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Analytical Estimation of Control Rod Shadowing Effect for Excess Reactivity Measurement of HTTR

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ABSTRACT

The fuel addition method is generally used for the excess reactivity measurement of the initial core. The control rod shadowing effect for the excess reactivity measurement has been estimated analytically for High Temperature Engineering Test Reactor (HTTR). 3-dimensional whole core analyses were carried out. The movements of control rods in measurements were simulated in the calculation.

It was made clear that the value of excess reactivity strongly depend on combinations of measuring control rods and compensating control rods. The differences in excess reactivity between combinations come from the control rod shadowing effect. The shadowing effect is reduced by the use of plural number of measuring and compensating control rods to prevent deep insertion of them into the core. The measured excess reactivity in the experiments is, however, smaller than the estimated value with shadowing effect.

1. INTRODUCTION

Excess reactivity is measured in inspections to confirm that the reactor satisfies its licensing limitation. The fuel addition method is used for the excess reactivity measurement of the initial core of High Temperature Engineering Test Reactor (HTTR). In the fuel addition method, the reactivity added by loaded fuels is measured after each fuel loading step and the excess reactivity is obtained by summation of each measured reactivity.

The reactivity added by loaded fuels is measured with insertion and withdrawal of control rods (CRs). CRs in reactivity measurement are sorted into the following three groups;

a) *Measuring CR*: The positive reactivity is supplied to the core by withdrawal of a CR in this group. The reactivity supplied to the core is measured with the positive period method or the inverse kinetic method (I.K. method).

b) *Compensating CR*: After the withdrawal of the *measuring CR* and the reactivity measurement, CRs in this group are inserted to make slightly sub-critical condition.

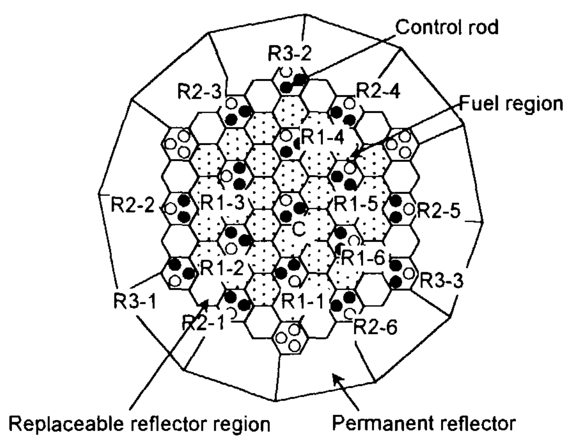


Figure 1. Horizontal view of HTTR core

Therefore, the CRs compensate the positive reactivity supplied by the *measuring CR*.

c) *Other CR*: CRs in this group don't move during reactivity measurement. Before reactivity measurement, the core is kept in critical condition with all CRs.

The excess reactivity means the reactivity worth of CRs that are inserted into the core at criticality. The reactivity of an inserted CR, i.e. *measuring CR* is influenced by the surrounding CRs. For example, the increase of neutron flux at the *measuring CR*, which is caused by the insertion of *compensating CR*, makes the reactivity worth of the *measuring CR* larger. On the other hand, the insertion of *compensating CR*s near the *measuring CR* makes the reactivity worth small. Such reactivity interaction among CRs as this is called shadowing effect.

Figure 1 shows the CR location of HTTR. The core has one center CR (C), six first ring CRs (R1), six second ring CRs (R2) and three third ring CRs (R3). Since the core has 16 CRs and the neutron moderator is graphite, the distance between CRs is small in respect of neutron diffusion. Therefore the shadowing effect is larger than that in water moderated reactors.

The analytical estimation of the shadowing effect of CRs was carried out for the fuel addition method on the initial loading of HTTR.

2. ANALYSIS METHOD

2.1 Nuclear Calculation Method

DELIGHT-7[1)] was used to make effective microscopic cross-sections of the fuel region. The cross-section of the CR was made by TWOTRAN-II[2)] with the super cell model including CR, CR guide block and fuel region. The effective multiplication factor, *keff* was calculated with CITATION-1000VP[3)]. The calculation scheme is shown in Figure 2[4)].

