Analysis of Control Rod Worth

in Experimental Fast Reactor JOYO

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Abstract

In JOYO, the measurement of control rod worths have been carried out in the beginning of the each cycle, using both period method and neutron source mutiplication method. In this paper, the calculational method of control rod worths in the design stage and the comparison with the design values and measured ones are shown. The reasons that the control rod worths change slightly in each cycle, are also investigated.

1. Introduction

The experimental fast reactor JOYO achieved initial criticality on April 24, 1977, as the first liquid metal fast reactor in Japan. After this, the reactor has completed two 50 MWt duty cycles and six 75 MWt duty cycles as a breeder core (Mark-I core). Then core conversion work was carried out, in which the Mark-I breeder core was replaced by the Mark-II irradiation test bed core. The Mark-II core achieved initial criticality on November 22, 1982. The reactor attained its maximum design output of 100 MWt on March 12, 1983. Since that time, the Mark-II operation has been done and sixteen cycles of rated power operation were conducted until November ,1988.

In the Mark-II core, in order to increase neutron density for irradiation tests, the followings were conducted :

- The number of fuel subassemblies was decreased from 79 to 67.
- The height of driver region was shortened from 60 cm to 55 cm.
- All blanket fuel assemblies were replaced by stainless steel reflectors.
- The plutonium enrichment of driver fuel was increased from 18 wt. % to 30 wt. %.

In addition, the various irradiation rigs which differ from driver fuel subassemblies in the content of fissile materials are loaded for various irradiation purpose. Thus, the Mark-II core has heterogeneity in its core. The main core parameters are given in Table 1. Core configuration, operation history and neutron spectrum at the core midplane are shown in Fig. 1, Fig. 2 and Fig. 3 , respectively.

All of the six control rods are loaded in the row 3, as shown in Fig. 1. Although the Mark-I. core had two regulating rods and four safety rods, all control rods have the same structure and function in the Mark-II core. Every control rod has seven control rod elements, in each of which 90 wt.% ^{10}B enriched B_4C pellets are charged. The height of B_4C pellet stack is 65 cm, and is 10 cm longer than the height of driver region . The nuclear life time of Mark-II control rods is designed as 10 at.% burn-up of

^{10}B . However, in actual Mark-II operation , they are taken out at about 8 at.% burn-up of ^{10}B, because of their mechanical life time. Specification of the control rod is given in Table 2 and its structure is illustrated in Fig. 4.

2. Evaluation of the Control Rod Worth at the Design Stage

2.1. Calculational Method

The reactor constant employed at the design stage was MICS-5.3 set which was a modified ABBN type 26 group constant set. The accuracy of this reactor constant was confirmed by the analysis of the mock-up critical experiment performed at Fast Reactor Critical Assembly (FCA) in Japan Atomic Energy Research Institute.

The control rod worth in the design stage was evaluated on both the virgin core and the equilibrium core. Those core configurations are shown in Table 3 , Fig. 5 and Fig. 1 , respectively. The calculation was made by two-dimensional X-Y triangular mesh, where axial buckling was calculated by two-dimensional R-Z calculation (calculational configuration is shown in Fig. 6).

The calculational codes used to obtain the control rod worths, as shown in Table 4, employed a diffusion equation or a transport equation for neutrons . The adequacy and the reliability are confirmed by the analysis of FCA mock-up critical experiment or the results of the measurement in JOYO Mark-I core.

2.2. Evaluation Scheme

The evaluation scheme of the control rod worths at the design stage was as follows:

(1) The reference value of the control rod worth was calculated from the difference of effective multiplication factor between the core with all control rods inserted and the one with no control rod by two dimensional X-Y (triangular mesh) diffusion theory with seven energy groups.

(2) Correction factors for the reference value were calculated by an one dimensional diffusion theory or an one dimensional transport theory , as described below.

(3) A correction factor was introduced from the difference between calculated value and measured one by FCA mock-up critical experiment. In addition, correction factors by the effect of ^{10}B burn-up and the change in the number of driver fuels in the core were also defined.

(4) Based on the reference value and the above mentioned correction factors, the most probable standard value of the control rod worth , together with its maximum and minimum, was evaluated.

2.3. Correction Factors

(1) Transport theory correction

Transport theory correction was obtained from the comparison of control rod worth obtained by one dimensional 26 groups S_4 calculation and the one by one dimensional 26 groups diffusion theory . The one dimensional calculation was adopted for a cylindrical model in which control rod was loaded in the core center. Control rod worth by diffusion theory is in overestimation as large as about 9 % compared with the one by the transport theory .

(2) Heterogeneity effect correction

Heterogeneity effect correction was applied for the homogenized reference calculation due to the heterogeneous structure of control rods , separating the absorber material and the other materials (stainless steel and sodium) in the calculational model . Control rod worths by the homogeneous theory are in overestimation as large as about 7 % compared with the heterogeneous one .

(3) Residual reactivity effect correction

Residual reactivity effect correction was induced by the reactivity effect of the control rod at fully withdrawal position. This effect is in underestimation for control rod worths as large as 1 %.

(4) Mesh size correction

In the reference calculation were used 6 triangular meshes per a subassembly. The correction factor was evaluated by detailed mesh calculation (24 triangular meshes per a subassembly). Control rod worth of the reference calculation is in underestimation as large as 3 % compared with the detailed one.

(5) Other corrections and design margin

As the result of the analysis for FCA mock-up critical experiment, in which was used the same calculation method as design one, the ratio of the calculation and the experiment (C/E) was 0.925 . Thus, the correction factor by this effect for the evaluation of standard value and maximum one is assumed 1.08 .

On account of decreasing of ^{10}B content according to the burn-up, the control rod worths decrease. For the decrease of ^{10}B content which corresponds to the maximum burn-up of control rod, control rod worths decreased 15 %. Accordingly the ^{10}B burn-up correction factor is 0.85 . At the evaluation of maximum value of control rod worth and the standard one, 1.0 and 0.92 are assumed as the correction factor, respectively.

Change in control rod worth due to the loading of additional five driver fuel subassemblies to the core was about 1 %. Thus the effect of core size to the control rod worth is small.

Finally, as the design margin of the control rod worths, the following items were considered :

o Fabrication error of B_4C pellet	about	2 %
o Error of measured value in FCA critical experiment	about	5 %
o Error due to the difference of configuration between FCA and JOYO	about	8 %

Summing up the above items, the design margin was estimated about 15 %. Thus, for the evaluation of the maximum value of the control rod worth and the minimum one, 1.15 and 0.85 are adopted as the correction factor, respectively.

2.4. Results of the Evaluation

The evaluated results of control rod worths by the above mentioned calculational method are as follows :

- o Reference value of control rod worths are shown in Table 5.
- o Correction factors are shown in Table 6. Sum of correction factors is 0.866 to standard value, 1.105 to maximum value and 0.623 to minimum one, respectively, and the results are shown in Table 7.
- o Stroke curve is shown in Fig. 7 and the maximum gradient of this curve is 2.4×10^{-3} /mm.

3. Measurement of Control Rod Worths

3.1. Measurement Methods

In JOYO, the measurements of control rod worths have been carried out at the beginning of each cycle, using both period method and neutron source multiplication method.

The methods are as follows :

(1) Period method

- Plant condition :
  - o Temperature of primary cooling system is about 250 $^{\circ}C$.
  - o Flow rate of primary cooling system is about 2520 m^3/h (rated flow rate).
- Measurement method :
  - o The change of neutron flux caused by withdrawal and insertion of the control rod is measured.

o By use of the measured values, the following inhour equation is solved and the control rod worth is obtained at real time.

$$\rho = \frac{\ln 2 \cdot \Lambda}{T_D} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i \cdot T_D / \ln 2}$$

where

ρ	:	added reactivity ($\Delta k/k$)
T_D	:	doubling time (s)
		(= $\ln 2 \cdot T_p$; T_p : period (s))
Λ	:	neutron generation time (s)
		(= lp / k eff , lp : life time of prompt neutron (s))
λ_i	:	decay constant of group i delayed neutron precursor
β_i	:	effective fraction of group i delayed neutron

Usually, the measurement is carried out only the movable range of control rod during rated power operation. So that, the stroke curves and total control rod worths are obtained by extrapolation.

