann. Nucl. Energy*, vol. 90, pp. 71–82, 2016.

[6] R. K. McCardell, D. I. Herborn, and J. E. Houghtaling, “REACTIVITY ACCIDENT TEST RESULTS AND ANALYSES FOR THE SPERT III E-CORE: A SMALL, OXIDE-FUELED, PRESSURIZED-WATER REACTOR.,” Phillips Petroleum Co., Idaho Falls, Idaho. Atomic Energy Div., 1969.

[7] R. M. Potenza, J. C. Haire, and W. E. Nyer, “Quarterly technical report SPERT project,” *IDO-17206*, 1966.

[8] T. G. Taxelius and R. M. Potenza, “Quarterly technical report SPERT project,” *IDO-17207*, 1967.

[9] W. G. Luscher and K. J. Geelhood, “Material property correlations: comparisons between FRAPCON-3.4, FRAPTRAN 1.4, and MATPRO,” Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2010.