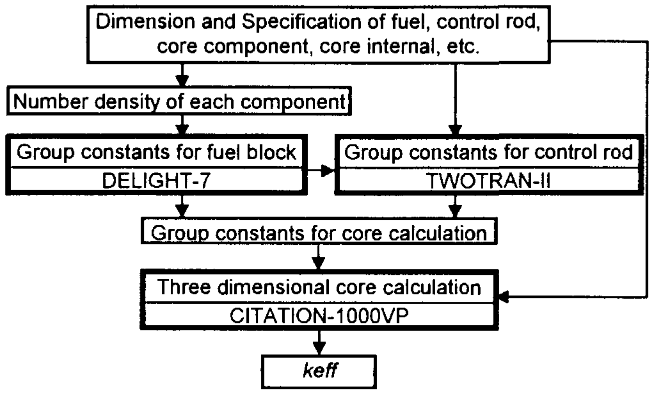


Figure 2. Program structure of HTTR nuclear calculations

2.2 Fuel Loading Steps and Excess Reactivity Measurement

The fuel loading order is shown in Figure 3. After the first criticality, three fuel columns are loaded in every fuel loading step. The reactivity added with the three fuel columns is measured with I.K. method at 21, 24, 27, 30 column loaded core.

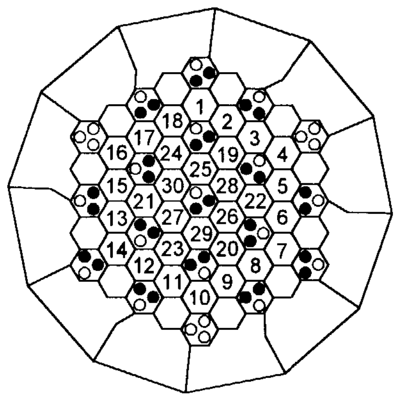


Figure 3. Fuel loading order

Figure 4 shows the measuring system of I.K. method. The neutron flux change caused by the withdrawal of the *measuring CR* was measured with gamma-ray compensated ionization chambers (CICs). The signal from the CIC is sent to the personal computer (PC) through the linear amplifier, the isolation amplifier and the analog/digital converter. In

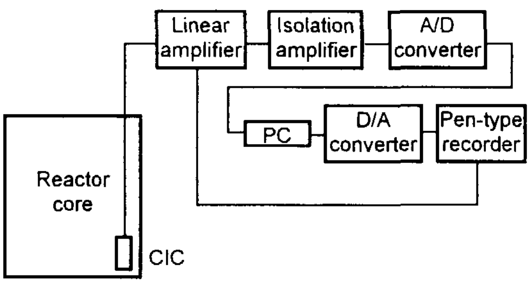


Figure 4. Reactivity measuring system

the PC, the point wise kinetic equation is solved numerically in real time.

2.3 Calculation Method of Shadowing Effect

Shadowing effect is classified into two parts, *shadowing effect A* and *shadowing effect B*.

The *shadowing effect A* is the reactivity interaction between the *measuring CR* and the *compensating CR*. It is expressed as follows;

$$\textit{Shadowng effect A} = \frac{\text{the reacitivty obtained by simulation of the measurement}}{\text{the reactivity obtained by withdrawal of the } \textit{measuring CR}} \quad (1)$$

The *shadowing effect B* is reactivity effect caused by existence of *other CRs* and is expressed as follows;

$$\textit{Shadowng effect B} = \frac{\text{the reactivity obtained by withdrawal of the } \textit{measuring CR}}{\text{the reactivity of fuel columns added into the core having no CRs}} \quad (2)$$

Total *shadowing effect* is given as follows;

$$\textit{Shadowng effect} = \textit{Shadowing effect A} \times \textit{Shadowing effect B} \quad (3)$$

The reactivity obtained by simulation of the measurement, the numerator of Eq.(1), is calculated with following procedures. In these procedures, the effect of the insertion of *compensating CRs* is considered into the calculation.

(i) A *measuring CR* is withdrawn from critical condition to slightly super-critical position and the reactivity supplied by this divided withdrawal is calculated from the *keffs* before and after the withdrawal of the *measuring CR*.
(ii) A *compensating CR* is inserted to slightly sub-critical position in calculation model.
(iii) These procedures, (i) and (ii), are repeated until the *measuring CR* is withdrawn to the critical position at the last fuel loading step.

The numerator of Eq.(1) is obtained by the summation of reactivities calculated in the procedure (i).