(2) Neutron source multiplication method

Plant conditions are the same as those of period method and the reactor is kept a critical point at all the control rod stroke even. From this condition, measurements of the counting rate of neutron are made with one control rod fully inserted in the reactor to get the subcriticality.

Then, control rod worths are calculated by the following equation.

$$\rho_{total} = \rho_{cri} + \rho$$

where

ρ_{total}	:	control rod worth
ρ_{cri}	:	control rod worth at critical point
ρ	:	subcriticality at fully inserted

$$\rho = \frac{C_x}{C} \cdot \Delta \rho_x$$

where

C_x	:	counting rate at insert X mm from critical point
$\Delta \rho_x$	:	difference of reactivity at insert X mm from critical point
C	:	counting rate at fully inserted

3.2. Measured Results and Comparison with Design Values

The measured results are shown in Table 8 and Fig. 8. From this, the ratios of the measured values of period method and neutron source multiplication method are 0.89 ~1.03 .

Average of the worth of all control rods is about 12.0 %Δk/k since 8th operation cycle from which the core is regarded as an equilibrium one. Therefore, average of the worth of one control rod is about 2.0 %Δk/k. Comparing with design value and measured one, the standard value is in overestimation as large as about 5 %. And the minimum value which is employed in the safety analysis is underestimation as large as about 20 %.

The stroke curve in the design stage which was calculated by two demensional R-Z geometry diffusion theory and the measured one in the 16th operation cycle are shown in Fig. 9, indicating good agreement.

4. Analysis of Measured Results

The measured control rod worths differ a little from each other in every duty cycle, as shown in Fig. 8 and Table 8. The reasons which cause such small differences are investigated from the point of the views described as follows :

- o The loading of irradiation rigs
- o ^{10}B burn-up of control rod
- o Burn-up effect of surrounding driver fuels

Calculations are made for the measured cores with following conditions :

o Calculation code	:	CITATION , three- dimensional Hex-Z diffusion theory.
o Withdrawal stroke of control rods	:	Full out and 450 mm .
o Number density	:	Actual value taking into account of burn- up.

4.1. The Effect of Loading of Irradiation Rigs

For the purpose of various irradiation tests , some irradiation rigs are loaded in the JOYO Mark-II core. The irradiation rigs used in JOYO are divided into three classes , called UNIS-A, UNIS-B and UNIS-C (see Fig. 10), where the UNIS-A has the maximum amount of fissile materials and the UNIS-B has the minimum one.

Changes in calculated control rod worths when an adjacent driver fuel subassembly of which burn-up is about 15,000 MWd/t is replaced to a new irradiation rig are given in Table 9. The replacements cause slight changes in the control rod worths, giving the minimum value when the UNIS-B is loaded at the adjacent position . For example, the change in control rod worths of CR-6 is shown in Fig. 11 . In this figure, it is also shown that the ratio of calculated value and measured one (C/E) is about 1.0 in each cycle, although a UNIS-B is loaded adjacent to the control rod.

4.2. The Effect of the Decrease of ^{10}B Content due to the Burn-up

The decreased amount of ^{10}B of a control rod due to the burn-up which was resulted through 296 days rated power operation is measured by post irradiation examination (PIE) . The measurement is carried out using both mass spectrometer and ion micro-analyzer. The measured results are given in Table 10, Table 11, and Fig. 12.

On the other hand, the decreased amount of ^{10}B is calculated by three dimensional Hex-Z diffusion theory, as shown in Table 12 and Fig. 12 . The measured values by the PIE and the calculated ones are in good agreement . The difference between them at the position of maximum burn-up is about 10 % .

In addition, the change in control rod worth by the decrease of ^{10}B content is calculated by three dimensional Hex-Z diffusion theory. As the result of this calculation , the control rod worth decreases by about 2.3 % when the ^{10}B content decreases about 5 at.% . At the present time, the life time of the control rods is about 8 at.% in JOYO. Consequently, the effect of the decrease of ^{10}B content on a control rod worth is small.

4.3. Burn-up Effect of Surrounding Driver Fuels

Control rod worths seem to be changed by the effect of heterogeneity of the core configuration which is introduced by the partial loading of fresh fuels. The effect is calculated by three dimensional Hex-Z diffusion theory, and it is found that control rod worths decrease by 1.1 % when the burn-up of surrounding six driver fuel subassemblies is increased by 10,000 MWd/t. Fig. 13 shows the comparison of the calculated values and the measured ones for this effect. It is clarified that this effect causes larger change in the control rod worths than the effect by the decrease of ^{10}B content does.

By the result of analysis, the changes in control rod worth caused by both the effect of heterogeneity of the local core configuration and the decrease of ^{10}B content are found out to be small. However, it is considered that the distribution of neutron flux which is dominating factor for the control rod worth is more dependent on the core configuration of JOYO than above mentioned factors, because the Mark-II core is a small core.

5. Conclusion

The principal results obtained are as follows :

- o The standard value of the control rod worths is in overestimation as large as about 5 %.
- o The minimum value of the control rod worths in the design stage which is employed in the safety analysis is in underestimation as large as about 20 %.
- o The stroke curve of the control rod worths calculated by two dimensional R-Z diffusion theory is in good agreement with the measured one.
- o The difference between calculated result of the change in control rod worth caused by the decrease of ^{10}B content and the measured one is small. The calculated values and the measured one are also in good agreement.
- o The difference between calculated amounts of the changes in the control rod worth by the effect of the heterogeneity of the core configuration which is introduced by the loading of fresh fuels and irradiation rigs and measured ones in each cycle is small. It is considered that the distribution of neutron flux is intensively dependent on the core configuration, because the Mark-II core is a small core.

Table 1 Main Core Parameters of JOYO

Description		MK-I First	MK-I Second	MK-II
Reactor Power	MWt	50	75	100
Primary Coolant Flow Rate	t/h	2,200	2,200	2,200
Reactor Inlet Temperature	°C	370	370	370
Reactor Outlet Temperature	°C	435	470	500
Core Stack Length	cm	60	60	55
Core Volume (max.)	l	294	304	250
Liniar Heat Rate (max.)	W/cm	210	320	400
Fuel Pin Diameter	mm	6.3	6.3	5.5
Fuel Pin Number/One Subassembly		91	91	127
Height of Axial Blanket Fuel	cm	Upper 40 Lower 40	Upper 40 Lower 40	— —
Height of Axial Reflector	cm	—	—	30
$PuO_2/(PuO_2+UO_2)$	w/o	~18	~18	~30
U^{235} Enrichment	w/o	~23	~23	~18
Location of Blanket S/As	row	5~9	5~9	—
Location of Reflectors	row	10	10	Inner 5~6 Outer(A)7~9 Outer(B) 10
Neutron Flux (max.)	$n/cm^2/s$	2.1×10^{15}	3.2×10^{15}	5.1×10^{15}
Neutron Flux (Core av.)	$n/cm^2/s$	1.4×10^{15}	2.0×10^{15}	3.7×10^{15}
Number of Control Rods		Safety Rod 4 Reg. Rod 2	Safety Rod 4 Reg. Rod 2	Control Rod 6
Max. Burn-up (pin av.)	MWd/t	25,000	42,000	75,000
Days of a Duty Cycle Operation	d	45	45	70

