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Physics And Control Of Pu-fueled Heavy Water Reactor FUGEN

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Abstract

The core physics of Pu-fueled FUGEN reactor is discussed with emphasis on the reactivity coefficients. Of the isotopes of Pu fuel, Pu-239 and Pu-241 are found to reduce coolant void reactivity, and Pu-240 to reduce fuel temperature coefficient. From the physics aspect of the core, reactor control and refueling problems are briefly discussed and evaluations are performed.

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I. Introduction

FUGEN is a heavy water moderated, boiling light water cooled, pressure tube type power reactor designed to generate 165 MWe, now under development by PNC of Japan. The outlook of this reactor is very similar to the CANDU-BLW(1), but several modifications are tried with special emphasis on reactor stability and fuel cycle.

The reactor is specially characterized by the use of plutonium fuel from the initial core, since it is of special interest for fuel cycle and also it is expected to have a favorable effect on coolant void reactivity. Another important feature of the reactor is in its reactor control system which employs a number of control rods together with the help of in core nuclear instrumentations for spatial power monitoring.

The physics aspect of the reactor is discussed in this paper in related to the use of Pu fuel with special interest on reactivity coefficients. Some of the introductory discussions will also be given about reactor control and refueling problems.

II. Outline of FUGEN Reactor

The reactor employs 28 rod fuel assembly as shown in Fig. 1, and 224 assemblies of such fuel are arranged in square array of 24 cm pitch to make an effective core of 4.0 m in diameter and 3.7 m in height. The central 96 fuel assemblies of the initial core contain plutonium enriched oxide fuel, i.e., a mixture of PuO_2 - UO_2, and the surrounding 128 assemblies contain slightly enriched UO_2 fuel. The ratio of moderator to oxide volume is approximately 8.0 and it is equal in both regions. The Pu-enriched fuel is expected to be used for refueling, but slightly enriched UO_2 can also be considered.

Another important feature of FUGEN reactor from the physics view point is that the reactor control system employs many in-core neutron monitors and 49 control rods. This control system will be effective in power mapping of the reactor, using an on-line process computer. It should be noted that FUGEN especially needs such as system to monitor burn up and refueling with Pu enriched fuel.

The core configuration with the initial loading pattern is illustrated in Fig. 2.

III. Physics of Pu-fueled FUGEN Core

In the original design of FUGEN, it was planned to employ 1.5% enriched UO_2 fuel from the beginning. In this design evaluation, the coolant void (loss of coolant) reactivity of the initial core was expected to be positive over the range of 1.5 - 2.0% $\Delta K/K$, but this gave a number of difficult problems from the safety aspect of the reactor. In order to diminish positive void reactivity and possibly even to make it negative, the use of plutonium fuel in the form of PuO_2 - UO_2 mixture came to be considered in the most recent design of the FUGEN reactor.

Briggs and Johnston, et al.[2] have shown an experimental evidence that the use of Pu fuel contributed to reducing the positive void coefficient, but there is little other experimental evidence to confirm such behavior of Pu fuel. Kato et al.[3] reported the result of numerical investigations on the effects of Pu on coolant void reactivity of the FUGEN core. In this paper, some more detailed physical behavior of Pu fuel will be discussed together with related problems on reactor control.

For numerical analyses, three nuclear calculation codes, CLUSTER-IV[4],[5] METHUSELAH-II[6] and MINI-WIMS[7] have been compared. The calculations by the MINI-WIMS code were carried out in the United Kingdom based on our input specification.

Two standard fuels are under consideration, 0.75 w/o Pu enriched PuO_2 - UO_2 and 1.5 w/o enriched UO_2. It is pointed out that the choice of Pu enrichment roughly matches 1.5% enriched UO_2, and thus avoiding undesirable power peaking when a two region core is made with these two fuels. The input data for the two fuel lattices are briefly shown in Table 1.

Table 1. Input specifications

Fuel Assembly

(i) 28 rod fuel assembly in 3 rings

Ring	No. of rods	Pitch circle radius of fuel rod centers (cm)
1	4	1.32
2	8	2.96
3	16	4.76

(ii) Fuel rod

Zone	I.D. (cm)	O.D. (cm)	Material	Density (g/cc)	Temperature (°C)
Fuel pellet	---	1.447	UO_2-PuO_2, UO_2	10.27	600
Void space	1.447	1.478	Void	---	---
Sheath	1.478	1.646	Zry-2	6.57	300

(iii) Isotopic composition of standard fuel

Isotope	Weight fraction in fuel (*) PuO_2-UO_2	UO_2
U-235	0.006221	0.013222
U-238	0.868695	0.868266
Oxygen	0.118467	0.118512
Pu-239	0.003838	----
Pu-240	0.001588	----
Pu-241	0.000926	----
Pu-242	0.000255	----

(iv) Structural tie rod

Four tubes of Zircaloy-2 (6.57 g/cm^3) with inner radius of 0.28 cm and outer radius of 0.35 cm are located on the ring with radius of 3.44 cm.

(v) Fuel channel

Zone	I.D. (cm)	O.D. (cm)	Material	Density (g/cc)	Temperature (°C)
Pressure tube	11.78	12.64	Zr-2.5w/o Nb	6.57	285
CO_2 gap	12.64	14.94	CO_2	---	170
Calandria tube	14.94	15.24	Zry-2	6.57	60

(vi) Moderator

D_2O (99.65 mol %), 60°C, 1.090 g/cc, 10 PPM B^{10}

(vii) Others

Channels on square lattice pitch of 24.0 cm

Coolant(*) temperature of 285°C

Assume bare core, axial buckling = 0.587×10^{-4} cm^{-2}

radial buckling = 1.166×10^{-4} cm^{-2}

Note: (*) The Pu fuel is the one released from the BWR.
(**) Coolant material, H_2O.

(1) Overall effect of Pu enrichment on coolant void reactivity

The survey calculations by METHUSELAH-II for the fuel lattices considered in FUGEN showed that Pu fuel is effective for reducing positive void coefficient, and with higher Pu enrichment, it would possibly become negative. The results of these, shown in Fig. 3, reveal that 0.75 w/o Pu enriched oxide fuel is more effective in producing this tendency than 1.5 w/o enriched uranium oxide, although these two fuels are approximately equal in fissile content.

The Pu fuel considered here has the isotopic contents to be expected from irradiated BWR fuel, and it is important that the way each isotope contributes to this result be understood. So, the spectral behavior of neutrons will be investigated along with void condition as related to neutron cross section characteristics, and the result is discussed in the following sections.

(2) Neutron spectrum behavior with coolant void fraction

It is commonly believed that the neutron energy spectrum in a reactor will become harder with increasing void fraction in the medium, but such a general belief does not always appear to be true in a FUGEN type reactor.

The thermal neutron spectrum, calculated by CLUSTER-IV, for the 0.75 w/o Pu enriched PuO_2-UO_2 and 1.5 w/o enriched UO_2 lattices are shown in Fig. 4 and 5. These fuel lattices will hereafter be simply referred to simply as 0.75 Pu and 1.5 U lattices. Is is interesting to note that the thermal neutron spectrum in the fuel is rather softer in the case of loss-of-coolant, and this tendency is more evident in a 0.75 Pu lattice, but in the heavy water moderator the spectrum is seen to be somewhat harder in both cases with increasing cooland void fraction.

From the view point of physics, it is understood from this spectral behavior that thermal neutrons, mostly generated in the moderator region, more easily penetrate into the fuel bundle in the case of loss-of-coolant, and the softer part of the energy spectrum increases. It is also noted that the light water coolant in this type of reactor behaves as an absorber rather than as a moderating or slowing down material.

To easily understand spectral behaviors such as this, the spectral indices S_1 and S_2 are defined in the following:

$$S_{1x} = \frac{\int_{\vec{r}\epsilon x} d\vec{r} \int_{Ec}^{\infty} dE\phi(\vec{r}, E)}{\int_{\vec{r}\epsilon x} d\vec{r} \int_{0}^{Ec} dE\phi(\vec{r}, E)} \qquad (1)$$

$$S_{2x} = \frac{\int_{\vec{r}\epsilon x} d\vec{r} \int_{E_1}^{Ec} dE\phi(\vec{r}, E)}{\int_{\vec{r}\epsilon x} d\vec{r} \int_{0}^{E_1} dE\phi(\vec{r}, E)} \qquad (2)$$

In this report, the thermal cut-off energy Ec was chosen as 0.625 eV, and E_1 was 0.14 eV. Hence, S_{1x} is the ratio of fast to thermal neutron fluxes indicating a component of fast neutron flux in region X, and S_{2x} is the ratio of the upper to lower parts of the thermal neutron flux giving its spectral shift behavior.

The spectral indices so far defined have been calculated by two computer codes, CLUSTER-IV and MINI-WIMS, and these were found in very good agreement. The indices obtained in the fuel pellets are shown in Fig. 6, and it is shown that S_1's increase with increasing coolant void, but S_2's decrease under the same conditions. It is also noted that the variation of these indices according to the voiding condition is greater for plutonium fuel than for the uranium. The METHUSELAH-II calculations also supported these general tendencies through the variation of microscopic average cross sections. It is very important that this general behavior of the neutron spectrum be understood, which reveal the way plutonium fuel affects the coolant void coefficient, and these are discussed in detail in the following section.