The reactivity obtained by the withdrawal of the *measuring CR*, the denominator of Eq.(1) and the numerator of Eq.(2), is calculated from the *keffs* before and after the withdrawal of the *measuring CR* without compensation of the reactivity. The *measuring CR* is withdrawn from the present critical position to the critical position at the last fuel loading step, where no *compensating CR* is inserted.

On the other hand, the reference excess reactivity is obtained as the reactivity of fuel columns added into the core which has no CRs, the denominator of Eq.(2). It is calculated as the reactivity of added fuels in the core that has no CRs after the first criticality. It is equal to the value calculated from *keff* of the core without CRs.

2.4 Investigated Cases

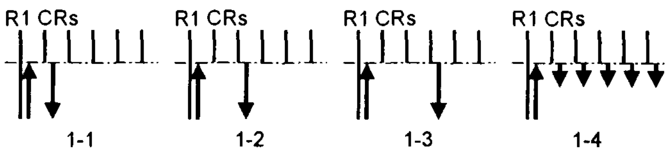
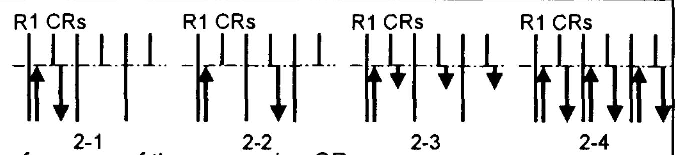
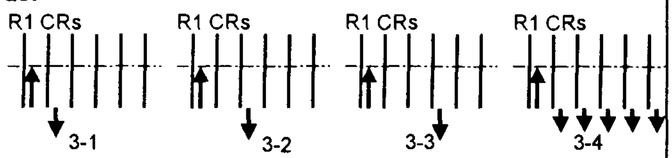
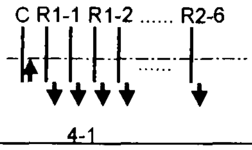
The combinations of the *measuring CR* and the *compensating CRs* are shown in Table 1. Since R1 CRs have large reactivity worth, R1 rods are used as *measuring* or *compensating CRs*. Furthermore, in the case 4-1, all CRs except R3 rods that are always fully withdrawn, are used as *measuring CRs* and *compensating CRs*.

3. RESULTS

3.1 Analytical results of shadowing effect

The analytical results are shown in Figure 5 and Table 2.

Table 1. Combinations of *measuring* and *compensating CR*s

1 *Measuring CR* is one of R1 control rods 1-1 *Compensating CR* is located at 60° position from the *measuring CR* 1-2 *Compensating CR* is located at 120° position from the *measuring CR* 1-3 *Compensating CR* is located at 180° position from the *measuring CR* 1-4 *Compensating CRs* are five CRs of R1 except the *measuring CR*	
2 *Measuring CRs* are three of R1 rods, which are located at intervals of 120°. Reactivity measurement of one of three *measuring CRs*, the *compensating CRs* are follows; 2-1 *Compensating CR* is located at 60° position from one of the *measuring CRs* 2-2 *Compensating CR* is located at 180° position from one of the *measuring CRs* 2-3 *Compensating CRs* are three CRs located at 60° and 180° position from one of the *measuring CRs*, i.e., the three rods inserted upper than *measuring CRs*. 2-4 *Compensating CRs* are the same as in the case 2-3, but the reactivity measurement for three *measuring CRs* is carried out in succession.	
3 *Measuring CRs* are six of R1, i.e. all R1 rods. 3-1 *Compensating CR* is located at 60° position from one of the *measuring CRs*. 3-2 *Compensating CR* is located at 120° position from one of the *measuring CRs*. 3-3 *Compensating CR* is located at 180° position from one of the *measuring CRs* 3-4 *Compensating CRs* are five CRs of R1 except the *measuring CR*	
4 *Measuring CRs* are thirteen rods except R3 rods. 4-1 *Compensating CRs* are twelve rods except one of the *measuring CRs*.	
Note: Upper directed arrow means withdrawal of *measuring CR*. Lower directed arrow means insertion of *compensating CR*. Broken line means critical position at the last fuel loading step.	

In the case 1 series, in which the *measuring CR* is one of the R1 rods, the calculated value of excess reactivity varies from −10% to +50% compared to the reference excess reactivity. Since the case 2 series has three *measuring CRs*, the insertion depth of the *measuring CRs* from the positions of the *other CRs* and the withdrawal distance of the *measuring CRs* is smaller than in the case 1 series. Therefore, the shadowing effect is smaller than that of the case 1 series.