Table 2 Specification of MK-II Control Rod

Control Rod	
Overall Length	2,250 mm
Outer Diameter of wrapper tube	64.7 mm
Number of Control Rod Elements	7
Absorber Material	
Type	B_4C Hot-Pressed Pellet
Pellet Diameter	16.3 mm
Height of a Pellet	25.0 mm
Height of B_4C Stack	650 mm
Pellet Density	2.14 g / cm^3
^{10}B Enrichment	90 w/ o

Table 3 Core Configuration of Virgin Core and Equilibrium Core

Core Component	Virgin	Equilibrium
Driver Fuel Subassembly	54	61
Control Rod	6	6
Reflector	246	239
Neutron Source	1	1
UNIS*1	3	3
MIR*2	3	3

*1 : Uninstrumented Irradiation Subassembly
*2 : Materials Irradiation Rig

Table 4 Examples of Calculation Codes for Control Rod Worth

Calculation Codes	Application
One Dimensional Diffusion Theory	Few - Groups Effective Cross Section
Two Dimensional Triangular Mesh Diffusion Theory	Standard Calculation of Control Rod Worth
One Dimension Transport Theory	Calculation of Correction Coefficient
Two Dimension X-Y and R-Z Geometry Diffusion Theory	Calculation of Axial Buckling

Table 5 Reference Value of Control Rod Worth

	Control Rod Worth
Virgin	0.148
Equilibrium	0.147

Table 6 Correction Factors for Control Rod Worth Calculation

Correction Item		Correction Factor		
		Minimum	Standard	Maximum
Correction in Calculation	Transport (S_4)	0.91	0.91	0.91
	Heterogeneity Effect	0.93	0.93	0.93
	Residual Reactivity Effect	1.00	1.00	1.01
	Mesh Effect	1.03	1.03	1.03
	Subtotal	0.87	0.87	0.88
Mock-up Test		1.00	1.08	1.08
^{10}B Burn-up		0.85	0.92	1.00
Core Size Effect		0.99	1.00	1.01
Design Margin		0.85	1.00	1.15
Total		0.623	0.866	1.105

Table 7 Corrected Value of Control Rod Worth

($\Delta k/k$)

	Virgin	Equilibrium
Minimum	0.0921	0.0914
Standard	0.128	0.127
Maximum	0.163	0.162

Table 8 Control Rods Worths and Core Configurations at Each Operation Cycle

Cycle No.	Total C / R Worth			Core Configuration			
	Calculated	P.M.*1	N.S.M.M.*2	Driver	UNIS-A	UNIS-B	UNIS-C
0	12.53	12.37	13.03	64	0	2	0
1	11.85	11.66	13.12	63	0	1	1
2	11.85	11.83	13.13	64	0	1	1
3	11.97	11.93	13.02	63	0	1	2
4	12.21	12.38	12.80	64	0	1	2
5	11.93	11.83	12.71	64	1	1	1
6	11.86	11.91	12.78	64	1	1	1
7	11.81	11.67	12.21	64	1	1	1
8	12.02	12.01	12.15	63	1	1	2
9	12.06	12.03	11.86	63	0	1	3
10	12.00	12.19	12.02	63	0	1	3
11	11.83	11.96	11.88	64	0	0	3
12	11.73	11.96	12.02	65	0	0	2
13	11.68	12.20	12.32	65	0	0	1
14	11.99	12.37	12.14	65	1	0	1
15	11.99	12.24	11.94	64	1	1	1
16	12.15	12.37	12.22	63	1	1	2

*1 : Period Method

*2 : Neutron Source Multiplication Method

Table 9 Calculational Results

Condition	Change of Control Rod Worth
270 EFPD (Burn-up of ^{10}B : ~6 at.%)	-2.7%
Driver Fuel Adjacent to Control Rod being replaced by Test Subassembly	
UNIS - A	-0.1%
UNIS - B	-3.6%
UNIS - C	-1.9%

Table 10 ^{10}B Burn-up Measured by Mass Spectrometer

Axial position (mm) (From Bottom of B_4C Stack)	^{10}B Burn-up (%)	
	Spe.No. PIN-01	Spe.No. PIN-01
12	---	6.11
24	7.02	---
110	4.41	---
300	1.96	---
317	---	1.18
505	1.08	---
640	0.927	---

Table 11 ^{10}B Burn-up Measured by Ion Microanalyzer

Axial Position (mm) (From Bottom of B4C Stack)	^{10}B Burn-up (%) Spe.No. Pin-01
12	7.24
98	5.71

Table 12 ^{10}B Burn-up Calculated by Three Dimensional Hex - Z Diffusion Theory

Axial Position (mm) (From Bottom of B_4C Stack)	^{10}B Burn-up (%)
25	7.94
75	5.58
125	4.32
175	3.34
225	2.83
275	2.13
325	1.70
375	1.25
425	0.87
475	0.27