(3) Four factors

To study each isotopic effect on the coolant void coefficient, the four-factors have been broken down into the following definitions, and their variations with coolant void fraction have been investigated.

$$f = \sum_i f i = \frac{\sum_i \int d\vec{r} \int_0^{Ec} dE \Sigma_a^{i\text{-th fuel}}(\vec{r}, E)\phi(\vec{r}, E)}{\int d\vec{r} \int_0^{Ec} dE \Sigma_a(\vec{r}, E)\phi(\vec{r}, E)}, \qquad (3)$$

$$\eta = \sum_i \eta_i = \frac{\sum_i \int d\vec{r} \int_0^{Ec} dE \nu \Sigma_f^{i\text{-th fuel}}(\vec{r}, E)\phi(\vec{r}, E)}{\int d\vec{r} \int_0^{Ec} dE \Sigma_a^{\text{fuel}}(\vec{r}, E)\phi(\vec{r}, E)}, \qquad (4)$$

$$\varepsilon = 1 + \sum_i \Delta\varepsilon_i = 1 + \frac{\sum_i \int dr \int_{Ec}^{\infty} dE \nu \Sigma_f^{i\text{-th fuel}}(\vec{r}, E)\phi(\vec{r}, E)}{\int d\vec{r} \int_0^{Ec} dE \nu \Sigma^{\text{fuel}}(\vec{r}, E)\phi(\vec{r}, E)}, \qquad (5)$$

$$P = \frac{1}{1 + \sum_i \Delta P_i}, \qquad (6)$$

and $$\Delta P_i = \frac{\int d\vec{r} \int_{Ec}^{\infty} \Sigma_a^{i\text{-th nuclide}}(\vec{r}, E)\phi(\vec{r}, E)}{\int d\vec{r} \int_0^{Ec} dE \Sigma_a(\vec{r}, E)\phi(\vec{r}, E)}, \qquad (7)$$

With these definitions, one also has

$$K_\infty = \varepsilon P \eta f = \frac{\int d\vec{r} \int_0^{\infty} dE \nu \Sigma_f (r, E)\phi(E)}{\int d\vec{r} \int_0^{\infty} dE \Sigma_a(\vec{r}, E)\phi(\vec{r}, E)}, \qquad (8)$$

where $\Sigma_a^{i\text{-th fuel}}$ and $\nu\Sigma_f^{i\text{-th fuel}}$, etc, are the macroscopic cross sections of i-th fuel isotope, and as one can assume, $\sum_i \Sigma_a^{i\text{-th fuel}} = \Sigma_a^{\text{fuel}}$ and $\sum_i \nu \Sigma_f^{i\text{-th fuel}} = \nu \Sigma_f^{\text{fuel}}$ etc.

The so far defined four factors, calculated by CLUSTER-IV, MINI-WIMS and METHUSELAH-II, are compared and shown in Figs. 7 to 10. As one observes, these calculations are in good agreement with each other showing similar tendencies with respect to variations of the void fraction, and this behavior of the four factors is understandable when one considers the spectral behavior discussed earlier. Some of the important discussions are briefly summarized below.

(i) It is quite clear that plutonium fuel will contribute to the suppression of positive void reactivity in the FUGEN type reactor, and among its isotopes, Pu-239 would be the one mostly contributing to this result through f and η. This is mainly due to the effect of thermal neutron spectral shift with voiding condition, i.e., spectral softening causes a reduction of the reaction rate near the Pu-239 resonance peak at 0.3 eV.

(ii) Fast fission factors are mostly determined by the non-thermal component of the neutron flux, and they show similar tendencies to the S_1 spectral indices. It should be noted that these fast fission factors defined here include the resonance fissions.

(iii) Although Pu isotopes have some effect on resonance escape probabilities, their effect makes only a fractional contribution, due to the small number in the fuel. This will be discussed in the following section in evaluating resonance integrals with respect to void and temperature change.

(4) Resonance integrals

To understand the effect of resonance absorption of each fissible isotope on void and temperature coefficients, the CLUSTER-IV calculated resonance integrals are listed in Table 2 and 3.

Among the Pu isotopes, Pu-240 has by far the biggest resonance integral mainly due to the giant resonance near 1 eV, but due to the small number in the fuel, the effect is exceeded by U-238 in the evaluation of P as shown in Fig. 10. However, it is worth noting that P-240 accounts for about 20% of total fast neutron absorption, with only 0.16 w/o in the fuel being considered.

The big resonance of Pu-239 at 0.3 eV was not taken into account in evaluating resonance integrals, because it belongs in the thermal energy region. In this report, the level broadening effect of Pu-239 resonance has been neglected because its level width in very broad and the effect seemed, for several reasons, to be small.

Table 2. Resonance integral(*) of each nuclide in 0.75 Pu lattice (barns)

Temperature	Nuclide	0% Void	35% Void	70% Void	100% Void
20°C	U-235		312.3		
	U-238		11.59		
	Pu-239		327.5		
	Pu-240		2,624.-		
600°C	U-235	317.6	316.8	315.5	313.4
	U-238	13.14	12.47	11.59	10.70
	Pu-239	337.7	335.0	331.0	325.3
	Pu-240	2,901.-	2,749.-	2,551.-	2,325.-
1,500°C	U-235		319.6		
	U-238		13.43		
	Pu-239		340.2		
	Pu-240		2,893.-		

(*) Calculated by CLUSTER-IV, and given here in fuel bundle average. These calculations do not include the effect from the 1/v tail.

Table 3. Resonance integrals(*) of each nuclide in 1.5 U lattice (barns)

Temperature	Nuclide	0% Void	35% Void	70% Void	100% Void
20°C	U-235		295.7		
	U-238		11.6		
600°C	U-235	304.7	303.2	300.8	296.8
	U-238	13.13	12.48	11.60	10.70
1,500°C	U-235		308.1		
	U-238		13.43		

(*) Calculated by CLUSTER-IV, and given here in fuel bundle average.

These calculations do not include the effect from the 1/v tail.

(5) Effective microscopic cross sections

The spectrum weighted effective microscopic cross sections will also be a good measure for understanding each isotopic effect on reactivity coefficients.

It was shown in the previous discussions that thermal neutron spectral shift plays a dominant role in varying the coolant void coefficient, and the effective microscopic thermal neutron absorption cross sections will be given here to show each isotopic effect with respect to the void condition. The results of such calculations by CLUSTER-IV are shown in Table 4, from which one might again conclude that Pu-239 and Pu-241 are the two main isotopes which contribute to improving coolant void reactivity.

On the other hand, the fast group effective microscopic absorption cross sections are given in Table 5 to show the isotopic effect on the fuel temperature coefficient, by which one can conclude that U-238 and Pu-240 are the main contributors to the improvement of the fuel temperature coefficient. Needless to say, the result with Pu-240 is mostly due to the giant resonance at around 1 eV energy.

Table 4. Relative variation of effective thermal microscopic absorption cross sections with void conditions (σ_a^{th})

Lattice	Nuclide	0% Void	35% Void	70% Void	100% Void
0.75 Pu	U-235	0.942	1.000 (373 b)	1.016	1.057
	U-238	0.951	1.000 (16.4 b)	1.014	1.049
	Pu-239	1.012	1.000 (1042 b)	0.977	0.938
	Pu-240	0.993	1.000 (197.4 b)	1.013	1.037
	Pu-241	1.007	1.000 (1044 b)	0.993	0.989
	Pu-242	0.995	1.000 (11.8 b)	1.014	1.047

Table 5. Relative variation of effective fast absorption cross sections with fuel temperature condition (σ_a^f)

Lattice	Nuclide	Fuel temperature 600°C	1500°C
0.75 Pu	U-235	1.000 (12.58 b)	0.994
	U-238	1.000 (0.82 b)	1.046
	Pu-239	1.000 (15.25 b)	0.999
	Pu-240	1.000 (83.6 b)	1.057
	Pu-241	1.000 (18.74 b)	0.988
	Pu-242	1.000 (32.9 b)	0.999

IV. Reactor Control System

Another important feature of FUGEN in regard to physics problems is the reactor control system, which employs a number of incore neutron monitors distributed throughout the core, together with three reactivity control methods. For reactivity control, (1) 49 control rods, (2) liquid poison in the moderator, and (3) moderator dump, are considered. The arrangements of these incore neutron monitors and control rods are shown in Fig. 2.

(1) Nuclear instrumentations

The nuclear instrumentations of the FUGEN reactor consist of 4 source monitors, 6 intermediate monitors, and 64 incore power monitors (IPM). The IPM's are located in 16 vertical channels in the core each having 4 monitors at different heights. The IPM's, which can be inter-calibrated by using a transverse incore probe, are to yield data for three dimensional power mapping using an on-line process computer.

Of these 64 IPM's, 16 from each quardrant of the core are grouped to make a region averaged power, with which the zonal power control of the reactor is planned together with the use of control rods. It is worth mentioning that the 16 vertical channels of IPM's are arranged in an asymmetrical manner, but in such a way that they would fill the unoccupies positions in other quardrants if one relocated them in quardrant symmetry.

Such an arrangement of IPM's is especially meaningful when one plans a quardrant symmetrical power control and refueling, since one can thus have 4 times the amount of data to be used for the spatial power mapping.

(2) Reactivity control system

Of the three reactivity control methods mentioned before, the control rod system works as the main reactivity control device, while the liquid poison works to control the long term burn up reactivity in the initial core, and the moderator dump is for shutdown of the reactor to meet safety criteria.

The control rods of FUGEN are of cylindrical shape. about 80 mm in diameter, considered to be black in thermal neutron energy, and containing boron carbide as the neutron absorber. Of the 49 control rods, 4 symmetrical rods from each guardrant are used for automatic zonal power control, another symmetrical 4 rods plus a central one are used for spatial power flattening with respect to long term burn-up of the core, and the remaining 40 rods are for safety shutdown purposes.

This control rod system is used for all reactivity control purposes except to compensate large burn-up reactivity provided in the initial core. The purposes are to provide reactor power control, the flattening of power distribution, normal shut-down of the reactor to cold condition, emergency fast shut-down, and for some other small reactivity adjustments.