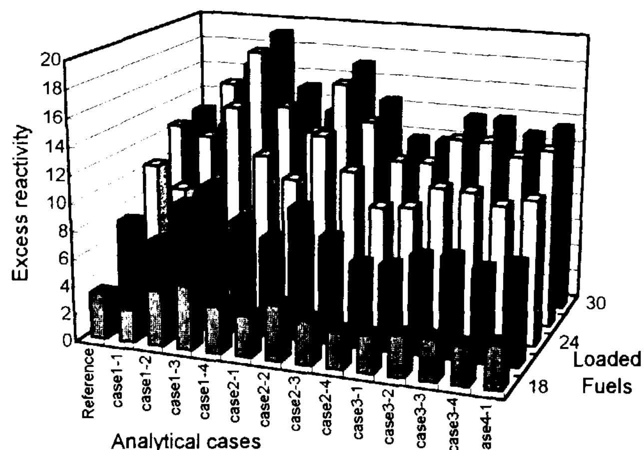


Figure 5. Analytical excess reactivity for various cases

Furthermore, in case 3 and 4 series which have many *measuring CRs* and *compensating CRs* the shadowing effect is smaller than in case 1 or 2 series.

Table 2. Calculated results of shadowing effect

	Loaded fuel column		18	21	24	27	30	Excess reactivity	
Without CRs	Keff		1.047	1.093	1.131	1.158	1.162	%Δk/k	Ratio to Without CRs
	Reactivity increase(%Δk/k)		3.30	3.99	3.10	2.10	0.25	12.7	
1-1	Shadowing effect	A	0.719	0.865	0.855	0.875	0.916		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.719	0.899	0.922	1.066	2.206		
	Expected value(%Δk/k)		2.37	3.59	2.86	2.23	0.56	11.6	0.91
1-2	Shadowing effect	A	1.208	1.211	1.187	1.181	1.039		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	1.208	1.258	1.280	1.438	2.502		
	Expected value(%Δk/k)		3.98	5.02	3.97	3.02	0.63	16.6	1.30
1-3	Shadowing effect	A	1.406	1.430	1.406	1.280	1.072		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	1.406	1.486	1.516	1.559	2.581		
	Expected value(%Δk/k)		4.63	5.93	4.70	3.27	0.65	19.2	1.51
1-4	Shadowing effect	A	1.026	1.152	1.112	1.056	0.987		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	1.026	1.197	1.199	1.286	2.377		
	Expected value(%Δk/k)		3.38	4.78	3.72	2.70	0.60	15.2	1.19
2-1	Shadowing effect	A	0.899	1.007	0.951	0.974	0.966		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.899	1.046	1.025	1.186	2.326		
	Expected value(%Δk/k)		2.96	4.18	3.18	2.49	0.59	13.4	1.05
2-2	Shadowing effect	A	1.216	1.342	1.231	1.127	1.082		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	1.216	1.394	1.327	1.373	2.605		
	Expected value(%Δk/k)		4.01	5.56	4.12	2.88	0.66	17.2	1.35
2-3	Shadowing effect	A	0.974	1.077	1.080	1.044	1.041		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.974	1.119	1.164	1.272	2.507		
	Expected value(%Δk/k)		3.21	4.47	3.61	2.67	0.63	14.6	1.15
2-4	Shadowing effect	A	0.787	0.835	0.850	0.908	0.943		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.787	0.868	0.916	1.106	2.271		
	Expected value(%Δk/k)		2.59	3.46	2.84	2.32	0.57	11.8	0.93
3-1	Shadowing effect	A	0.809	0.846	0.861	0.864	0.918		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.809	0.879	0.928	1.052	2.211		
	Expected value(%Δk/k)		2.67	3.51	2.88	2.21	0.56	11.8	0.93
3-2	Shadowing effect	A	0.894	0.988	1.092	0.979	0.992		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.894	1.027	1.177	1.192	2.389		
	Expected value(%Δk/k)		2.95	4.10	3.65	2.50	0.60	13.8	1.08
3-3	Shadowing effect	A	0.913	1.026	1.009	0.999	1.008		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.913	1.066	1.088	1.217	2.427		
	Expected value(%Δk/k)		3.01	4.25	3.37	2.55	0.61	13.8	1.08
3-4	Shadowing effect	A	0.848	0.927	0.958	0.953	0.951		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.848	0.963	1.033	1.161	2.290		
	Expected value(%Δk/k)		2.80	3.84	3.20	2.43	0.58	12.9	1.01
4-1	Shadowing effect	A	0.954	0.987	0.969	0.962	0.962		
		B	—	1.039	1.078	1.218	2.408	—	—
		A×B	0.954	1.025	1.045	1.172	2.316		
	Expected value(%Δk/k)		3.14	4.09	3.24	2.46	0.59	13.5	1.06

