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BWR MOX Core Physics Experiments and Preliminary Analysis

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ABSTRACT

An experimental program, BASALA, has been planned to measure the main neutronic parameters of high moderation 100% MOX BWR mock up cores in the CEA-EOLE critical facility. The first part of the experiments that simulates hot operating conditions of BWR was completed by June 2001 The experiments include five critical cores: a reference core, an increased void core, two different type burnable poison cores and an increased water rod core. The measurement parameters are the critical mass and the core power distribution and the worth of the above-mentioned heterogeneities. The analysis has been done by NUPEC with a deterministic code, SRAC and a continuous energy Monte Carlo code, MVP, combined with the JENDL-3.2 nuclear data library. The preliminary results show that the critical keffs of the five cores are 1.004 to 1.008 for SRAC and about 1.009 for MVP, and the radial power distribution and the worth of the increased void, the burnable poisons and the increased water rods are well reproduced by both SRAC and MVP. The general trend of the analysis results has a good consistency with the previous experiments of the MISTRAL program.

1. INTRODUCTION

NUPEC, CEA and their associated industrial partners have launched an experimental program, BASALA [1,2], to measure the main neutronic parameters of high moderation 100% MOX BWR core and the program is progressing in the EOLE critical facility of CEA

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from September 2000. Following the MISTRAL program [3-8], the program takes an integral part of the series of the neutron physics experiments for the high moderation 100% MOX LWR cores. The analysis of the obtained data has been contributing to validation and improvement of the core analysis scheme for such an advanced core concept. The experiments of the BASALA program comprise two core configurations with different lattice pitches representing hot operating and cold condition of BWR. A core configuration of the hot operating condition, which is referred as BASALA-H, has a reference core and its derivative cores. The former is designed for measurements on basic core characteristics and the latter for measurements on the perturbations caused by increasing void fraction (referred as High Void Core), adding burnable poisons of Gd2O3-UO2 fuel rods (referred as Burnable Poison Core), and increasing water rods (referred as Water Rod Core). The experiment of BASALA-H was completed by June 2001. Analysis of the experiments is progressing in NUPEC and CEA. The present paper shows the experimental results and preliminary analysis of BASALA-H conducted by NUPEC.

2. EXPERIMENTAL RESULTS OF BASALA-H

2.1 REFERENCE CORE

The reference core is consisting of sixteen 9x9 full assemblies and twenty partial assemblies in the peripheral region. The MOX rods composing the assemblies have the same geometry of the standard PWR 17x17 assembly with an outer diameter of 9.5 mm, except for the fuel effective length of about 800 mm. The fuel pellets are composed of mixed dioxide of plutonium and depleted uranium, and contained by Zry claddings. Those rods are sealed by over-claddings for adjusting the core moderation ratio and protecting the rods in handling. The diameter of the over-cladding, the fuel rod pitch and the assembly pitch are determined to be 10.2, 11.3 and 114.1 mm respectively in order to represent gross and local moderation ratio of the original BWR 9x9 fuel in the hot operating condition with in-channel void fraction of 40%. The two large water rods of the original assembly are simulated by 7 water rods of 10.2 mm in diameter. Four assemblies in the core center are consisting of a test region that is surrounded by a driver zone of the 9x9 full assemblies and the partial assemblies. In the test zone, the assembly is composed of the four types of MOX fuel rods, 3.0, 4.3, 7.0 and 8.7 wt% of Pu total, with the lower plutonium content MOX rods at the periphery of the assembly facing water gaps. The driver zone is mainly loaded with 7 % MOX rods.

The core configuration shown in Figure 1 is the reference core for the critical mass measurement on November 17, 2000. The moderator temperature was 19.6 ℃, no boron was diluted and the doubling time was 27.1 sec.

Measurement items are radial and axial power distribution with using gross gamma-spectrometry. The Amplified Source Method [3] is also applied to obtain the reactivity worth of introducing a highly voided region, Gd2O3 fuel rods and additional water rods into the four or two assemblies in the test region. The results will be shown in the chapter 3.

2.2 HIGH VOID CORE

One of the derivative cores is devoted to measurements of the reactivity effect of increasing void fraction of the core and the power distribution. In this core, all fuel rod of the four assemblies in the test region were attached with a thick over-cladding (11.25 mm in diameter) in the full length in order to simulate in-channel void fraction of 65 % in BWR. The critical state was reached by increasing number of fuel rods in the driver region to compensate the negative effect of the increased void and the radial and axial power distribution was measured with the gross gamma-spectrometry.

The core configuration shown in Figure 2 is the high void core for the critical mass measurement on January 24, 2001. The moderator temperature was 19.6 ℃, no boron was diluted and the doubling time was 63.2 sec.

2.3 BURNABLE POISON CORE

The second derivative core is dedicated to the study of burnable poison fuel rods. In the two assemblies diagonally located in the test region, 8 or 16 MOX rods were replaced by Gd_2O_3 (2.5 wt%)-enriched UO2 (4.9 wt%) fuel rods. The critical states were reached by increasing number of fuel rods in the driver region to compensate the negative effect of the burnable poison, and the radial power distribution was measured with the gross gamma-spectrometry.

The core configuration shown in Figure 3 is the 8 Gd_2O_3 core for the critical mass measurement on March 21, 2001. The moderator temperature was 19.7 ℃, no boron was diluted and the doubling time was 19.3 sec. The core configuration shown in Figure 4 is the 16 Gd_2O_3 core for the critical mass measurement on April 27, 2001. The moderator temperature was 19.8 ℃, no boron was diluted and the doubling time was 21.2 sec.

2.4 WATER ROD CORE

The third derivative core is related to the measurements on high moderation lattice effect. In this core, each assembly in the test region has eight additional water rods replacing MOX rode. This caused positive reactivity effect so that the critical states were reached by decreasing number of fuel rods in the driver region to compensate the positive effect, and the radial power distribution was measured with the gross gamma-spectrometry.

The core configuration shown in Figure 5 is the water rod core for the critical mass measurement on June 20, 2001. The moderator temperature was 19.8 ℃, no boron was diluted and the doubling time was 95.8 sec

3. ANALYSIS OF EXPERIMENTS

3.1 ANALYSIS METHOD

NUPEC has been applying two different analysis methods, SRAC [9] and MVP [10], to analyzing the experimental results with the common nuclear data library, JENDL-3.2 [11]. The former is a deterministic code system representing lattice analysis codes generally used for LWR core design and its analysis results provide us with information about validation of physics models and a nuclear data library. The latter is a continuous energy Monte Carlo calculation code and the analysis results give us information solely on the nuclear data library. Combining two different analysis results also offers us information on the validity of the physics models in the analysis code.