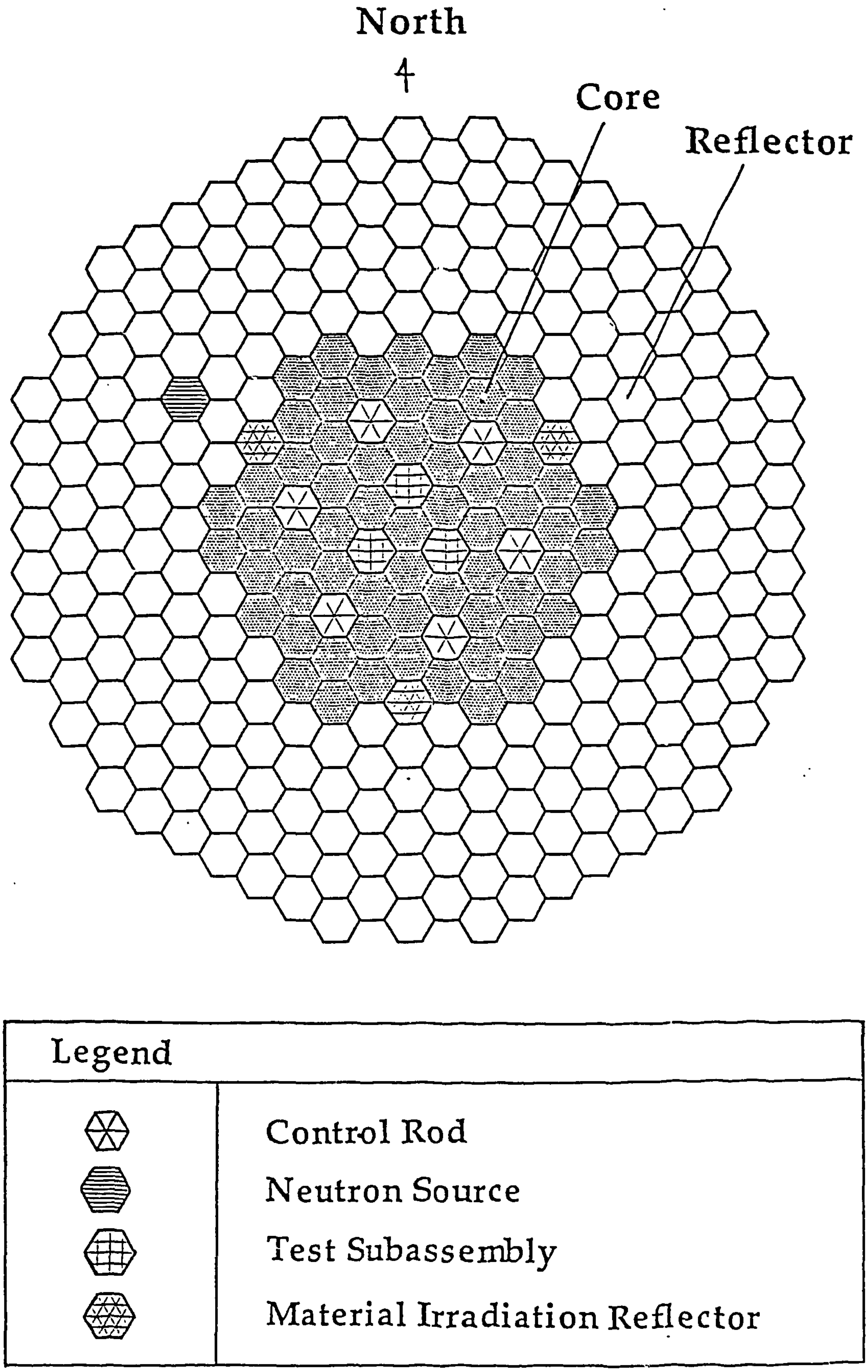


Fig. 1 MK-II Equilibrium Core

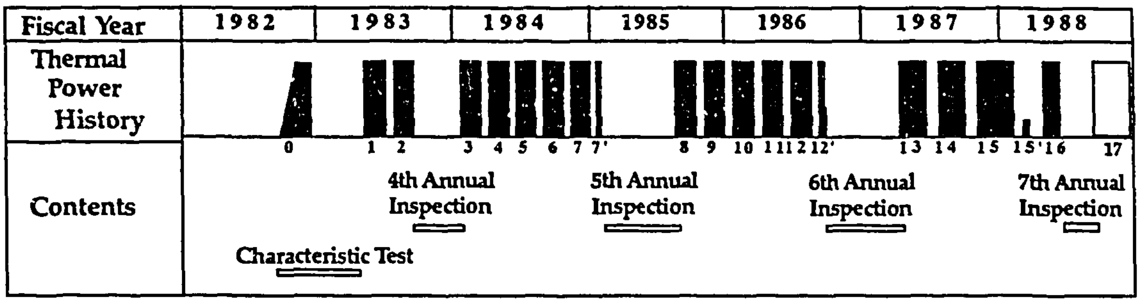


Fig. 2 Operation History of JOYO

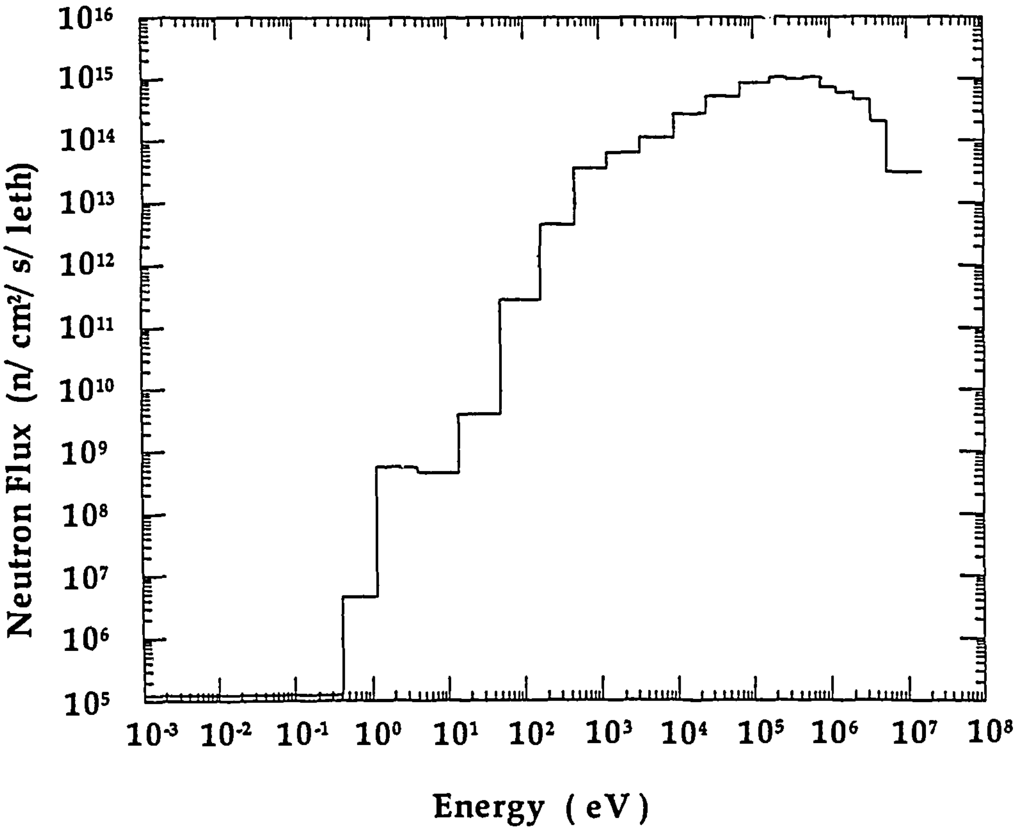
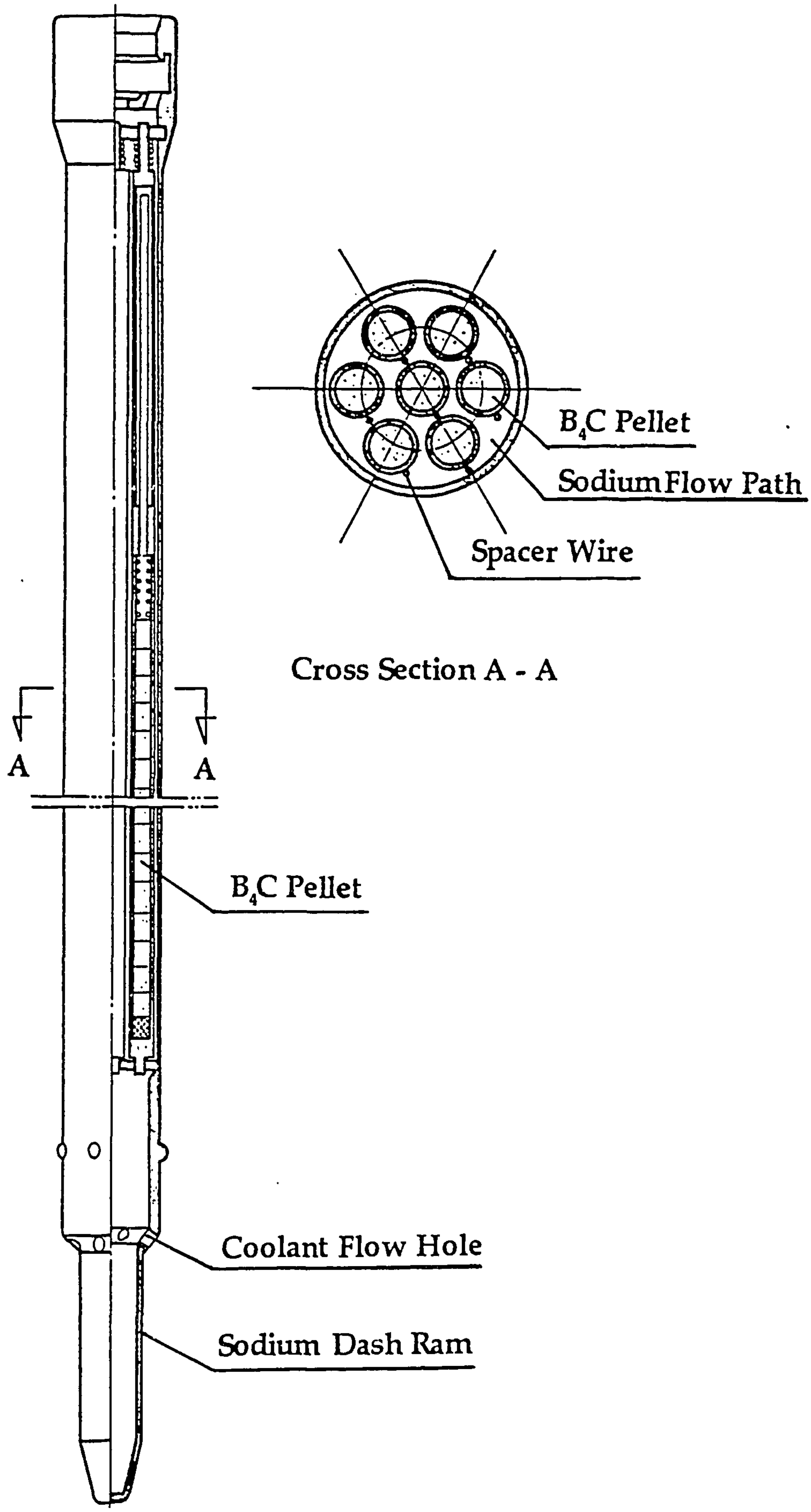