3.2 Comparison between measured and calculated excess reactivity

The case 4-1 is selected in the measurement because the shadowing effect is small from the analytical results and all CRs except three R3 CRs are used at the same insertion depth in normal operation. Figure 6 shows the comparison between the measured excess reactivity and the calculated excess reactivity with shadowing effect. The calculated excess reactivity is larger than measured one. The reason is considered followings;

(i) The first criticality was to be achieved at 16 fuel column loaded core in the analysis, but in the measurement, it is achieved at 19 fuel column loaded core.

(ii) The reactivity effect of the insertion of *compensating CRs* increases the measured reactivity since the insertion makes the reactivity importance, i.e. relative neutron flux, around the *measuring CR* larger. The insertion of *compensating CRs* was overestimated in the calculation model since the vertical mesh width of the calculation model is larger than that of the insertion depth in the measurement.

The increase of the excess reactivity caused with fuel loading, however, is similar in analyses and measured results.

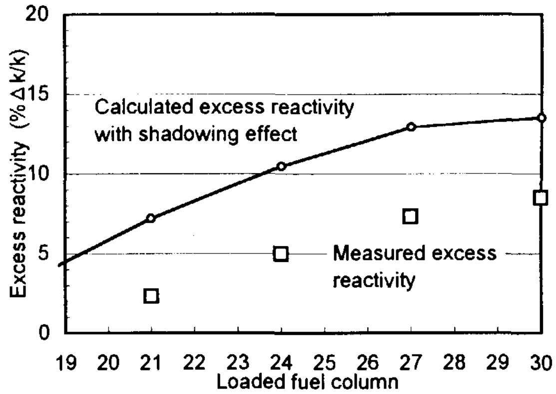


Figure 6. Comarison between measured and calculated excess reactivity.

4. CONCUSION

The CR shadowing effects have been evaluated analytically in application of the fuel addition method to excess reactivity measurement of HTTR. In the analysis, the movements of CRs have been simulated. The excess reactivity obtained by the simulation depends on the combinations of *measuring CRs* and *compensating CRs*. It varies from –10% to +50% in comparison with the reference excess reactivity calculated from the effective multiplication factor of the core where all CRs are fully withdrawn. The CR shadowing effect is reduced by the use of several of *measuring CRs* and *compensating CRs*. As a result, the following combinations of CRs are recommended;

(i) Thirteen CRs of C, R1 and R2 will be used for the reactivity measurement. The reactivity of each CR is measured by the use of the other twelve CRs for reactivity compensation.

(ii) Six CRs of R1 will be used for the reactivity measurement. The reactivity of each CR is measured by the use of the other five CRs for reactivity compensation.

The measured excess reactivity with fuel addition method is smaller than that of the analytical results with shadowing effect because of the difference of first criticality fuel columns between measured and analyses and over-evaluation of the insertion of *compensating CRs*.

REFERENCE

1) R.Shindo, K.Yamashita and I.Murata, "DELIGHT-7; One-dimensional fuel cell burnup analysis code for High Temperature Gas-cooled Reactors(HTGRs)", JAERI-M 90-048, (1990) (in Japanese)

2) K.D.Lathrop, and F.W.Brinkley, "TWOTRAN-II : An Interfaced, Exportable Version of the TWOTRAN Code for Two-Dimensional Transport", LA-4848MS (1973).

3) H.Harada and K.Yamashita, "The reactor core analysis code CITATION-1000VP for High Temperaturze Engineering Test Reactor", JAERI-M 89-135 (1989) (in Japanese)

4) K.Yamashita, et. al. "Nuclear Design of the High-Temperature Engineering Test Reactor (HTTR)", Nucl. Sci. Eng., 122, 212~228 (1996).