(1) Analysis with SRAC

SRAC is a code system consisting calculation modules for pin cell and core calculations. Collision probability calculations for each pin cell configuration were performed by a Pij module coupled with an ultra fine energy structure resonance-shielding module (PEACO) to generate 107 cross sections. A 3x3 multi-cell configuration containing a burnable poison rod in the central position was also applied for the analysis of the burnable poison cores. The cross sections are spatially averaged and collapsed into 16 energy groups. Two-dimensional 16-group core calculations in a X-Y geometry were performed with a diffusion theory module, CITATION, and a discrete ordinate transport theory module, TWOTRAN or TWODANT [12]. Measured axial buckling was used to calculate axial leakage from the core.

(2) Analysis with MVP

Almost all of important components in the EOLE core tank were explicitly modeled in the three-dimensional geometry. The number of batches in the calculation was 1000 and the neutron history in a batch was 10000 so that total number of neutron history was 10 millions that lead to obtain a statistical error of 0.02 %Δk in the keff calculation and 1 % in the radial power distribution.

3.2 ANALYSIS RESULTS

(1) Criticality

The criticality calculations were carried out for the reference, the high void, the burnable poison and the water rod cores shown in Figures 1 to 5. The calculated results of the critical keffs are shown in Table Ⅰ. The difference of keff among the reference and the derivative cores is less than 0.1% Δ k for each analysis method that is comparatively smaller than the introduced reactivity worth in the derivative cores, the minimum +0.7 % Δ k for the water rod core to the maximum -2.2 % Δ k for the burnable poison core (16 Gd_2O_3). The results show that the SRAC and the MVP analysis slightly over-estimates keff for the cores of BASALA-H. This trend was also observed in the analysis of MOX cores in the MISTRAL and EPICURE programs with combination of JENDL-3.2 [5-7]. The Table Ⅱ shows the comparison of keffs among those experiments.

Table Ⅰ. Critical keff of BASALA-H (NUPEC)

Core	Reference	High Void	Burnable Poison-$8Gd_2O_3$	Burnable Poison-$16Gd_2O_3$	Water Rod
SRAC-CITATION	1.0039	1.0031	1.0038	1.0036	1.0044
SRAC-TWOTRAN	1.0078	1.0088	1.0076*	1.0085*	1.0086
MVP**	1.0086	1.0085	1.0088	1.0092	1.0094

*TWODANT, **Statistical error is 0.0002 Δk (1σ)

Table Ⅱ. Critical keff of EPICURE, MISTRAL and BASALA-H (NUPEC)

Item	EPICURE		MISTRAL				BASALA-H (Reference)
	UH1.2	MH1.2	Core 1	Core2	Core 3	Core 4	
UO_2/MOX	UO_2	MOX Main part	UO_2	MOX	MOX	MOX	MOX
Homogeneous /Mock up	Homo-geneous	Homo-geneous	Homo-geneous	Homo-geneous	Homo-geneous	PWR-Mock up	BWR-Mock up
Core diameter （cm）	54	69	41	60	59	62	61^{*1}
H/HM^{*2}	3.7	3.7	5.1	5.2	6.2	5.8	5.0
SRAC-CITATION	0.9956	1.0027	0.9903	1.0048	1.0049	1.0074	1.0039
SRAC-TWOTRAN	1.0007	1.0013	0.9981	1.0041	1.0042	1.0074	1.0078
MVP	1.0051	1.0027	1.0048	1.0070	1.0077	1.0093	1.0086

*1: Length of the side of the core
*2: Hydrogen to heavy metal atomic ratio

The comparison of the results of MVP indicates that the difference of keff between the UO_2 cores and the MOX cores is less than 0.4% Δk for JENDL-3.2. The comparison of the results of SRAC shows that the difference of keffs between homogeneous MOX cores in the MISTRAL and the BASALA-H is less than 0.4% Δk.

(2) Power Distribution

The gross gamma spectrometry was conducted to obtain a gross core radial power distribution and an assembly inside power distribution. Figure 6 shows a typical measurement map. Figures 7 to 11 show the comparison between the measured and the calculated radial power distribution in the direction traversing (see Figure 6) from the left bottom to the right top of the reference core and derivative cores. The calculated results are well reproducing the gross and local heterogeneous power distributions. Table Ⅲ shows a summary of difference between the measured and the calculated results of the traversing direction in a root mean square error.

Table Ⅲ. Difference of Power Distribution between Measurement and Calculation in Root Mean Square Error (NUPEC)

Core	Reference	High Void	Burnable Poison-$8Gd_2O_3$	Burnable Poison-$16Gd_2O_3$	Water Rod
SRAC-CITATION	1.8	1.9	2.3	1.8	2.0
MVP	1.6	1.6	1.8	1.2	1.7

Note: Measurement error is 1.5%(1 σ) and statistical error of MVP is 1%(1 σ)

Shown in Figure 12 are the measured and the calculated data for the power distribution in the left bottom assembly in the test region for the reference core. A rather large discrepancy seen in (I, 5) may be caused by the error of the measured data that is indicated by the large asymmetry of the data of (I, 5) and (E, 1). Analyses of the measurement process seem to be necessary.

(3) Worth of Void, Burnable Poison and Water Rod

Preliminary reactivity worth of the heterogeneities obtained with the Amplified Source Method in the reference core is compared with the calculation and shown in Table Ⅳ. The calculated results of MVP are close to the measured data and those of SRAC-CITATION over-estimate the measured values. Further study will be planned for inquiring the measurements and the calculations.

Table Ⅳ. Comparison of Worth between Measurement and Calculation (NUPEC)

(Unit: pcm)

	SRAC-CITATION (C/E)	SRAC-TWOTRAN (C/E)	MVP (C/E)	Measured data (Relative Error %)
High Void	- 1497 (1.16)	- 1329 (1.03)	- 1292 ± 33 (1.00)	- 1290 ± 69 (5.4)
Burnable Poison-$8Gd_2O_3$	- 2130 (1.07)	- 2090* (1.05)	- 2049 ± 33 (1.03)	- 2000 ± 108 (5.4)
Burnable Poison-$16Gd_2O_3$	- 2300 (1.07)	- 2140* (0.99)	- 2201 ± 33 (1.02)	- 2156 ± 116 (5.4)
Water Rod	855 (1.15)	850 (1.14)	790 ± 33 (1.06)	743 ± 40 (5.4)

* TWODANT

CONCLUSIONS

The core physics experiments, BASALA-H, aim to measure the main nuclear parameters of the hot operating condition of high moderation 100% MOX BWR core. The reference core and the derivative cores were composed of the BWR 9x9 MOX mock up assemblies. The measurement items were the critical mass, the power distribution, and the worth of the increased void fraction, the burnable poisons and the increased number of water rods. The preliminary analysis of NUPEC shows that the trend of the critical keffs of the BASALA-H cores is similar to the previous MISTRAL cores, and the radial power distribution of the reference and the derivative cores and the worth of the increased void fraction, the burnable poisons and the increased water rods are well reproduced by the analysis with the same accuracy of the MISTRAL cores.