V. Refueling Problems

(1) General principle for refueling

Since FUGEN is expected to use Pu enriched oxide for refueling as well as for the initial loading, some complications have to be considered in evaluating refueling problems compared to the use of only U fuel. As for the general principle on which to set up refueling criteria, the following items have been considered in the beginning.

(i) Through the period of transition to equilibrium core, the loss-of-coolant void reactivity must be below set limitation at all times.

(ii) The power coefficient must also be negative.

(iii) The power peaking factor after refueling must be within a set-limitation, with a reasonable margin of error.

(iv) Target burn-up of the fuel must be achieved.

(v) A higher conversion ratio is more desirable.

Some of these requirements are mutually exclusive to each other, but the best refueling sequence has to be found with emphasis on conditions (i) to (iii).

(2) Refueling analyses

Based on the general principles so far discussed, a trial refueling sequence has been sought for the same core discussed in the earlier section. The flow chart of such refueling analyses, developed for FUGEN, is first shown in Fig. 11.

In this method, the refueling sequence is sought basically by trial and error using a three dimensional thermo-nuclear code LAYMON, an improved version of the FLARE code[8] for refueling of the FUGEN reactor. A typical example of refueling calculations is given here.

The basic idea of calculational model and related limitation conditions are briefly described first.

(i) The initial core loading pattern is as shown in Fig. 2.

(ii) In the period prior to the beginning of the first refueling, the fuel continues to burn by removal of the liquid poison from the moderator until it is reduced to zero.

(iii) All refuelings are done with 0.75 PuO_2-UO_2 fuel, and after first refueling, no liquid poison is used.

(iv) Control rod patterns before and after the initial 2,700 MWD/TU of burn-up are as shown in Fig. 13.

(v) Refueling always takes place in 90 degree rotating symmetry, and 4 fuel assemblies are changed at one time.

(vi) Peaking facto $\leq$ 2.13.
(i.e., axial x radial = 1.35 x 1.58)

(vii) MCHFR > 1.9 for both regions.

(viii) MLPD $\leq$ 17.5 KW/ft for inner core.
MLPD $\leq$ 15.8 KW/ft for outer core.

(ix) No fuel shuffling considered.

(x) Maximum period for irradiation $<$ 5 years

(xi) Maximum burn-up of fuel assembly 30,000 MWD/TU

(xii) Maximum burn-up of fuel pellet 40,000 MWD/TU

It is planned to refuel 4 assemblies at one time as any unlimited refueling would soon induce local peaking to exceed thermal limitation. The given method therefore searches for the refueling sequence by trial and error, but based on some simple rules from experiences, in such direction as to seek for the spatial power flattening. An example of searched refueling sequence is shown in Fig. 12, and some of the related parameters are illustrated in Table 6 - 7. Those shown in Table 6 are the main parameters during the period of liquid poison removal, and those in Table 7 are the parameters after start up

TABLE 6 MAIN PARAMETER FOR REFUELING SEQUENCE (I) PAGE 1.

NO.	TAPE LABEL	P.F.C I	P.F.C J	EIGENVALUE LAMBDA	EIGENVALUE DEL*	D. W DAYS	D. W DEL	EXP. GWD/TU	PEAK POWER VALUE	I	J	K	MCHFR VALUE	I	J	K	MLPD KW/F	ORIFICED CHANNEL POWER	I	J	K	KW/F
	RODIN-01			1.010700		0.0	0.		2.018	3	4	7	2.16	3	4	8	16.42	0.925	1	8	8	7.53
	RODIN-02			1.000000		29.7	30.		1.938	3	4	7	2.26	3	4	8	15.77	0.931	8	1	8	7.57
	RODIN-03			1.010087		29.7	0.		1.930	3	4	7	2.27	3	4	8	15.70	0.958	1	8	8	7.79
	RODIN-04			1.000021		58.6	29.		1.858	4	4	7	2.38	4	4	8	15.12	0.958	1	8	8	7.79
	RODIN-05			1.010066		58.6	0.		1.852	4	4	7	2.39	4	4	8	15.07	0.991	1	8	8	8.06
	RODIN-06			1.000007		88.7	30.		1.789	4	4	7	2.48	4	4	8	14.56	0.988	1	8	8	8.04
	RODIN-07			1.010058		88.7	0.		1.777	4	4	7	2.50	4	4	8	14.46	1.026	1	8	8	8.35
	RODIN-08			1.000009		120.0	31.		1.722	4	4	7	2.59	3	5	9	14.01	1.022	1	8	8	8.32
	RODIN-09			1.010055		120.0	0.		1.703	4	4	7	2.62	3	5	9	13.85	1.064	1	8	9	8.66
	RODIN-10			1.000002		152.6	33.		1.655	4	4	7	2.69	3	5	9	13.46	1.060	1	8	9	8.62
	RODIN-11			1.009702		152.6	0.		1.629	4	4	7	2.73	3	5	9	13.26	1.104	1	8	9	8.98
	RODIN-12			1.000009		185.0	32.		1.587	3	5	7	2.79	1	6	10	12.92	1.096	8	1	9	8.91
	RODIN-13			1.010177		185.0	0.		1.606	1	3	8	2.63	1	3	11	13.07	0.925	1	8	9	7.52
	RODIN-14			1.000011		217.6	33.		1.533	1	3	9	2.74	1	3	11	12.47	0.931	1	8	9	7.57
	RODIN-15			1.009956		217.6	0.		1.481	1	3	9	2.87	1	3	11	12.05	0.976	8	1	9	7.94
	RODIN-16			1.000006		251.3	34.		1.420	1	3	9	2.99	1	3	12	11.55	0.983	1	8	10	8.00
	RODIN-17			1.009944		251.3	0.		1.390	4	4	7	3.15	1	4	12	11.31	1.033	1	8	10	8.40
	RODIN-18			1.000000		286.5	35.		1.368	5	3	7	3.19	1	6	12	11.13	1.035	1	8	10	8.42
	RODIN-19			1.009937		286.5	0.		1.343	3	5	6	3.22	1	6	12	10.93	1.087	1	8	10	8.84
	RODIN-20			0.999954		323.3	37.		1.330	3	5	6	3.25	1	6	12	10.82	1.084	8	1	10	8.82
	RODIN-21			1.009951		323.3	0.		1.301	1	6	6	3.29	1	6	12	10.59	1.136	1	8	10	9.24
	RODIN-22			0.999970		361.1	38.		1.289	1	6	6	3.32	1	6	12	10.49	1.128	1	8	10	9.18
	RODIN-23			1.006578		361.1	0.		1.275	1	6	6	3.35	1	6	12	10.38	1.151	1	8	11	9.36
	RODIN-24			0.999988		386.7	26.		1.268	1	6	6	3.37	1	6	12	10.32	1.155	1	8	11	9.39

P.F.C = POSITION OF FUEL CHANGE
D . W = THE DAYS OF WORKING .
* = PERCENT

TABLE 7 MAIN PARAMETER FOR REFUELING SEQUENCE (2) PAGE 2.

NO.	TAPE LABEL	P.F.C I	P.F.C J	EIGENVALUE LAMBDA	EIGENVALUE DEL*	D. W DAYS	D. W DEL	EXP. GWD/TU	PEAK POWER VALUE	I	J	K	MCHFR VALUE	I	J	K	MLPD KW/F	ORIFICED CHANNEL POWER	I	J	K	KW/F
1	RF-PU-01	2	4	1.006063		386.7			1.546	2	5	6	2.80	2	5	11	12.58	1.123	2	8	10	9.14
				0.999976	0.61	409.8	23.		1.548	2	5	6	2.80	2	5	11	12.59	1.117	2	8	10	9.09
2	RF-PU-02	4	2	1.002773		409.8			1.535	2	5	6	2.83	2	5	11	12.49	1.097	2	8	10	8.92
				0.999985	0.28	420.2	10.		1.534	2	5	6	2.84	2	5	11	12.48	1.078	2	8	10	8.77
3	RF-PU-03	2	2	1.002413		420.2			1.524	2	5	6	2.86	2	5	11	12.40	1.057	2	8	10	8.60
				0.999989	0.24	429.2	9.		1.525	2	5	6	2.86	2	5	11	12.41	1.041	2	8	10	8.47
4	RF-PU-04	1	5	1.003702		429.2			1.618	2	5	6	2.66	2	5	11	13.16	1.030	1	8	11	8.38
				0.999989	0.37	443.1	14.		1.614	2	5	6	2.67	2	5	11	13.13	1.030	1	8	11	8.38
5	RF-PU-05	3	5	1.003823		443.1			1.716	2	5	6	2.50	2	5	10	13.96	1.019	2	8	10	8.29
				0.999979	0.38	457.3	14.		1.712	2	5	6	2.51	2	5	10	13.93	1.023	2	8	9	8.32
6	RF-PU-06	3	3	1.003449		457.3			1.713	2	5	6	2.52	2	5	10	13.94	0.997	2	8	9	8.11
				0.999983	0.35	470.0	13.		1.708	2	5	6	2.53	2	5	10	13.90	0.987	2	8	8	8.03
7	RF-PU-07	5	3	1.003332		470.0			1.684	2	5	6	2.58	2	5	10	13.70	0.964	2	8	8	7.84
				0.999983	0.33	482.1	12.		1.670	2	5	6	2.62	2	5	10	13.59	0.956	2	8	8	7.77
8	RF-PU-08	5	1	1.004024		482.1			1.686	2	5	6	2.59	2	5	10	13.72	0.942	1	8	7	7.66
				0.999976	0.40	496.5	14.		1.672	2	5	6	2.62	2	5	10	13.60	0.945	1	8	7	7.68
9	RF-PU-09	1	3	1.003207		496.5			1.668	2	5	6	2.62	1	5	11	13.57	0.923	1	8	7	7.51
				0.999984	0.32	508.2	12.		1.664	2	5	6	2.61	1	5	11	13.54	0.913	1	8	7	7.43
10	RF-PU-10	2	6	1.003064		508.2			1.732	2	5	6	2.50	2	5	10	14.09	0.935	2	8	7	7.61
				0.999975	0.31	519.1	11.		1.724	2	5	6	2.50	2	5	10	14.03	0.947	2	8	7	7.70

P.F.C = POSITION OF FUEL CHANGE
D . W = THE DAYS OF WORKING
* = PERCENT

of first refueling.

