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Analyses of the B&W-1810 and KRITZ-2 Critical Experiments with nTRACER

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1. Introduction

nTRACER [1] is a direct whole core transport calculation code being developed at Seoul National University (SNU). It has been used to analyze the OPR1000 [1], AP1000 [2] and APR1400 [3] pressurized water reactor cores and to solve the realistic core benchmark problems such as BEAVRS [4] and VERA [5]. In this way, the simulation capability of nTRACER for the commercial reactors has been validated consistently. However, validations for the experimental reactors with various geometries or properties had not been conducted sufficiently. For this reason, this work is aimed to verify the simulation capability of nTRACER by performing calculations for the critical experiment benchmarks. Two critical experiments, B&W-1810 [6] and KRITZ-2 [7] critical experiments, were analyzed in this work. The results from nTRACER were compared not only with the measurements but also with the results from McCARD [8] which is continuous energy Monte-Carlo code of SNU. In both experiments, k-eff and pin power distributions were compared.

2. Core Designs and Modeling Strategies

Since nTRACER has been developed focus on analyzing commercial PWR reactors, it is very hard to represent core model of experimental reactors. Therefore, to analyze target reactors, it is very significant to simplify the actual core structures to make into nTRACER model. In this section, core specifications of each experiment and appropriate modeling strategies are described.

2.1 B&W-1810 Critical Experiments

The B&W-1810 critical experiments consist of four different types of core and each core can be classified depending on the presence of 4.02 w/o enriched UO_2 fuel rods and UO_2-Gd_2O_3 fuel rods. All of these four cores have 4808 fuel rods and 153 water holes. Core1, the first basic core, have only 2.46 w/o enriched UO_2 fuel rods and does not have UO_2-Gd_2O_3 fuel rods. Core12, the second basic core, has same loading pattern with Core1 except that its central zone is occupied with 4.02 w/o enriched UO_2 fuel rods. Core5 and Core14 are variation of Core1 and Core12 respectively, containing UO_2-Gd_2O_3 fuel rods in a specific pattern.

Three kinds of fuel rods are used in this work. The first one is 2.46 w/o enriched fuel rod clad with aluminum, the second one is 4.02 w/o enriched fuel rod swaged in stainless steel tube without fuel-clad gap, and the last one is UO_2-Gd_2O_3 fuel rod with 4w/o burnable absorber so that its nominal enrichment is 1.944w/o. The boron concentrations were adjusted to meet the criticality when moderator level is 145.0 cm at 25 ℃.

Fig. 1 and Fig. 2 show the detailed radial description of McCARD modeling and nTRACER modeling respectively for the core 1. With the capability of McCARD to deal with the flexible geometry, McCARD model was made identical to the benchmark model given by reference, designed up to core tank radially and from the aluminum base plate to the fuel rod above the water level axially [6].

However, it is difficult to make exactly the same model with the actual core configuration with nTRACER because it uses a square cell as a basic component of geometry. Therefore, nTRACER model was made with several simplifications from the actual benchmark model. First, the core should be composed of assemblies of equal lengths. In this result, the moderator was designed more than the actual one and the flexible core tank was neglected. Second, the “egg-crate” grid was also impossible to design. Therefore, its model was reconstructed to preserve the volume. In addition, due to the calculation property of nTRACER solver, the solutions did not converge in the region where the number density is too low. Consequently, only parts of the fuel rods below the water level were designed.