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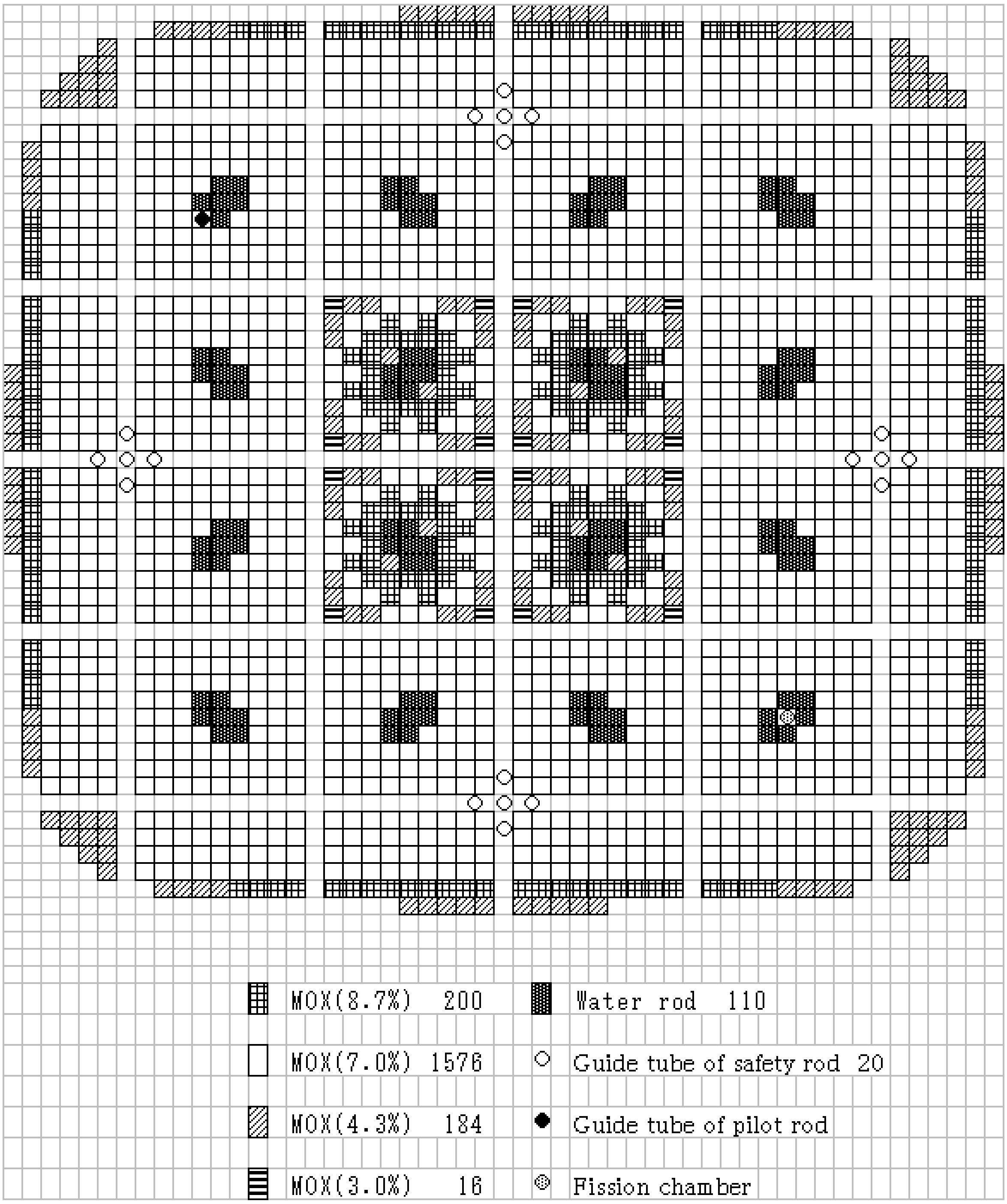


