Effect of Uncertainty in Nuclear Constants on Nuclear Characteristics Sensitivity Analysis of Nuclear Constants for the Core of MONJU Reactor

May, 1972

HITACHI, LTD.

T J202 72-05T
May, 1972

Effect of Uncertainty in Nuclear Constants on Nuclear Characteristics Sensitivity Analysis of Nuclear Constants for the Core of MONJU Reactor*

Abstracts

Sensitivity analysis of nuclear constants for MONJU nuclear characteristics was performed. In this analysis, the sensitivity coefficients for each nuclear constant were calculated. From these results, the degree of the necessity for the further evaluation of each nuclear constant has been discussed. Main results are;

(1) Sensitivity Coefficients
Nuclear constants having a large sensitivity coefficient are as follows.

(a) For effective multiplication factor,
ν and σ_f of ^{239}Pu, ν and σ_f of ^{238}U($\gtrsim$1.4MeV), ν and σ_f of ^{241}Pu (400~10keV) have positive values. σ_f of ^{238}U(1.4Mev~10keV) and σ_f of Fe(100~10keV) have negative values. Among them, especially ν and σ_f of ^{239}Pu have large values.

(b) For breeding ratio,
ν of ^{239}Pu(1.4MeV~10keV), ν of ^{238}U($\gtrsim$1.4MeV), ν of ^{240}Pu(400~10keV) and σ_c of ^{238}U(400~10keV) has positive value. σ_c of ^{239}Pu(400~10keV) have a negative value. Among them, ν of each fuel element has especially large values.

(c) For Na-void reactivity (100% void ratio),
ν and σ_f of ^{239}Pu, σ_f of ^{239}Pu($\lesssim$10keV), ν and σ_f of ^{238}U($\gtrsim$1.4MeV) and σ_{in} of ^{238}U(1.4~0.4MeV) have negative values. Among them, especially ν and σ_f of ^{239}Pu have large values. σ_f of Na(1.4~0.4MeV) has a positive value.

(d) For Doppler reactivity (1173°K → 1473°K),
σ_t of ^{16}O(400~10keV) and σ_t of Na(400~10keV) have the largest values in all moderating elements. ν and σ_f of ^{239}Pu(1.4MeV~10keV) have the largest values in all fuel elements.

(2) Future Study in Nuclear Constants.
From the results of sensitivity coefficients and the present status of nuclear constant uncertainties, the evaluation of the following nuclear constants must be emphasized; σ_f and σ_c of ^{239}Pu($\lesssim$400keV), σ_{in} of ^{238}U($\gtrsim$1.4MeV), σ_c of ^{238}U(100~10keV), σ_f of ^{240}Pu(1.4~0.4MeV), σ_f of ^{241}Pu($\lesssim$100keV), σ_t of ^{16}O(400~100keV), σ_c of Fe(100~10keV).

Masaaki Yamamoto**
Koichi Maki**
Atsushi Zukeran**

---

* Work performed under constracts between Power Reactor and Nuclear Fuel Development Corporation and Hitachi, Ltd.

** Hitachi, Ltd.

Contents

1. Preface 1

2. Survey and study of literature concerning sensitivity analysis 3

   2.1 Methods used up to now and their problems 3

   2.2 The main results of the previously performed sensitivity analyses 3

3. Method of analysis 16

   3.1 Choice of standard library 16

   3.2 Method of calculation of sensitivity coefficients ... 17

4. Improvement of sensitivity coefficient calculation program 20

5. Test of HIM-1 as standard nuclear constants 24

   5.1 Outline of Bench Mark series No.1 - No.4 24

   5.2 Study on the results of analysis 26

6. Calculations of sensitivity coefficients 33

   6.1 Calculation model 33

   6.2 Determination of the condition of convergence for sensitivity coefficient calculations 34

   6.3 Sensitivities coefficients not including interrelations 34

   6.4 Sensitivity coefficients including interrelations ... 35

7. Study on the required accuracy for nuclear constants 67

   7.1 Method of determining the required accuracy 67

   7.2 Target accuracy for design values of core characteristics 68

   7.3 Required accuracy for nuclear constants 69

   7.4 Comparison between accuracy requirements and uncertainties of nuclear constants up to now 69

8. Postscript 74

   Acknowledgement 74

   References 75

Fig. 1 Sensitivity Coeff. of ^{239}Pu ν for K_{eff} 12
Fig. 2 Sensitivity Coeff. of ^{239}Pu σ_f for K_{eff} 12
Fig. 3 Sensitivity Coeff. of ^{239}Pu σ_c for K_{eff} 12
Fig. 4 Sensitivity Coeff. of ^{238}U σ_c for K_{eff} 12
Fig. 5 Sensitivity Coeff. of ^{239}Pu ν for Breeding Ratio .. 13
Fig. 6 Sensitivity Coeff. of ^{239}Pu σ_f for Breeding Ratio . 13
Fig. 7 Sensitivity Coeff. of ^{239}Pu σ_c for Breeding Ratio . 13
Fig. 8 Sensitivity Coeff. of ^{238}U σ_c for Breeding Ratio . 13
Fig. 9 Sensitivity Coeff. of ^{239}Pu ν for Na-Void Reactivity 14
Fig. 10 Sensitivity Coeff. of ^{239}Pu σ_f for Na-Void Reactivity 14
Fig. 11 Sensitivity Coeff. of ^{239}Pu σ_c for Na-Void Reactivity 14
Fig. 12 Sensitivity Coeff. of ^{238}U σ_c for Na-Void Reactivity 14
Fig. 13 Sensitivity Coeff. of ^{239}Pu ν for Doppler Reactivity 15
Fig. 14 Sensitivity Coeff. of ^{239}Pu σ_f for Doppler Reactivity 15
Fig. 15 Sensitivity Coeff. of ^{238}U σ_c for Doppler Reactivity 15
Fig. 16 Sensitivity Coeff. of ^{16}O σ_{el} for Doppler Reactivity 15
Fig. 17 Micro data change routine 21
Fig. 18 Sensitivity Coefficients Calculation Routine 22
Fig. 19 SUNRISE - 4 - 3 22
Fig. 20 Whole Flow Diagram 23
Fig. 21 Central Spectrums of Bench Mark Cores 30
Fig. 22 Sensitivity Coefficients for K_{eff} (No. 1) 58
Fig. 23 Sensitivity Coefficients for K_{eff} (No. 2) 59
Fig. 24 Sensitivity Coefficients for Breeding Ratio (No. 1) 60