Fig. 3 Neutron Spectrum at The Core Midplane



Control Rod

Fig. 4 Structure of Control Rod

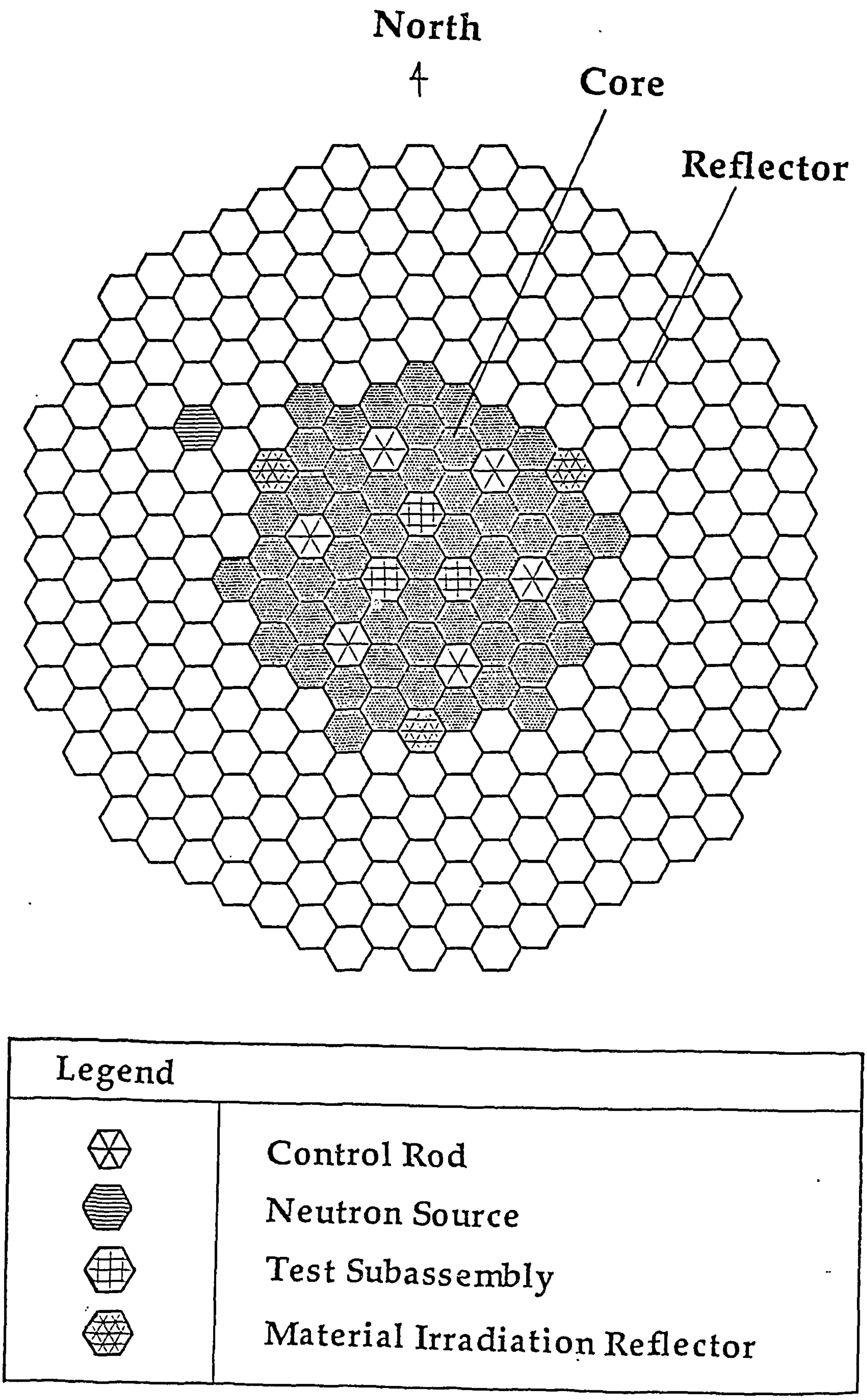


Fig. 5 MK-II Virgin Core