VI. Conclusions

Summarized in the following are the basic conclusions obtained about physics of Pu fueled FUGEN reactor.

(1) It is certainly believed that Pu fuel is capable of reducing positive coolant void reactivity. The isotope of Pu-239 mainly contributes to this result, influencing to decrease η and f with increasing void condition. This is quite understandable when one considers thermal neutron spectral effect in related to its cross section behavior. Also, the behavior of Pu-241 is similar to Pu-239 but its effect is small because of the small number in the fuel.

(2) Thermal neutron spectrum in the fuel pellets tends to become softer when void increases, which is resulted from the effect of loss of absorption helped by the increasing stream of thermal neutrons into the fuel bundle from the moderator region.

(3) Among the isotopes of Pu fuel, Pu-240 gives the biggest negative contribution to the fuel temperature coefficient. However, its effect is exceeded by U-238 because the dominant part of resonance absorption comes from the latter due to its large number of existance in the fuel.

(4) Hence, any mixture of Pu isotopes will certainly contribute negatively to the power coefficient of the reactor.

(5) A number of incore nuclear instrumentations and 49 control rods characterize the FUGEN reactor control system. This control system is especially useful in such technical problems as zonal reactor control, three dimensional power mapping, refueling management, etc.

VII. Acknowledgement

The authors wish to express their heartiest thanks to Dr. K. Yamamoto, Mr. K. Matsuoka and Mr. A. Watari of Hitachi, Ltd., for their collaborating contributions in completing this work. Also, Mr. M. Ishida and K. Kurihara, together with the above three people, are acknowledged as the originators of CLUSTER-IV Code.

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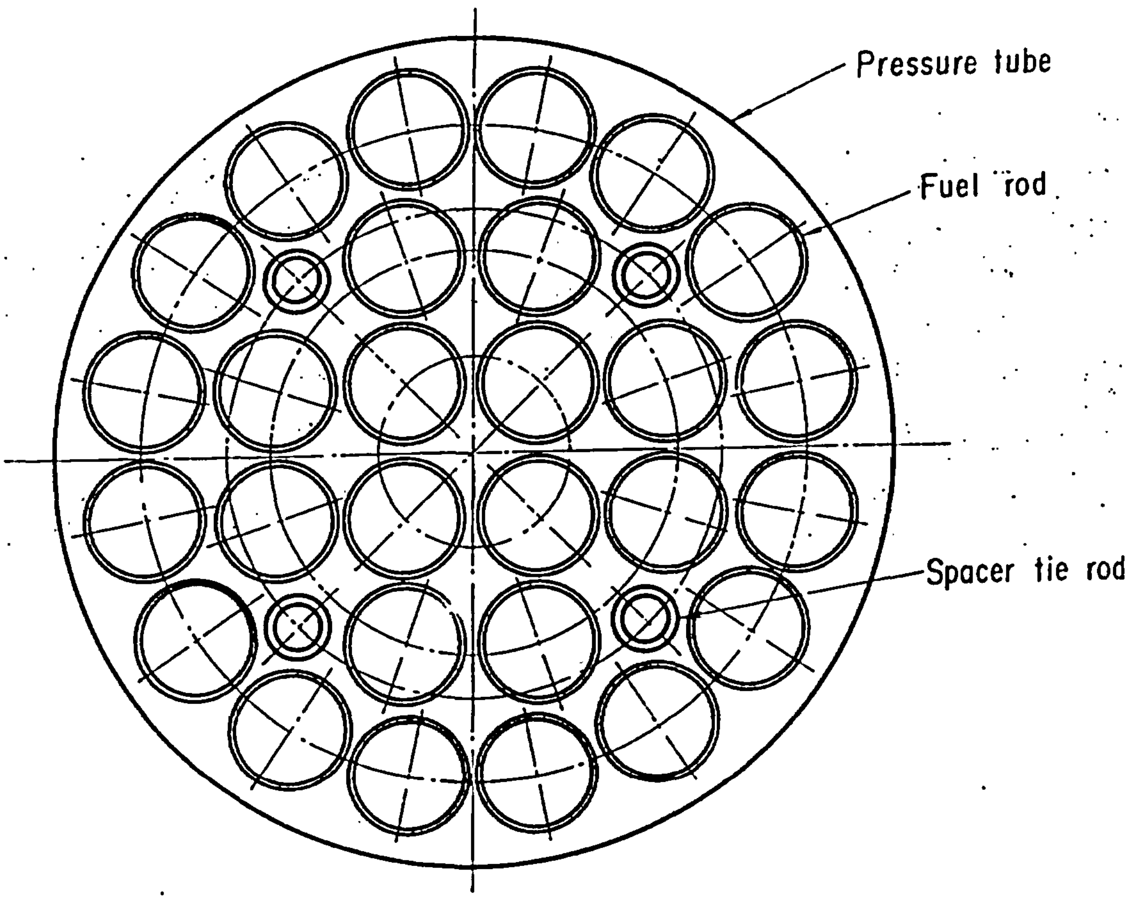
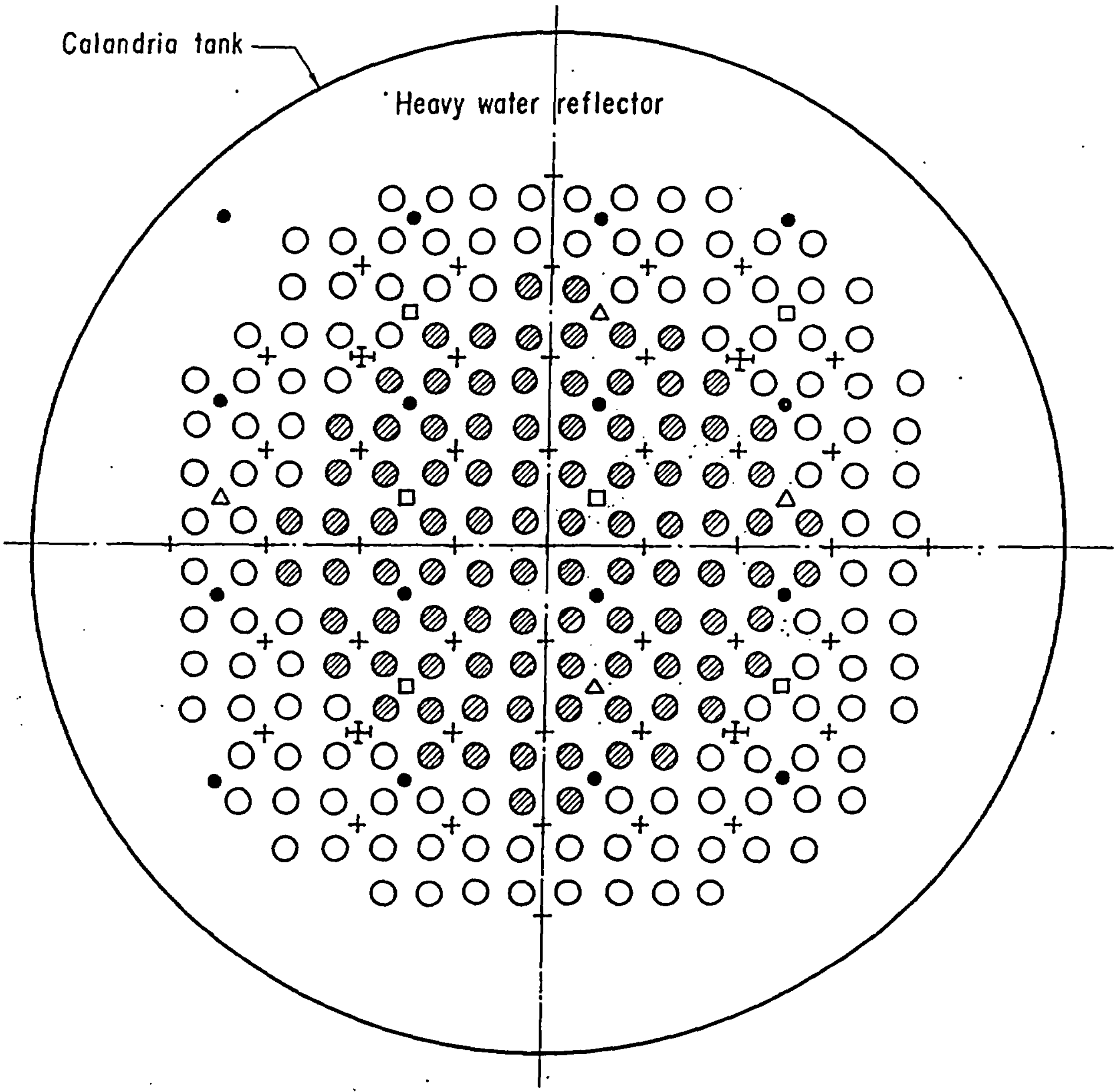