Figure 1. Core Configuration of Reference Core of BASALA-H

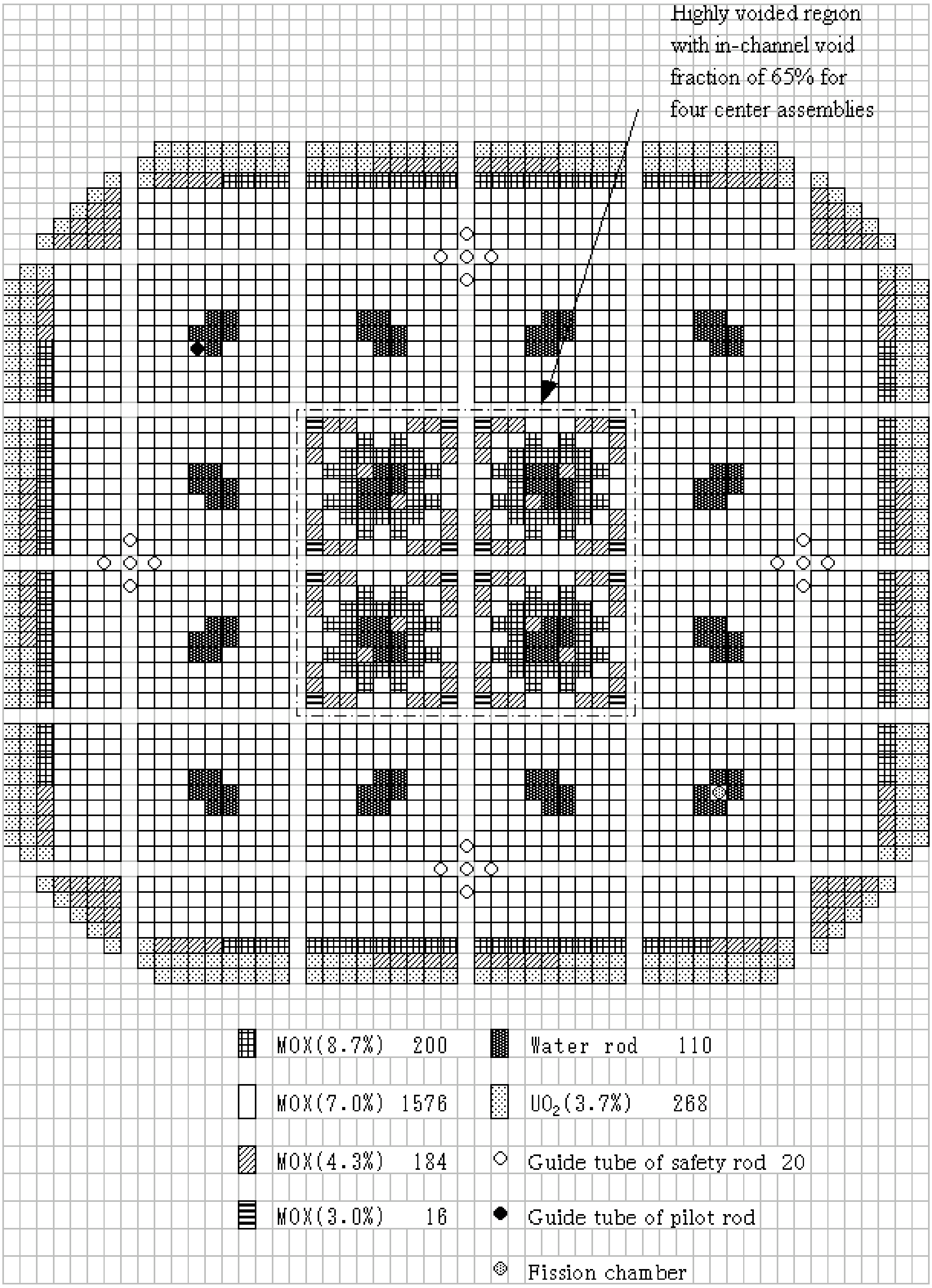


Figure 2. High Void Core

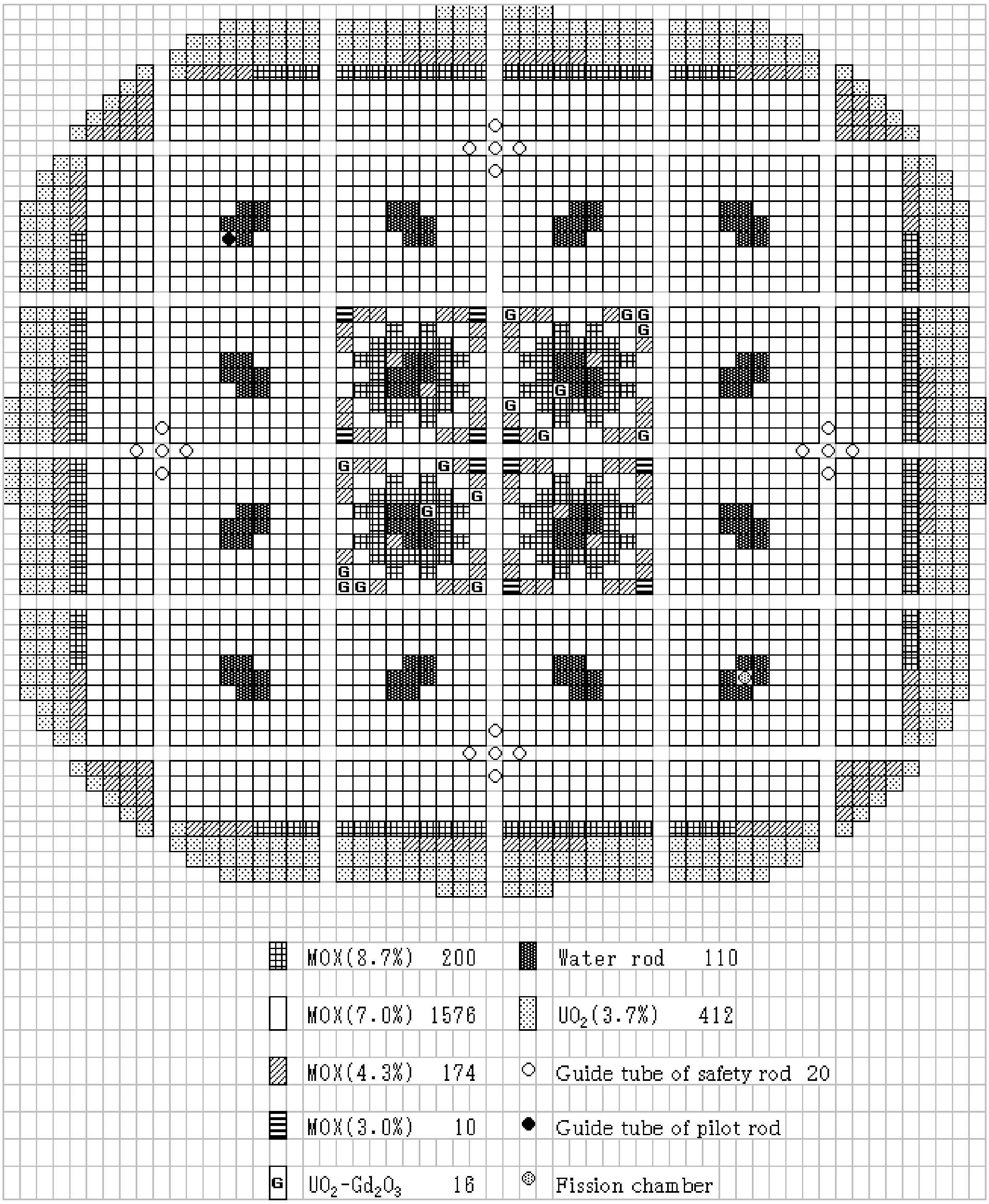


Figure 3. Burnable Poison Core (8 Gd_2O_3-UO_2)