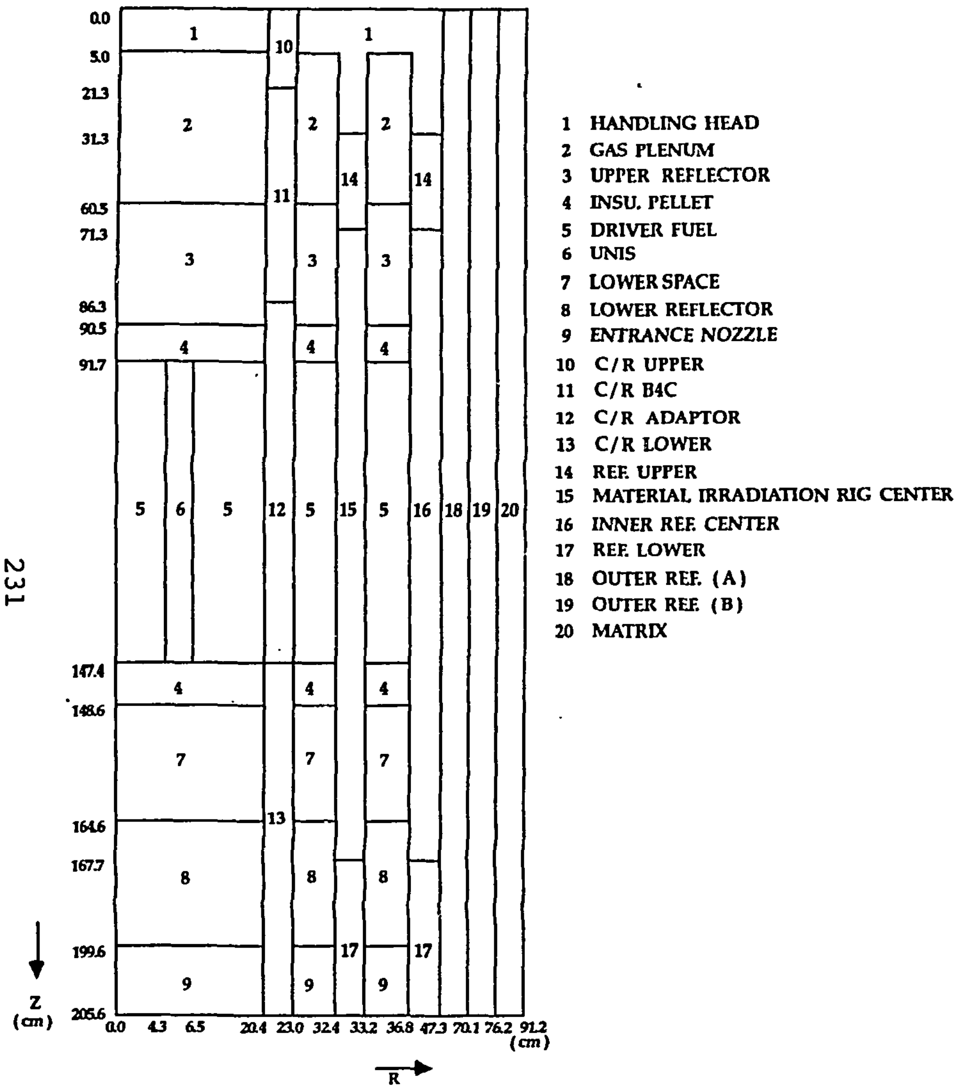


Fig. 6 Calculational Configuration of Equilibrium Core

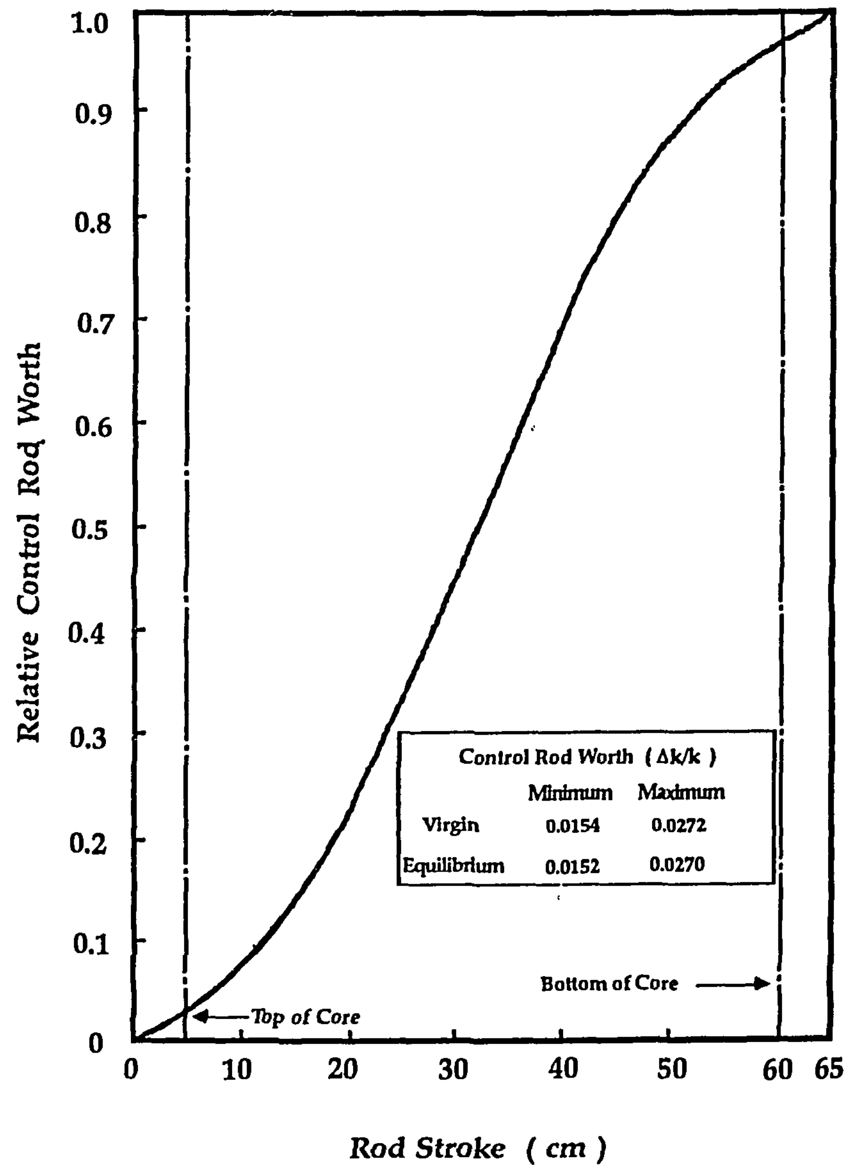


Fig. 7 Stroke Curve