Fig. 1 Fuel assembly of FUGEN



○	FUEL ASSEMBLY UO_2	128	●	IPM	16x4
⊘	PuO_2-UO_2	96	□	IM	6
+	CONTROL ROD	45	△	SM	4
╪	REGULATING ROD	4			

Fig. 2 CORE CONFIGURATION

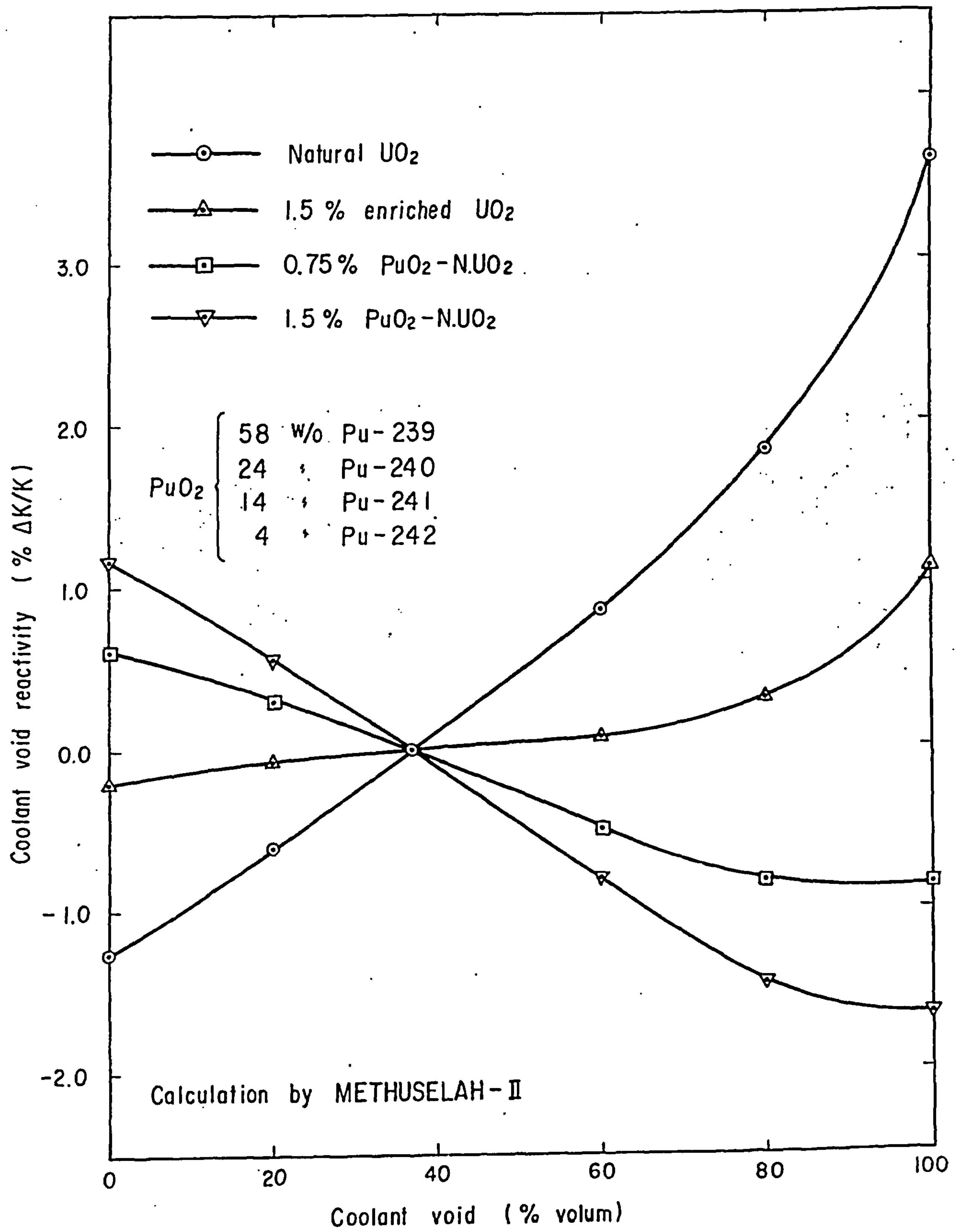


Fig. 3 Effect of plutonium enrichment on coolant void reactivity

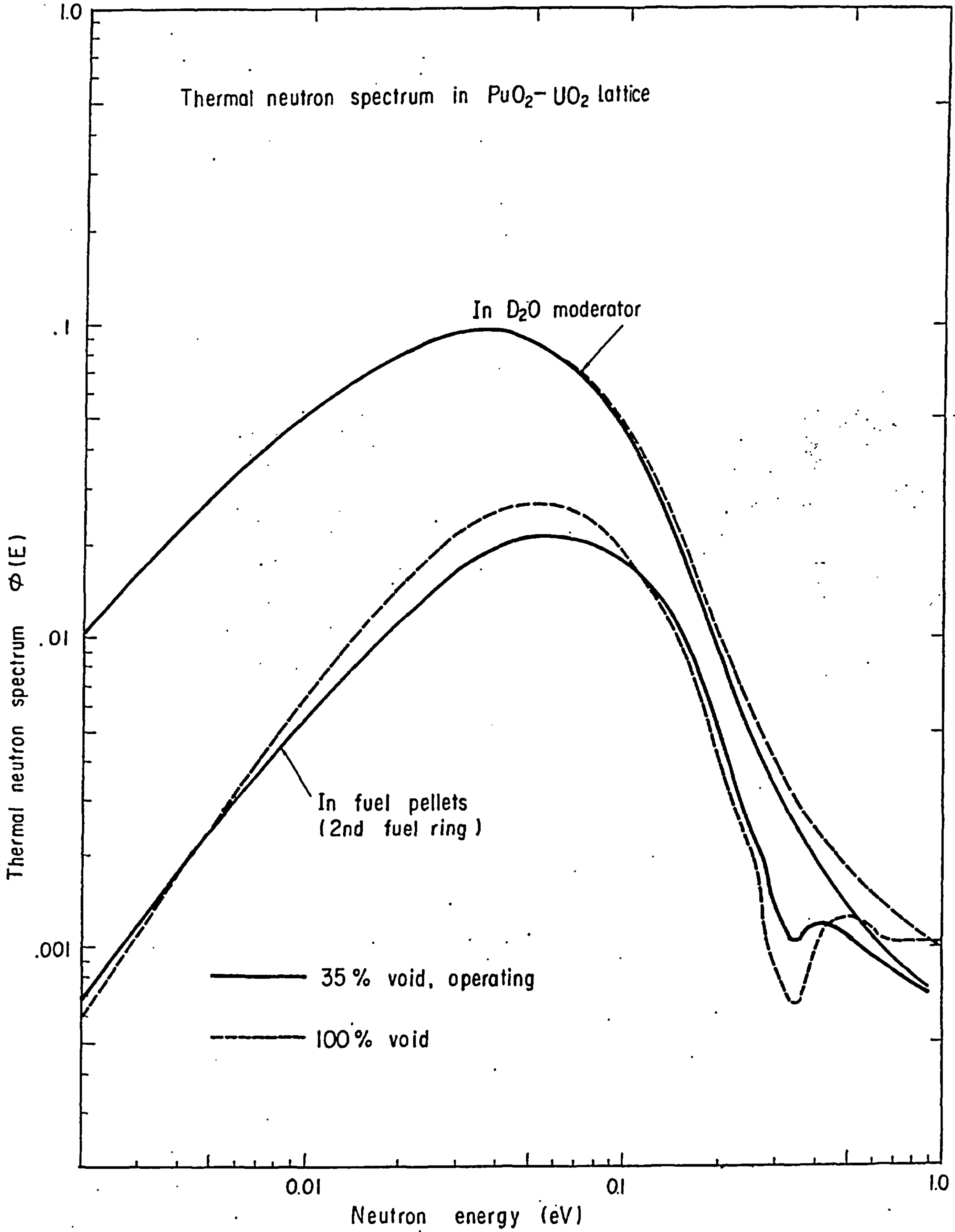


Fig. 4 Thermal neutron spectrum in 0.75 % Plutonium enriched PuO_2-UO_2 fuel