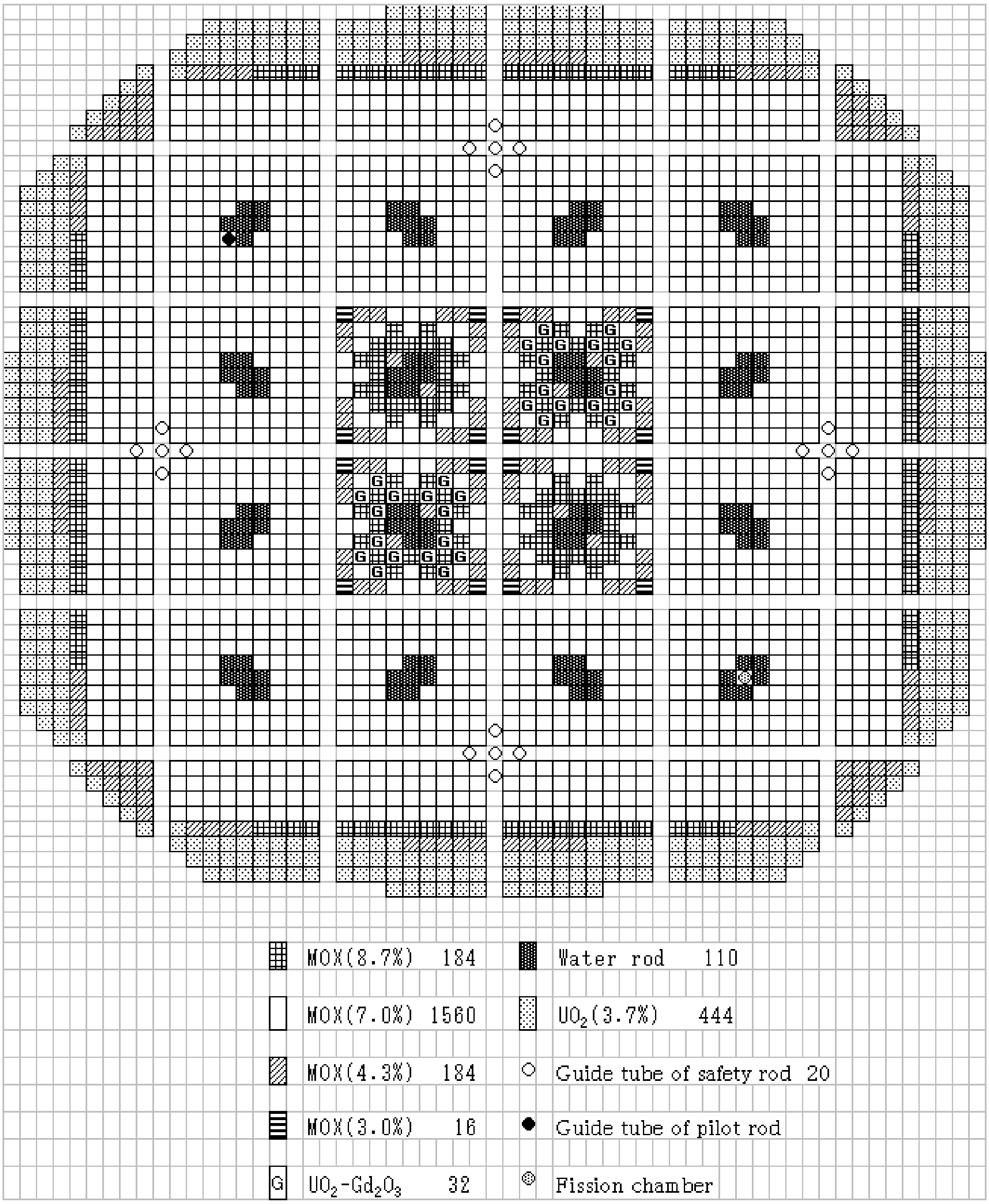


Figure 4. Burnable Poison Core (16 Gd_2O_3-UO_2)

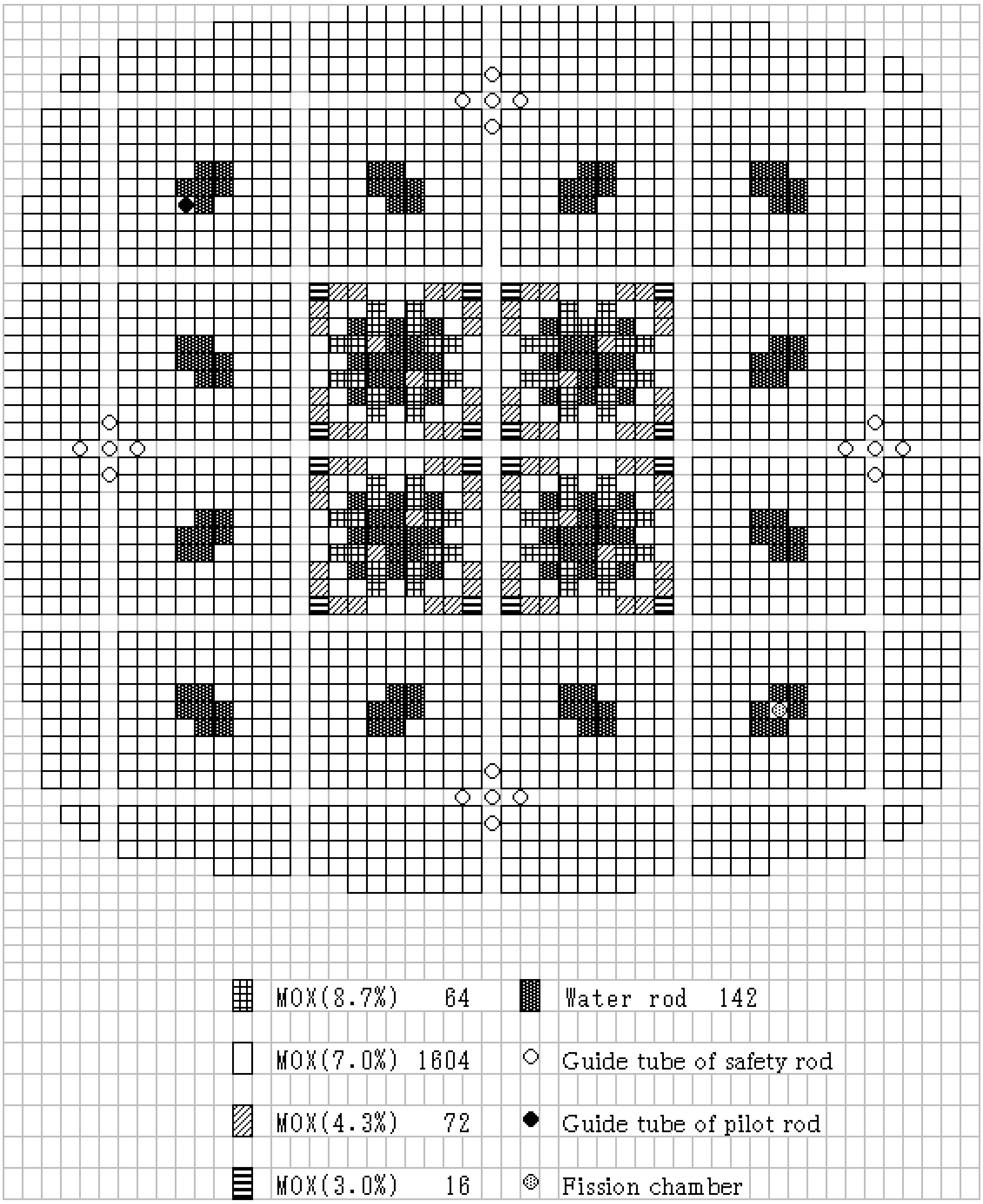
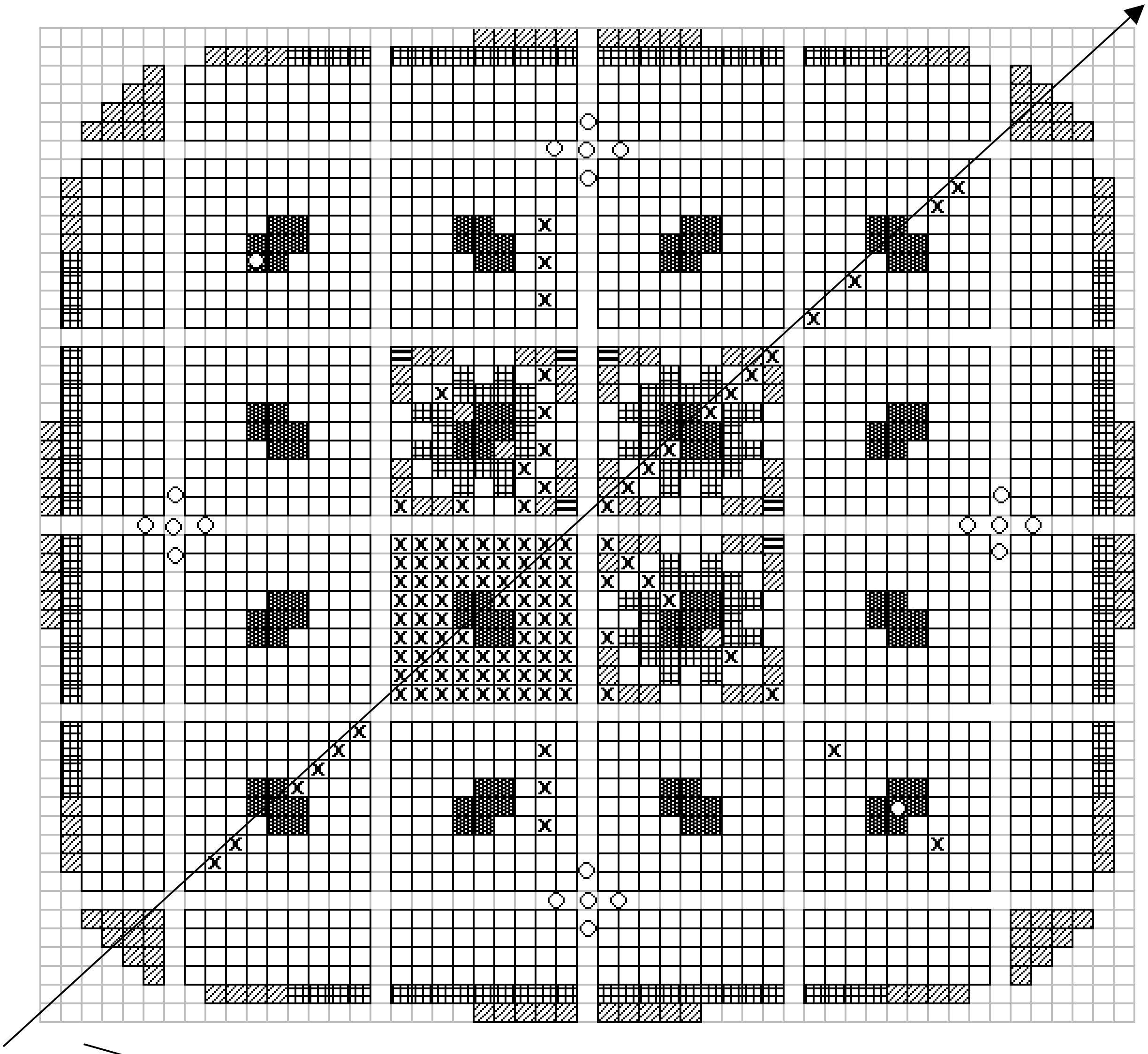