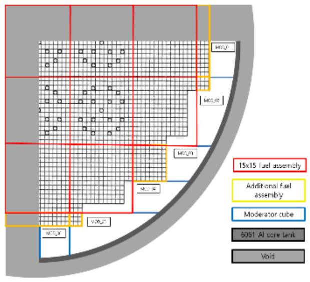

Fig. 1. Radial configuration of the McCARD model of the B&W-1810 experiments

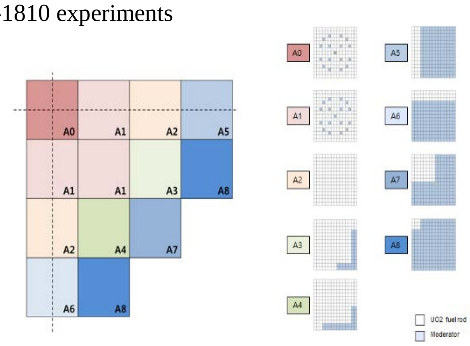

Fig. 2. Radial configuration of the nTRACER model of the B&W-1810 experiments

2.2 KRITZ-2 Critical Experiments

Three types of cores are analyzed in KRITZ-2 experiments at room temperature and elevated temperature up to 245℃. In KRITZ-2:1 core (denoted as Core1), 44x44 UO_2 fuel rods are loaded, and in KRITZ-2:13 core (denoted as Core13), 40x40 UO_2 fuel rods are loaded. UO_2 rods used in these two cores are identical. In KRITZ-2:19 core (denoted as Core19), 25x24 MOX fuel rods are loaded. In the KRITZ-2 reactor consisting of a cylindrical pressure tank with a height of 5m and a diameter of 1.5m, the insert vessel is placed which is composed of square inner part and cylindrical outer part. For convenience, let's call the inner part of the insert vessel "inner vessel" and the outer part of the insert vessel "outer vessel". The inner vessel contains fuel rods and is filled with moderator up to the level to meet criticality at given temperature. The region between the inner and outer vessel is filled with saturated vapor, and the thin annulus between outer vessel and the core tank is filled with moderator at the same level with that in the inner vessel. Below the bottom of the fuel, reflector extends to 40 cm, and the fuel rods are supported by cylindrical stainless steel beams. The KRITZ-2 reactor is asymmetric and has different moderator thicknesses Δ for each direction. Criticality in each experiment was obtained by adjusting boron concentration and water level at low power about 10W.

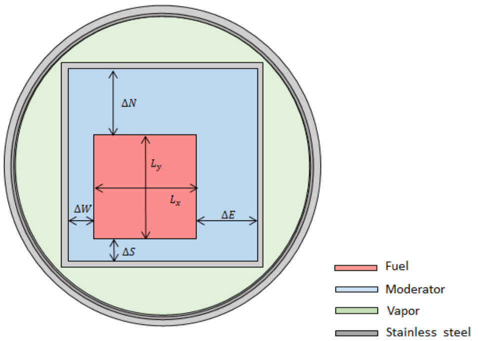

Fig. 3. Radial configuration of the McCARD model of the KRITZ-2 experiments

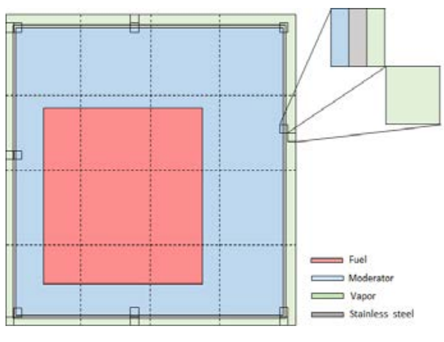

Fig. 4. Radial configuration of the nTRACER model of the KRITZ-2 experiments

Fig. 3 and Fig. 4 show the specific descriptions of McCARD modeling and nTRACER modeling respectively. The benchmark book gives the details of MCNP model as the benchmark model. The simplifications made in the benchmark model are following. Equipment such as neutron source, detectors and safety shutters in the region between inner and outer vessel was not modelled. In addition, structures above the top of the fuel rods were neglected. Spacer grids were also not modelled [7]. The McCARD model is identical to the benchmark model. It was designed up to the core tank radially and the top of the fuel rods axially.

Because of several properties of nTRACER geometry and solver mentioned in 2.1, several simplifications and assumptions were introduced to nTRACER model. First, because the basic component of geometry in nTRACER is a square cell, it is difficult to model the flexible structures. Therefore, cylindrical outer vessel and core tank were neglected. Second, vapor region above the water level and between the inner and outer vessel makes trouble in nodal and CMFD solver. For this reason, only the parts of the fuel rods below the water level are modelled axially and only a little part of the vapor region out of the inner vessel was modelled radially. Third, there are some cells filled with only vapor to complete the proper number of pins in each assembly. Moreover, some pins near the inner vessel boundaries contain both stainless steel inner vessel and vapor region because the thickness of the inner vessel(~0.35cm) is less than the pin pitch(~1.6cm). Details of this modeling is shown in Fig. 4. For this reason, the number density of vapor was manually increased to prevent the divergence.