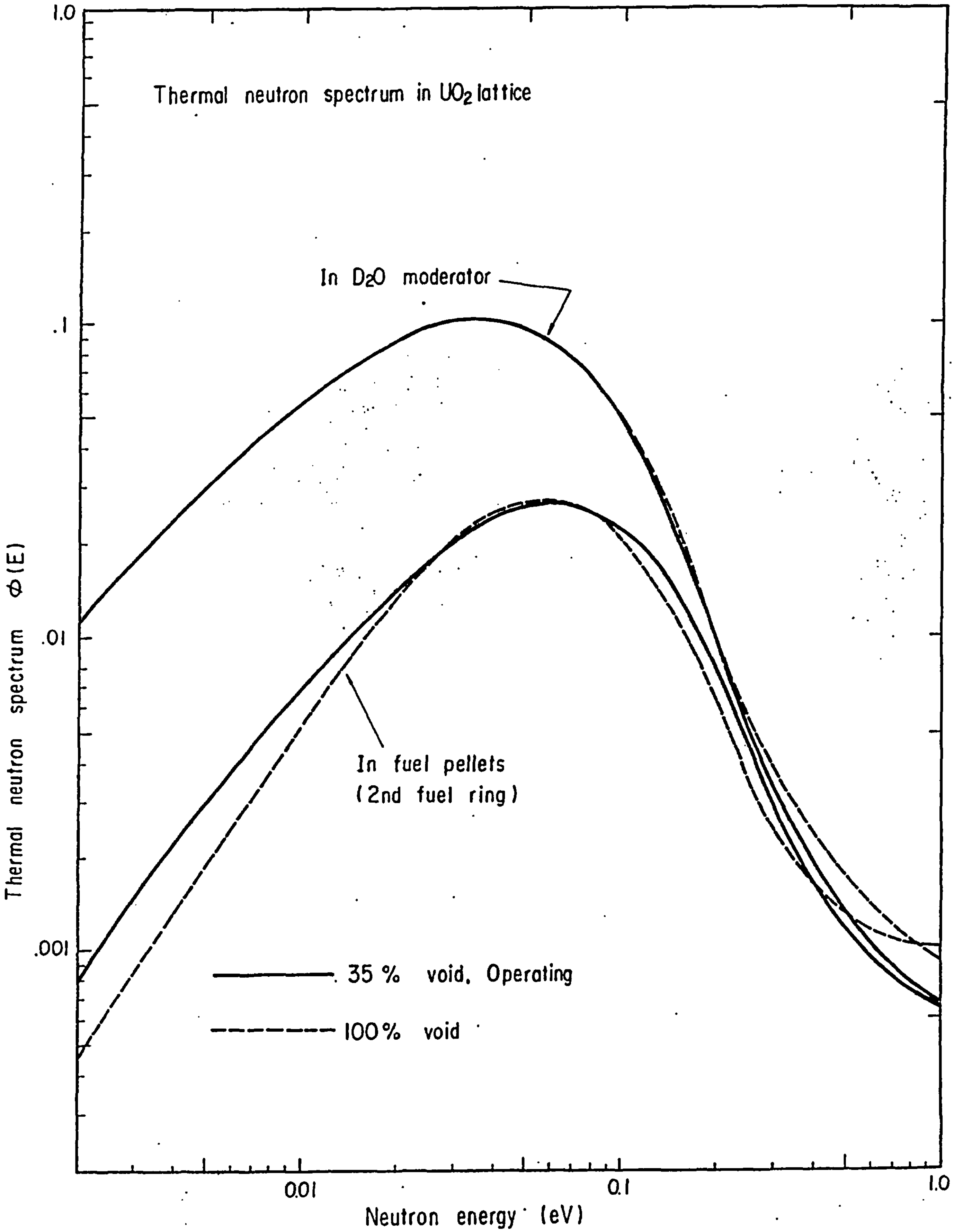


Fig.5 Thermal neutron spectrum in 1.5 % enriched UO_2 fuel

$$S_1 = \int_{0.625\,eV}^{\infty} \phi(E)\,dE \Big/ \int_{0}^{0.625\,eV} \phi(E)\,dE$$

$$S_2 = \int_{0.14\,eV}^{0.625\,eV} \phi(E)\,dE \Big/ \int_{0}^{0.14\,eV} \phi(E)\,dE$$

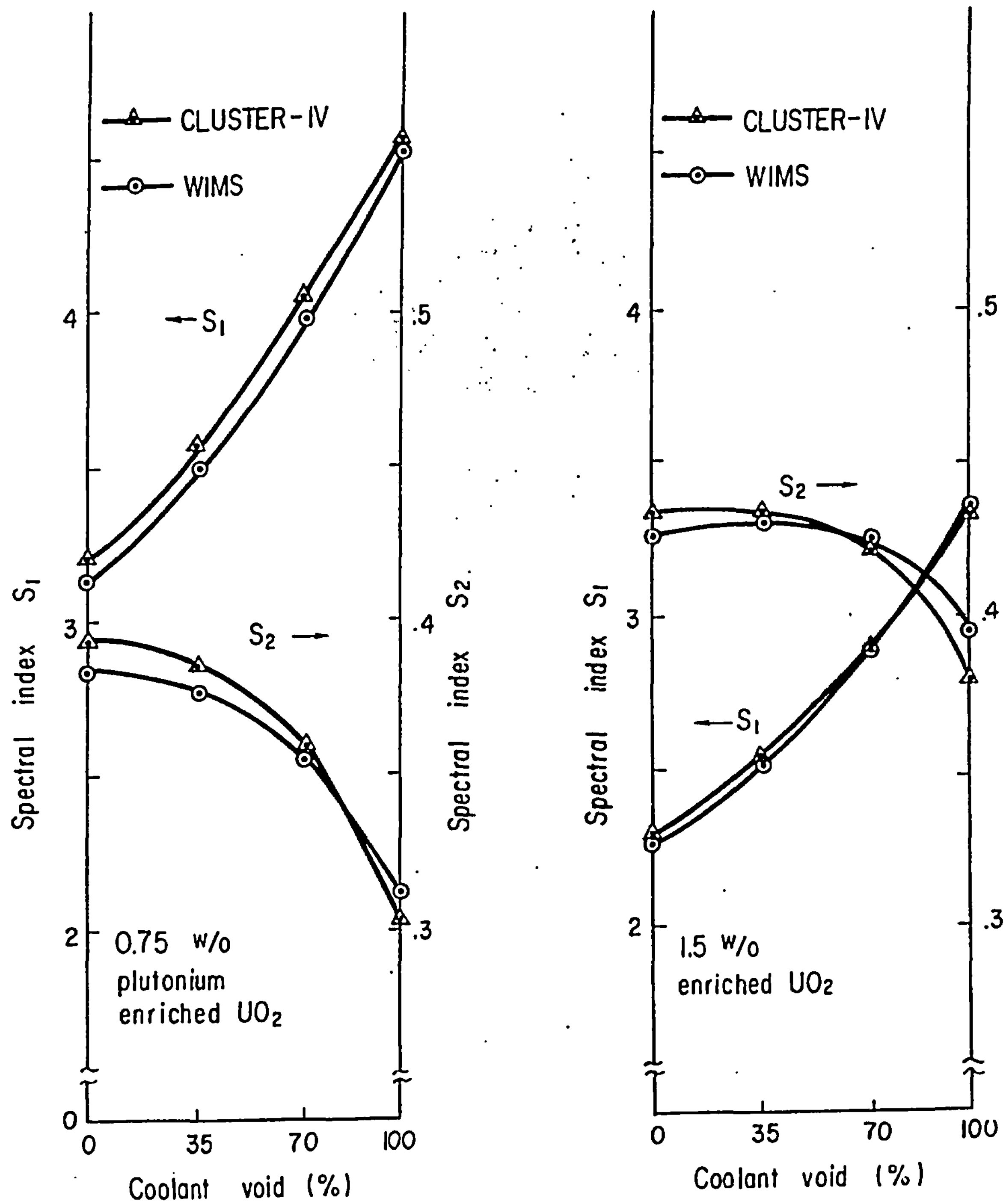


Fig. 6 Spectral indices with coolant void fraction

(S_1 and S_2 evaluated in fuel)