Figure 5. Water Rod Core



Direction of Power Distribution in Figures 7 -11

Figure 6. Typical Measurement Point (X) with Gross Gamma Scanning

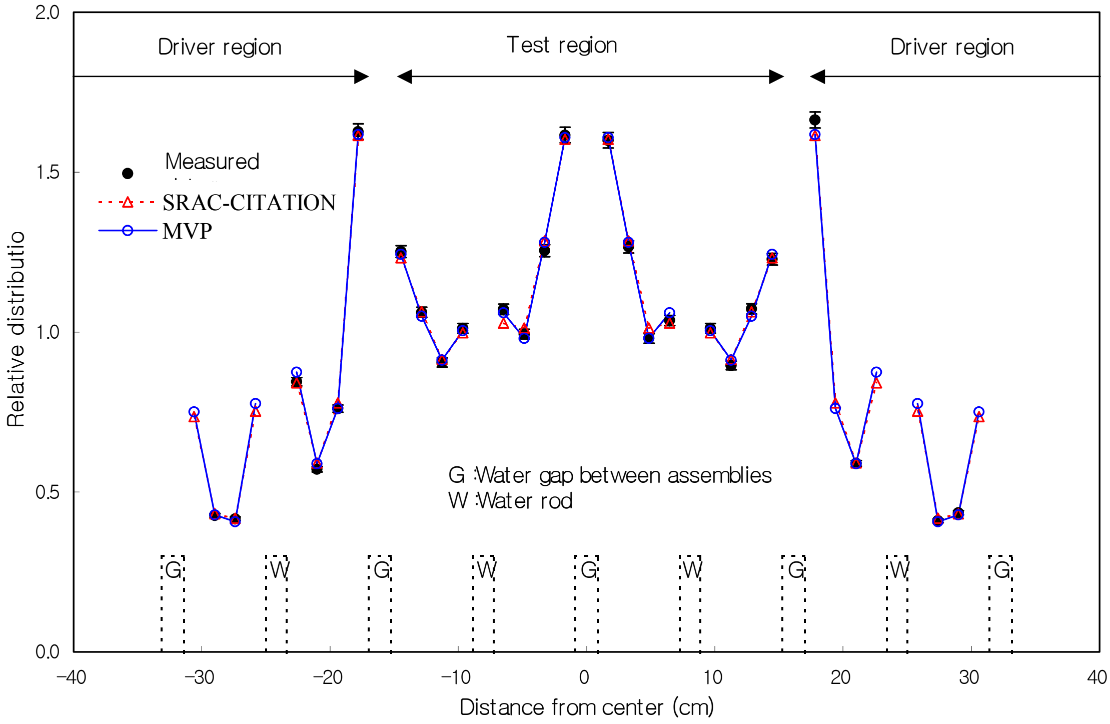


Figure 7. Comparison between Measured and Calculated Power Distribution of Reference Core