3. Calculation Results

The McCARD calculations were performed with 400 inactive and 800 active cycles and 2,000,000 particles per cycle. The nTRACER calculations were performed with P2 scattering MOC with ray spacing of 0.05cm and 16/4 azimuthal/polar angles in the octant of the solid angle sphere. Libraries used in both McCARD and nTRACER were generated from ENDF/B-VII.0.

If comparing nTRCER result with reference directly, it is hard to figure out whether the errors were from simplification of modeling or the capability of nTRACER. Therefore, for all cores in both critical experiments, three calculation cases were prepared and compared if needed. The first one (case1) is running a McCARD model with McCARD, the second one (case2) is running an nTRACER model with McCARD, and the last one (case3) is running an nTRACER model with nTRACER. By comparing case1 and case2, errors due to the simplification of a model can be checked. By comparing case2 and case3, errors due to the performance of nTRACER can be checked. Because they are critical experiments, the error of k-eff is defined as the difference from 1.

3.1 Results of the B&W-1810 Critical Experiments

For the B&W-1810 experiments, mid-plane power distributions only through the center assembly were given from the benchmark book [6]. Table I shows the nTRACER calculation results. In all cores, nTRACER showed good agreements in both k-eff and power distribution. In all cores, the differences of k-eff are less than 70 pcm and all pins have pin power errors less than 1.2% compared with the experimental measurements.

Table I: Comparison results with the measurements in the B&W-1810 critical experiments

	Core1	Core5	Core12	Core14
k-eff	1.00004	0.99936	0.99992	0.99961
Δρ (pcm)	4	-64	-8	-39
Abs. Pin ΔP (%)	0.33	0.42	0.31	0.38
	0.80	1.00	0.66	0.92
Rel. Pin ΔP (%)	0.27	0.47	0.30	0.36
	0.64	1.13	0.63	0.80

For more verification, the pin power distributions for the full core of nTRACER were compared with those of McCARD. The results show good agreements with RMS values within 0.5% and the maximum errors less than about 1.6%.

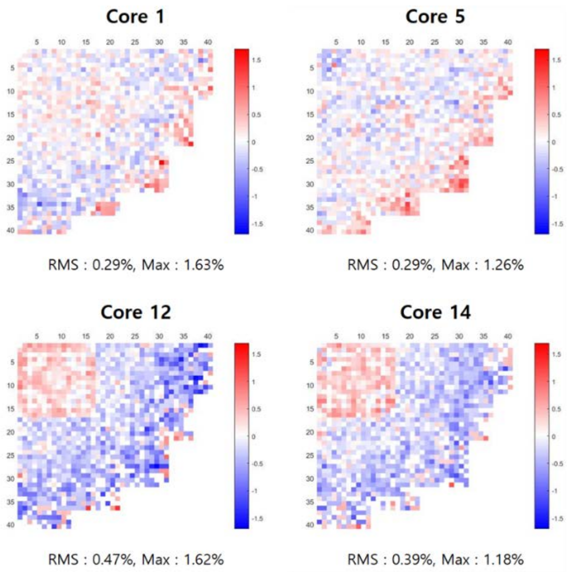

Fig. 5. Error distributions of the pin powers for the full core compared with McCARD in the B&W-1810 critical experiments

3.2 Results of the KRITZ-2 Critical Experiments

For the KRIT-2 experiments, only the pin powers in specific locations were measured. Table II shows differences of the calculated k-eff from criticality for all calculation cases. Table III shows the comparison results between each case. When comparing with the criticality, not only nTRACER results but also McCARD results with simplified model show extremely large underestimations of k-eff, especially in the Core1 with the differences larger than 1000 pcm. For figuring out the cause of these big errors more specifically, calculation cases were compared each other. Table III shows that the differences between case1 and case2 are much larger than those between case2 and case3 in all cores. In other words, the huge errors of nTRACER calculations were mainly from the simplification of modeling, negligence of the fuel rods extending to the vapor region rather than the capability of nTRACER. This tendency is more apparent as the portion of the fuel rods above the water level which cannot be modelled in nTRACER increases. For this reason, it is not appropriate to verify the performance of nTRACER by directly comparing with the measurements. It is more suitable way to compare the nTRACER and McCARD results with the same model. According to the Table III, the differences between these two results are all within about 230 pcm.