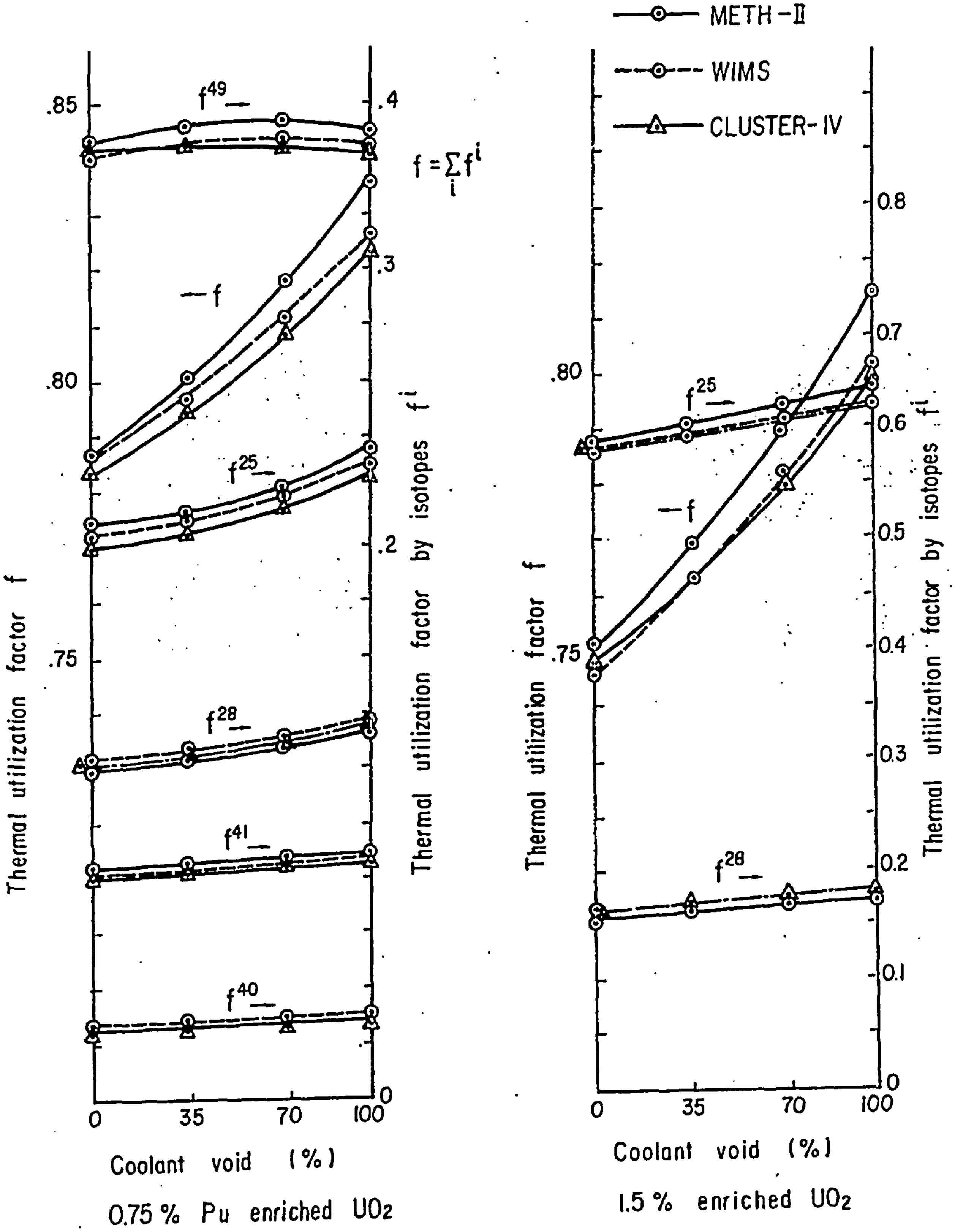


Fig. 7 Thermal utilization factors by each isotopes with coolant void fraction

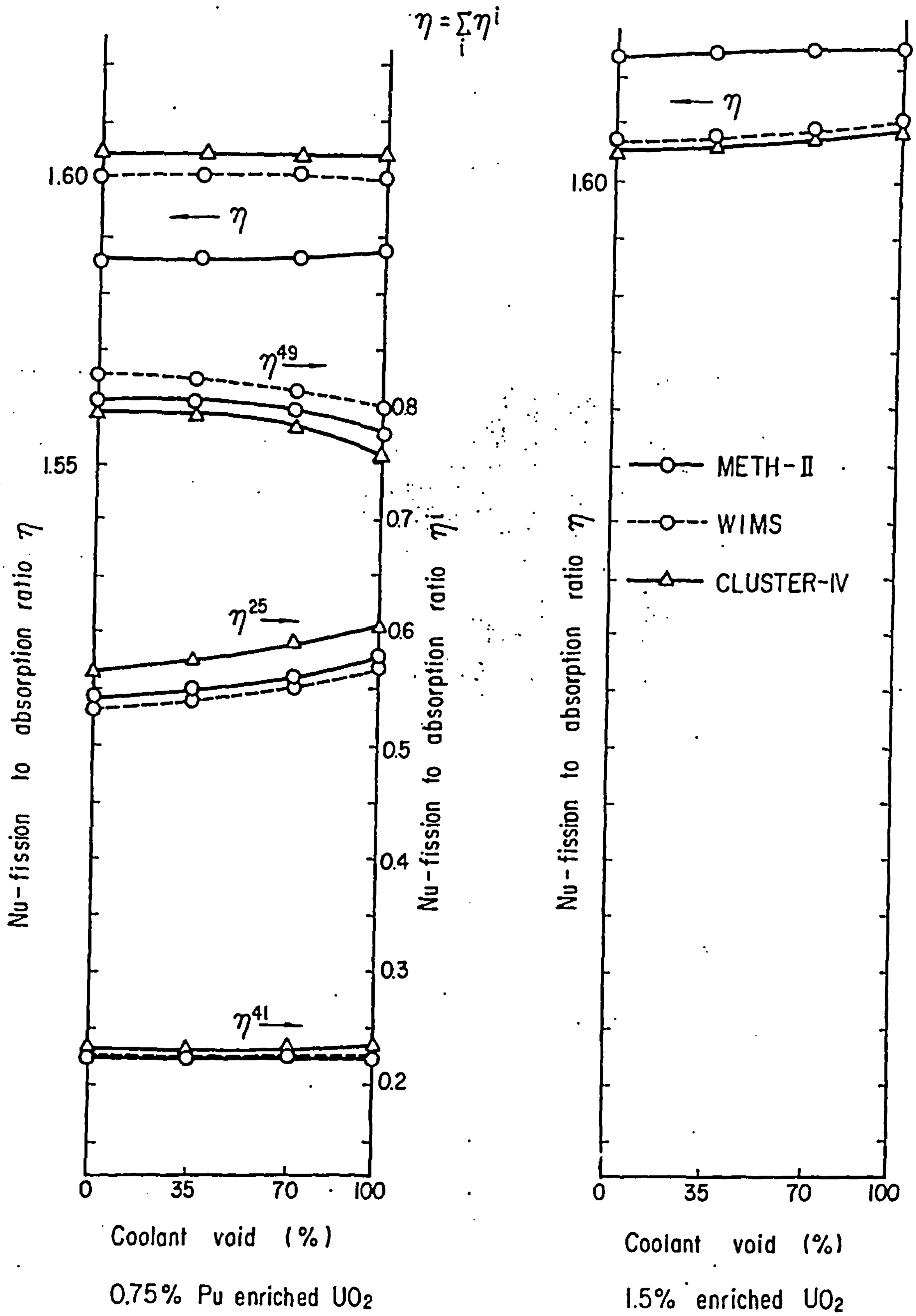


Fig.8 Nu-fission to absorption ratios by each isotopes with coolant void fraction