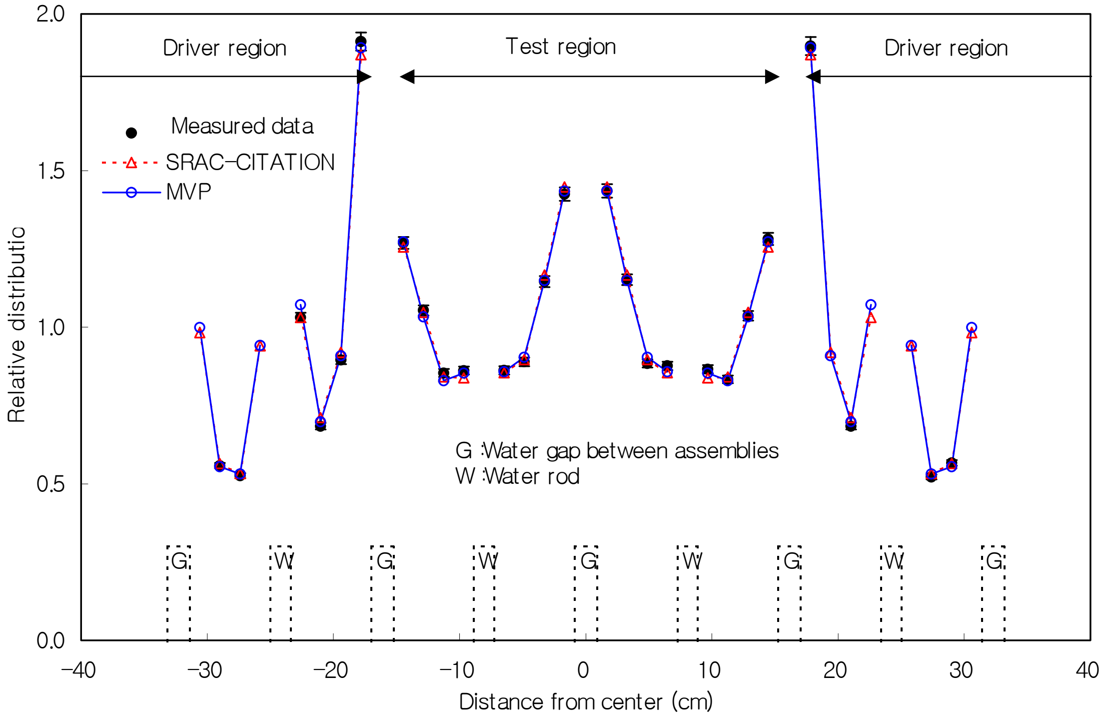


Figure 8. Comparison between Measured and Calculated Power Distribution of High Void Core

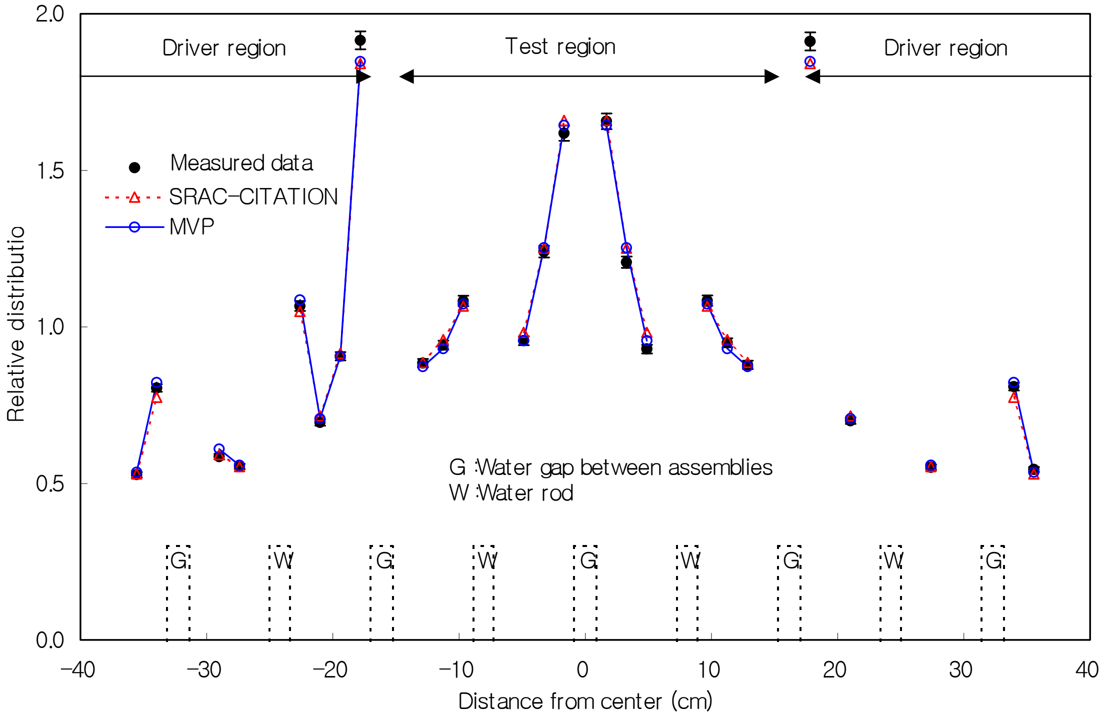


Figure 9. Comparison between Measured and Calculated Power Distribution of Burnable Poison Core (8 Gd_2O_3)

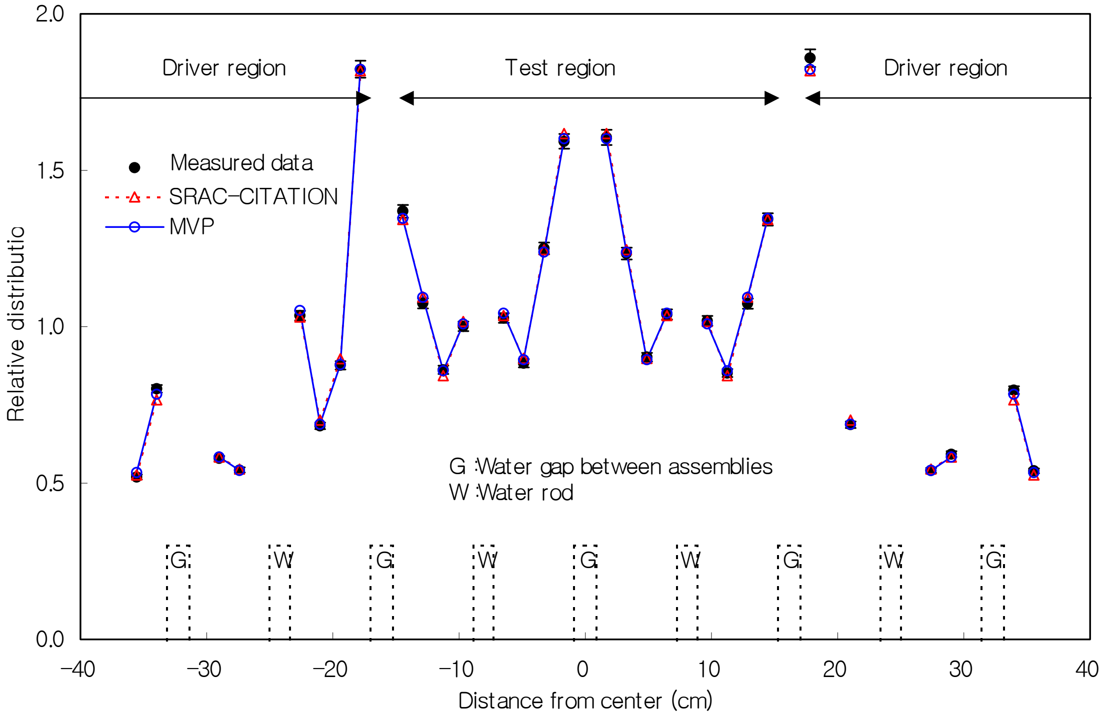


Figure 10. Comparison between Measured and Calculated Power Distribution of Burnable Poison Core (16 Gd_2O_3)