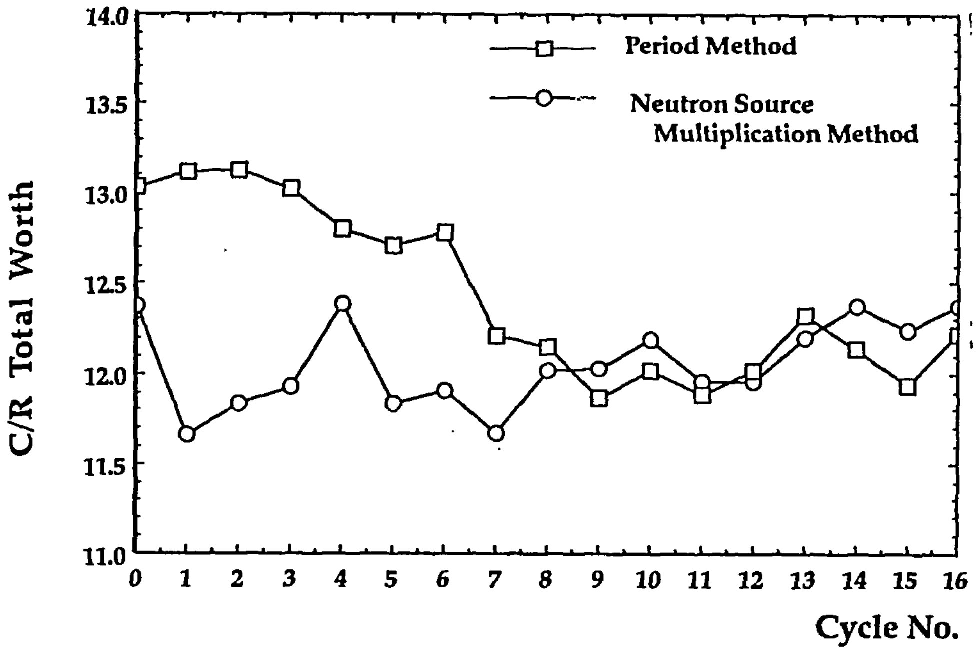


Fig. 8 Measured Results of Control Rod Worth

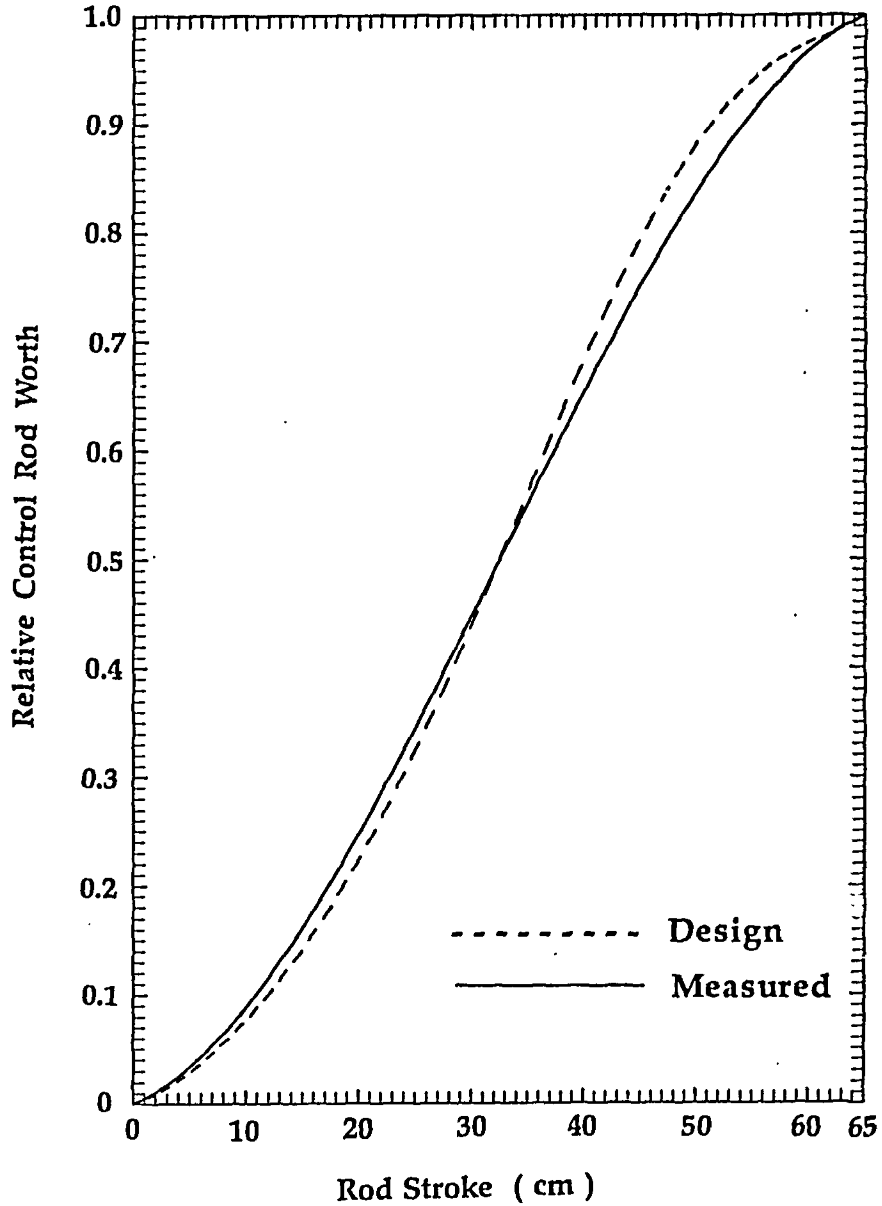
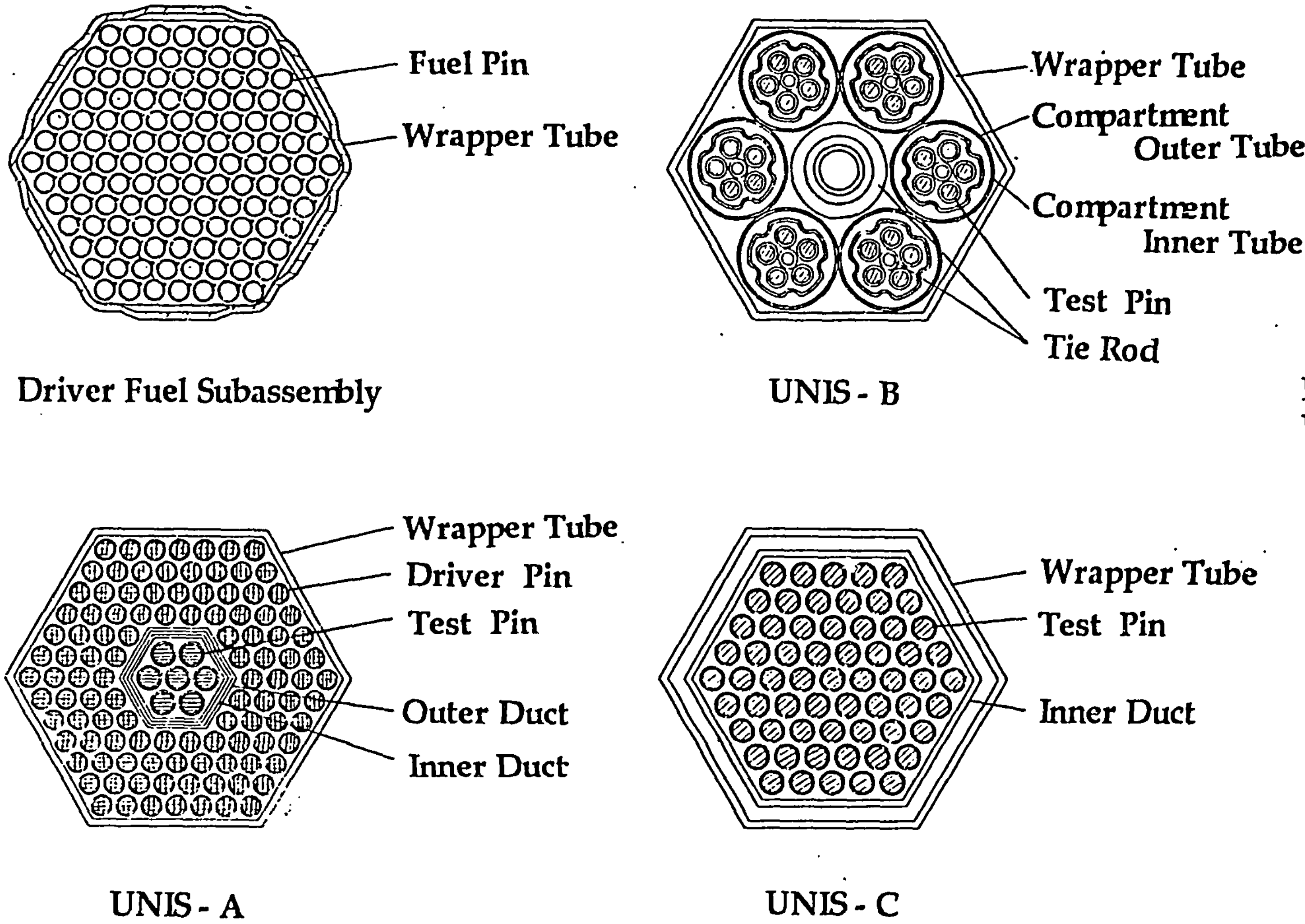