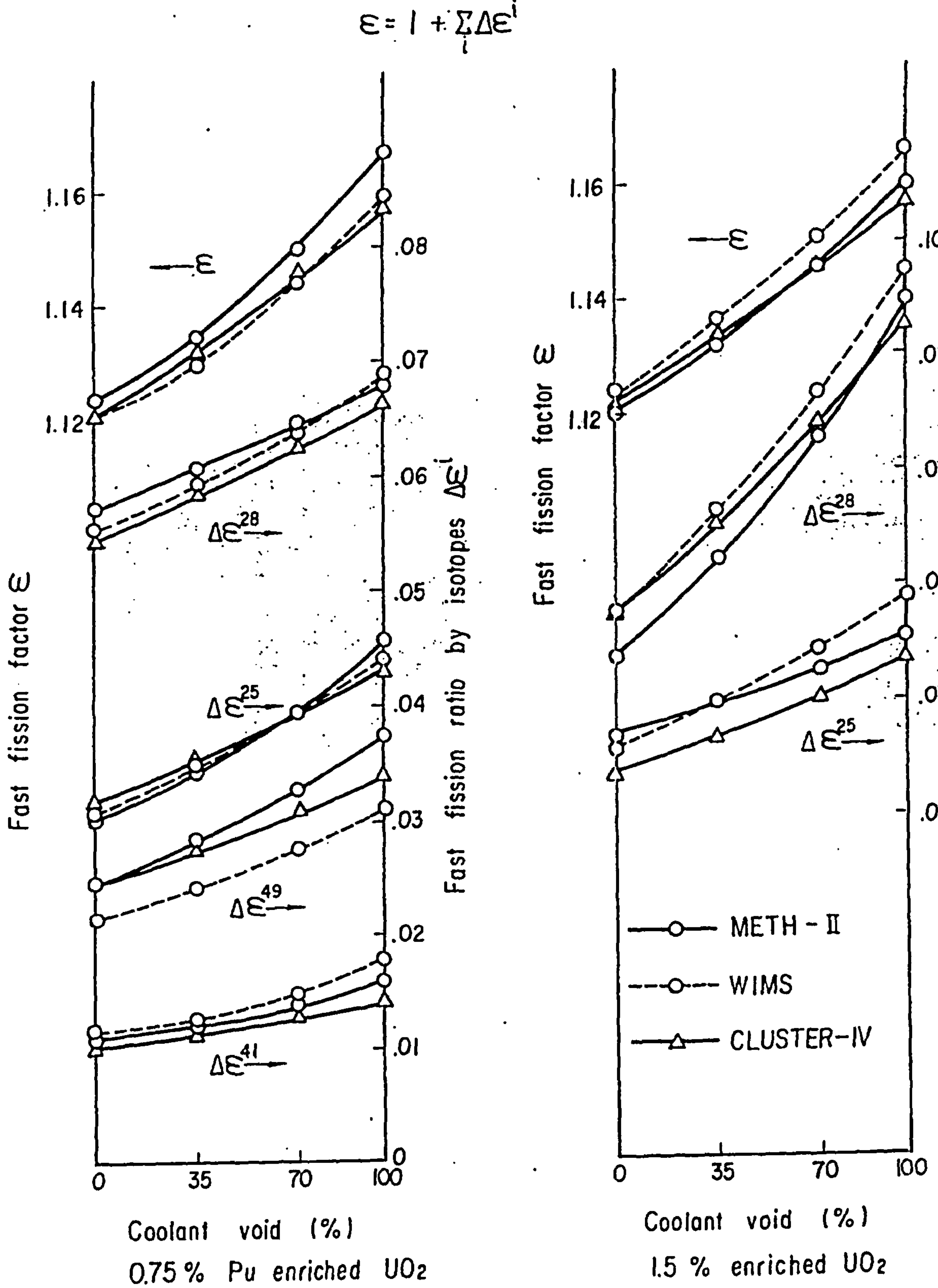


Fig.9 Fast fission factors by each isotopes with coolant void fractions

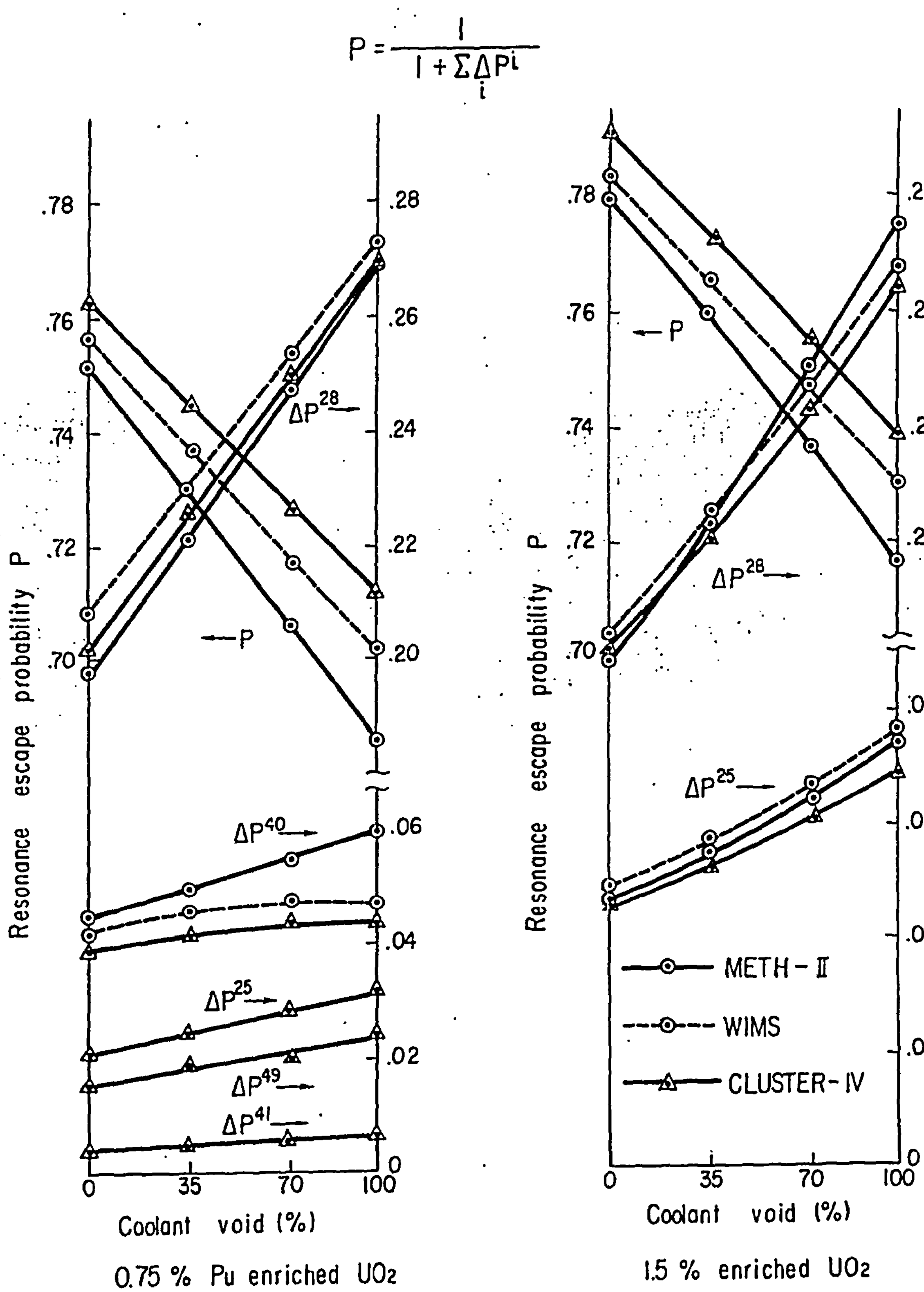


Fig. 10 Resonance escape probabilities by each isotopes with coolant void fraction

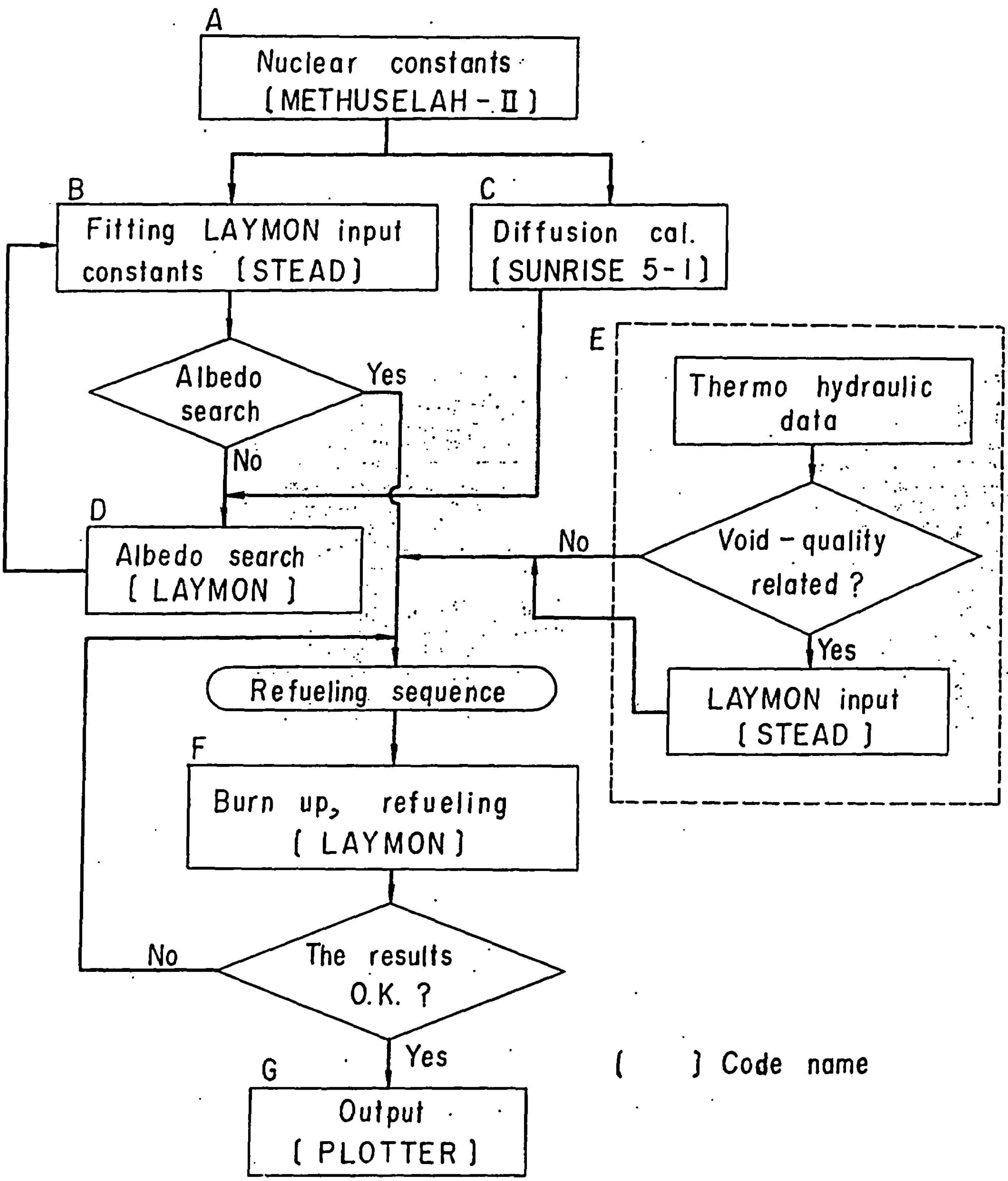
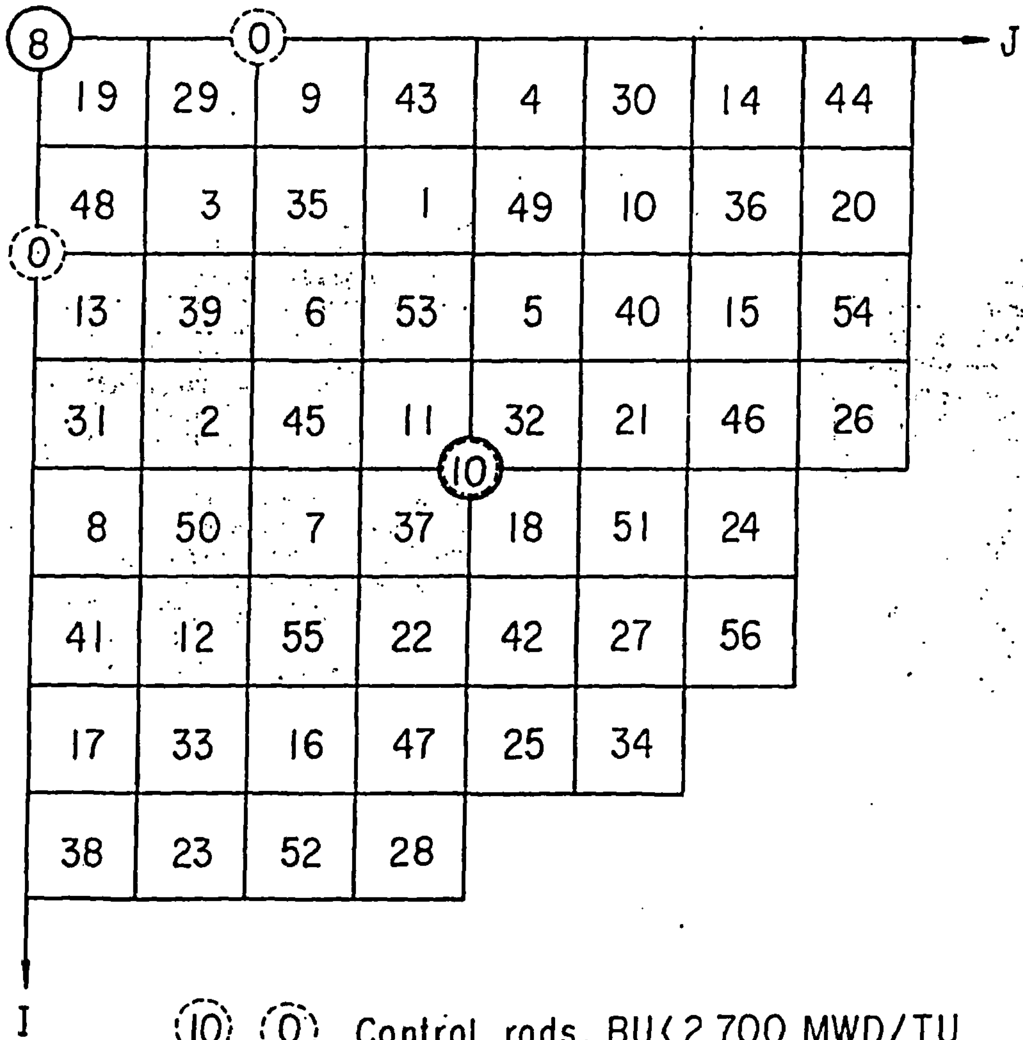


Fig. 11 Flow chart of burn up and refuling calculations



(10) (0) Control rods, BU< 2,700 MWD/TU

(10) (8) " " , BU> " "

Full in ~ Full out = 0 ~ 16

Fig. 12 Refueling sequence (ex ample)