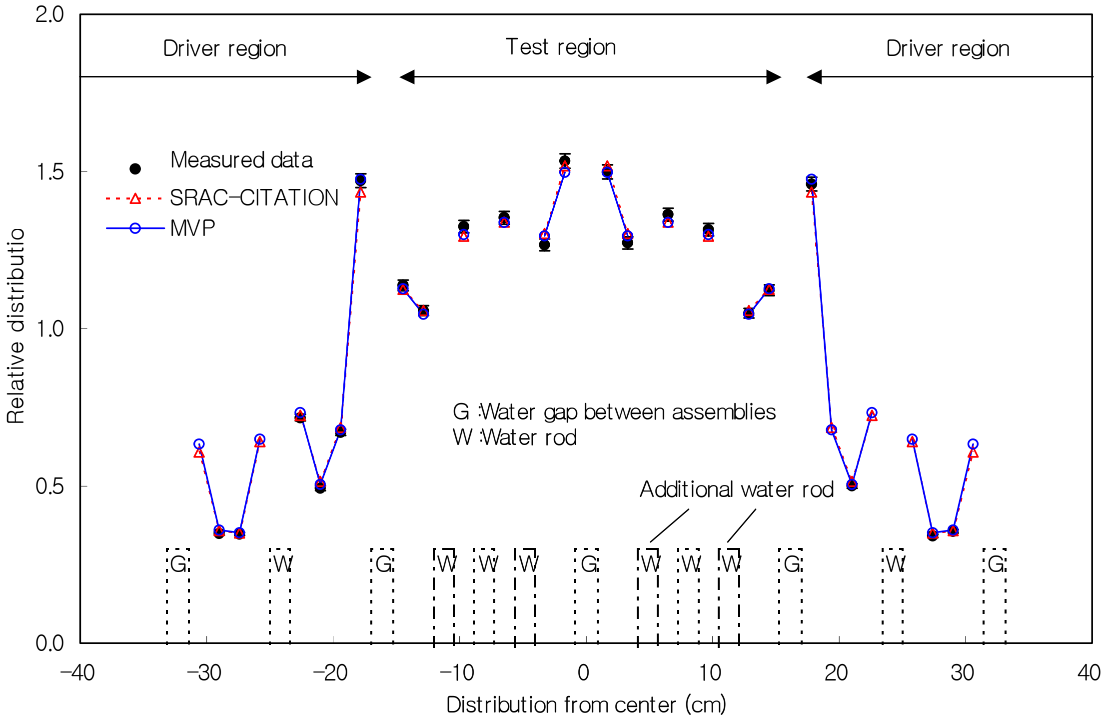


Figure 11. Comparison between Measured and Calculated Power Distribution of Water Rod Core

Measured data   Core center

	A	B	C	D	E	F	G	H	I
1	1.246	1.133	0.966	1.229	1.188	1.234	1.023	1.266	1.420
2	1.090	1.023	0.868	0.926	0.800	0.933	0.906	1.102	1.246
3	0.888	0.838	0.892	1.074	1.118	0.952	0.873	0.907	1.027
4	1.095	0.864	1.038	WR	WR	0.941	0.941	0.914	1.250
5	1.058	0.750	1.060	WR	WR	WR	1.104	0.807	1.230
6	1.082	0.843	0.885	0.889	WR	WR	1.075	0.922	1.231
7	0.856	0.792	0.795	0.881	1.056	1.032	0.877	0.872	0.994
8	0.972	0.933	0.771	0.833	0.746	0.861	0.835	1.027	1.155
9	1.100	1.011	0.881	1.082	1.075	1.133	0.923	1.111	1.255

Normarized within assembly

Calculated by SRAC-CITATION   Core center

	A	B	C	D	E	F	G	H	I
1	1.231	1.129	0.975	1.206	1.180	1.237	1.030	1.238	1.407
2	1.084	1.032	0.877	0.940	0.827	0.946	0.915	1.128	1.238
3	0.911	0.850	0.899	1.058	1.100	0.960	0.889	0.915	1.030
4	1.104	0.890	1.038	WR	WR	0.902	0.960	0.946	1.237
5	1.054	0.765	1.060	WR	WR	WR	1.100	0.827	1.180
6	1.069	0.849	0.901	0.876	WR	WR	1.058	0.940	1.206
7	0.856	0.790	0.803	0.901	1.060	1.038	0.899	0.877	0.975
8	0.987	0.934	0.790	0.849	0.765	0.890	0.850	1.032	1.129
9	1.081	0.987	0.856	1.069	1.054	1.104	0.911	1.085	1.231

Normarized within assembly

Relative difference   Core center

	A	B	C	D	E	F	G	H	I
1	-1.16	-0.36	0.87	-1.83	-0.62	0.28	0.72	-2.23	-0.90
2	-0.48	0.92	1.13	1.50	3.39	1.39	1.07	2.36	-0.62
3	2.62	1.39	0.79	-1.44	-1.63	0.83	1.83	0.86	0.35
4	0.80	3.08	-0.01	WR	WR	-4.13	2.04	3.47	-0.98
5	-0.33	2.04	-0.04	WR	WR	WR	-0.40	2.43	-4.00
6	-1.17	0.68	1.82	-1.47	WR	WR	-1.62	1.91	-1.98
7	-0.07	-0.26	0.94	2.32	0.37	0.60	2.51	0.62	-1.92
8	1.49	0.12	2.49	1.89	2.56	3.46	1.78	0.55	-2.24
9	-1.66	-2.40	-2.84	-1.16	-1.89	-2.53	-1.33	-2.38	-1.90

Difference: (Calculated-Measured)/Measured(%)
Max: 4.1%, RMS: 1.8%

Figure 12. Comparison between Measured and Calculated Power Distribution in An Assembly for Reference Core