Fig. 9 Comparison of Design and Measured Stroke Curve



Fissile material Inventory of UNISs to Driver's one Ratio

UNIS-A	~ 90%
UNIS-B	~ 30%
UNIS-C	~ 60%

Fig. 10 Cross Sections of Subassemblies

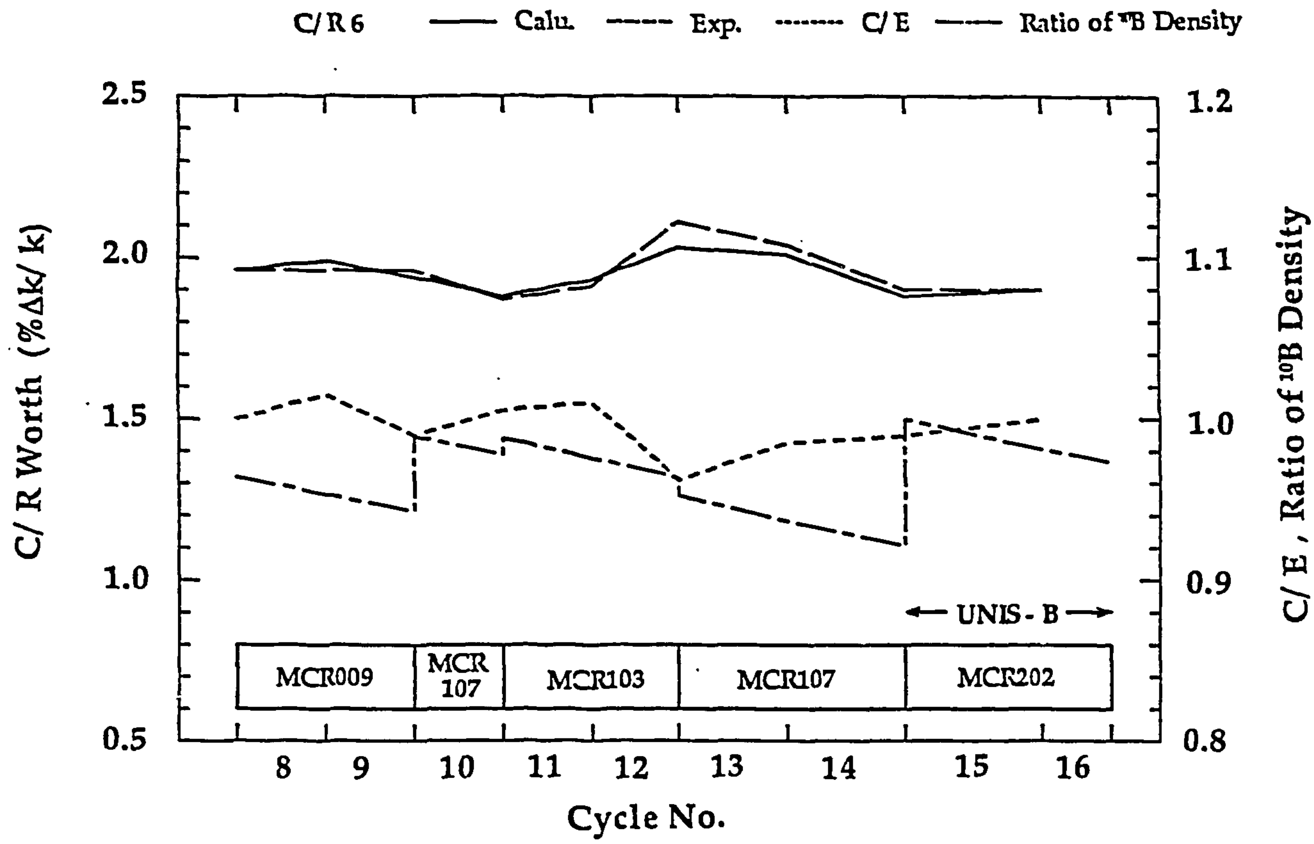


Fig. 11 Change of Control Rod Worth upto 7th Cycle Operation Run

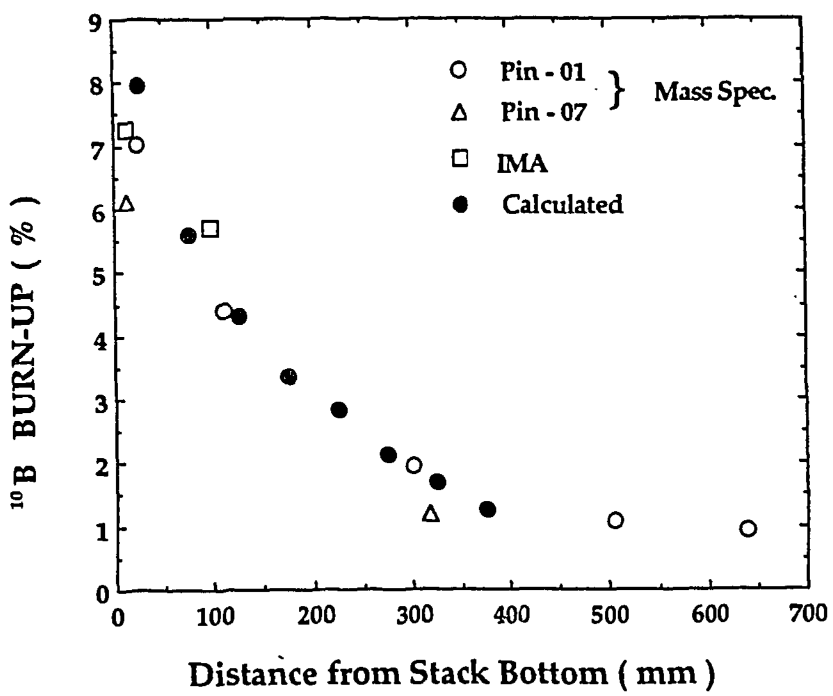


Fig. 12 Burn-up of Control Rod

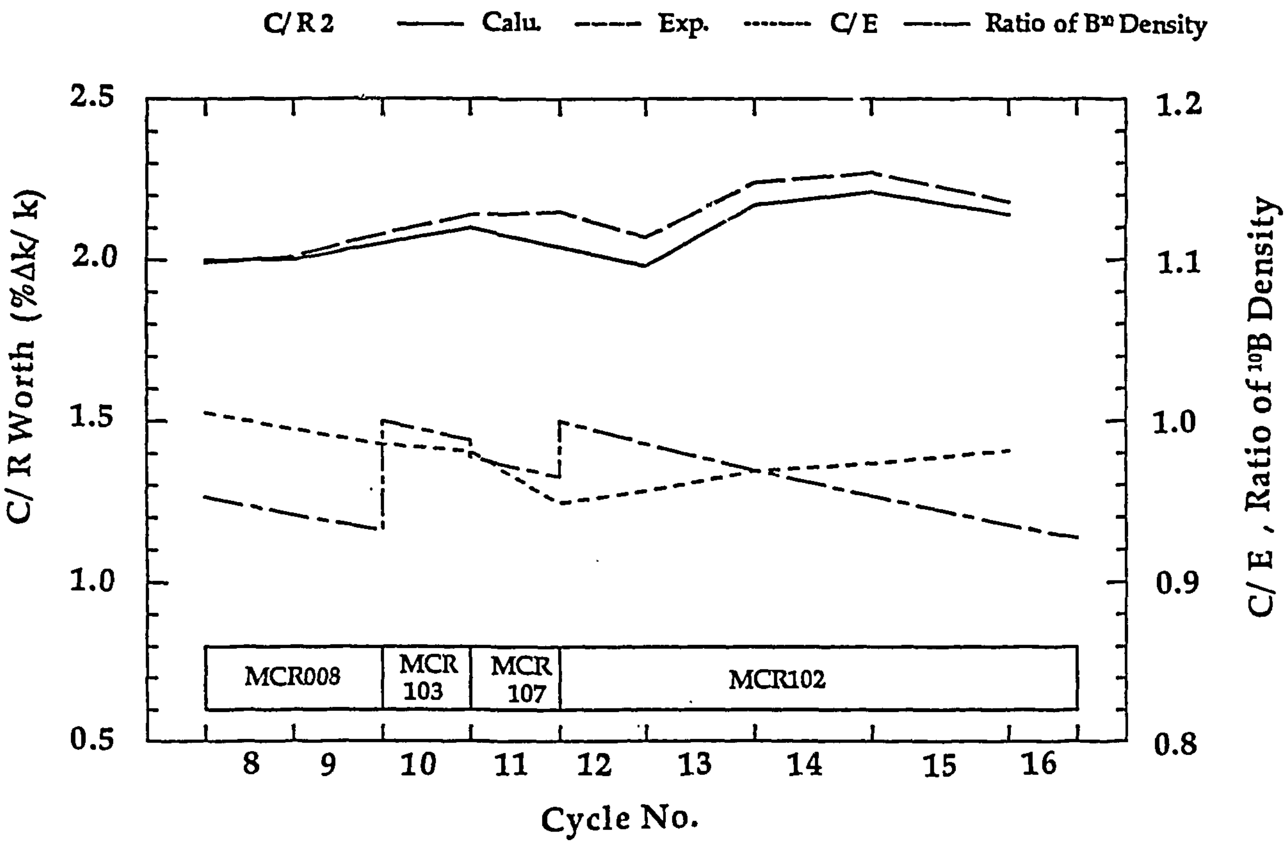


Fig. 13 Change of Control Rod Worth upto 7th Cycle Operation Run