Table II: Difference of k-eff (pcm) from criticality in the KRITZ-2 critical experiments

Core Case		Case 1 (McCARD model, McCARD run)	Case 2 (nTRACER model, McCARD run)	Case 3 (nTRACER model, mTRACER run)
1	cold	-137	-1286	-1438
	hot	-338	-919	-1031
13	cold	93	-262	-274
	hot	-72	-458	-577
19	cold	446	-76	-16
	hot	84	-211	20

Table III: Difference of k-eff (pcm) between each calculation case in the KRITZ-2 critical experiments (ref. vs)

Core Case		Case 1 vs Case 2 (Error due to Modeling)	Case 2 vs Case 3 (McCARD vs nTRACER)
1	cold	-1149	-152
	hot	-581	-112
13	cold	-355	-12
	hot	-386	-119
19	cold	-522	60
	hot	-295	231

The pin power distributions were compared with the experimental measurements. In all cores, most pins have the relative errors less than 3.0% except the pins on the periphery or the location reported to have high uncertainty due to experimental defects. The pin power comparison between nTRCER and McCARD with the same model show better agreements. The results are shown in Table IV. RMS values and the maximum errors in the cores with UO_2 fuel are within about 0.4% and 1.5% respectively. In the core with MOX fuel, they are well within about 0.5% and 1.7% each.

Table IV: Power differences with McCARD results in the KRITZ-2 critical experiments

Case		Core 1		Core 13		Core 19	
		Cold	Hot	Cold	Hot	Cold	Hot
Abs Error (%)	RMS	0.12	0.32	0.18	0.32	0.40	0.46
	Max	0.41	0.75	0.54	0.77	0.78	1.01
Rel. Error (%)	RMS	0.16	0.38	0.24	0.40	0.47	0.51
	Max	0.72	1.37	1.06	1.52	1.56	1.67

CONCLUSIONS

To verify the simulation capability of nTRACER for the experimental reactors, B&W-1810 and KRITZ-2 critical experiments were analyzed. By comparing with not only experimental measurements but also with the results of Monte-Carlo code McCARD, the validity of nTRACER was confirmed in the situation where the direct comparison with measurements was not appropriate. Overall, in both experiments, nTRACER solutions showed good agreements.

In B&W-1810 critical experiments, out of 4 types of cores, the maximum difference of k-eff from criticality was 64 pcm. Especially, in core1 and 12 without UO_2-Gd_2O_3, the errors were within 10 pcm. The errors of pin powers were also significantly small. For the center assembly, all RMS values were within 0.5% and the maximum error was 1.13% in the Core 5. For the full cores as well, compared with the McCARD results, nTRACER showed good agreements with all RMS values within 0.5% and the maximum error less than 1.7%.

In KRITZ-2 critical experiments, k-eff values calculated from nTRACER were far lower than 1. By comparing calculation cases each other, it turned out that the modeling simplification such as negligence of the fuel rods above the water level led to the considerable errors in the nTRACER results. When run by McCARD, differences of k-eff of the models between with and without simplifications were from 295 pcm to about 1150 pcm. With the same simplified model, nTRACER results overall agree with McCARD results, with the errors within 231 pcm. The pin power errors were also reasonable. Compared with measured values detected at some specific locations, most pin power errors were less than 3.0%. In addition, compared with McCARD for the full cores, RMS and the maximum error are less than about 0.4% and 1.5% each for the cores with UO_2 fuel rods and 0.5% and 1.7% each for the core with MOX fuel rods.

Through this work, not only the capability of nTRACER was confirmed but also a new issue was raised as well which had not made any trouble in calculation for the commercial reactors before. From the calculation of the core of which fuel rods were exposed to the air, it turned out that the negligence of the fuel rods above the water level could lead to the considerable errors. Therefore, it is expected that if nTRACER can handle void region, it will significantly reduce the errors of k-eff and pin power errors.

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