Fig. 25 Sensitivity Coefficients for Breeding Ratio (No. 2) . 61

Fig. 26 Sensitivity Coefficients for Void Reactivity (No. 1) 62

Fig. 27 Sensitivity Coefficients for Void Reactivity (No. 2) 63

Fig. 28 Sensitivity Coefficients for Void Reactivity (No. 3) 64

Fig. 29 Sensitivity Coefficients for Doppler Reactivity (No. 1) 65

Fig. 30 Sensitivity Coefficients for Doppler Reactivity (No. 2) 66

Table 1	Method and Problem of Sensitivity Analysis up to now	8
Table 2	Composition of Bench Mark Core	29
Table 3	Comparison of experimental value and calculated value of effective multiplication factor (Bench Mark core)	31
Table 4	Comparison of experimental value and calculated value of reaction rate ratio (Bench Mark Core)	32
Table 5	Atomic number density in the middle of equilibrium MONJU core	39
Table 6	Energy section in sensitivity analysis	40
Table 7	Sensitivity Coeff. in Conversion Condition 1.0×10^{-5}	41
Table 8	Sensitivity Coeff. in Conversion Condition 5.0×10^{-7}	42
Table 9	Sensitivity Coeff. in Conversion Condition 5.0×10^{-6}	43
Table 10	The number of iteration in each conversion condition	44
Table 11	Effective Multiplication Factor K_{eff} (for 10% changed nuclear constants)	45
Table 12	Sensitivity Coefficients for K_{eff} (no interrelation)	46
Table 13	Breeding Ratio (for 10% changed nuclear constants)	47
Table 14	Breeding Ratio (for 10% changed nuclear constants) Corrected by Effective Multiplication Factor	48
Table 15	Sensitivity Coefficients for Breeding Ratio (no interrelation)	49
Table 16	Void Reactivity (for 10% changed nuclear constants)	50
Table 17	Sensitivity Coefficients for Void Reactivity (no interrelation)	51
Table 18	Doppler Reactivity (for 10% changed nuclear constants)	52
Table 19	Sensitivity Coefficients for Doppler Reactivity (no interrelation)	53

Table 20	Sensitivity Coefficients for K_{eff} (contained interrelation)	54
Table 21	Sensitivity Coefficients for Breeding Ratio (contained interrelation)	55
Table 22	Sensitivity Coefficients for Void Reactivity (contained interrelation)	56
Table 23	Sensitivity Coefficients for Doppler Reactivity (contained interrelation)	57
Table 24	Target Accuracy of Core Nuclear Design	70
Table 25	Uncertainties of Nuclear Constants up to now	71
Table 26	Required Accuracy for Nuclear Constants	72
Table 27	Ratio of Required Accuracy to Uncertainty of Nuclear Constants	73

1. Preface

This report has the following aims; systematical discussion about the effects of the uncertainty of nuclear constants on the nuclear characteristics for the core of "MONJU", studying the problems of the nuclear constants in designing the core of "MONJU" reactor and obtaining the basic information in studying the direction of the improvement of nuclear constants in the future.

The effects of the uncertainty of nuclear constants on the nuclear characteristics have hitherto been studied with various types of reactor core systems. In performing the present work, we have examined the various papers which have so far been published with regard to sensitivity analysis in an attempt to study the concrete concepts and methods of sensitivity analysis and further to clarify the problems encountered in carrying out the sensitivity analysis.

In carrying out the sensitivity analysis, we at first planned to use the group constants based ENDF/B-II for the standard group constants. But later we found that there was some problems with the effective multiplication factor derived by ENDF/B-II. So, we checked the validity of using HIM-I for the standard group constants. For this purpose, we performed the experimental analysis of Bench Marks by HIM-I. As a result, we reached the conclusion that HIM-I had no particularly big problem at the present time and decided to use HIM-I for the standard group constants.

Calculations of sensitivity coefficients were made with the "MONJU" equilibrium intermediate reactor. Calculations were made by the cylindrical one-dimensional diffusion calculation. The sensitivity coefficients were obtained for the effective multiplication, doppler reactivity, Na-voidreactivity, and breeding ratio. We further obtained the required accuracy for the nuclear constants from the obtained sensitivity coefficients, for future studies on the improvement of the nuclear constants.

2. Survey and study of literature concerning sensitivity analysis

2.1 Methods used up to now and their problems

The results of literature survey are summarized in Table 1, in which the column under the heading of "Object" paid special attention to the type of core and the nuclear material composing the core. Under the heading "Calculating Model", the cross section library and format model are described. In the "Method of Sensitivity Analysis", the basic concepts of the method analysis and the kinds of sensitivity coefficient to which attention was paid are summarized. The column "Problems and Comments" decribes the results and the findings therefrom and the characteristics features of the methods and so forth.

2.2 The main results of the previously performed sensitivity analysises

The results so far obtained from the sensitivity analysises were graphically summarized and the following points were clarified.

(1) The difference of sensitivity coefficients depending on the system and the method employed.

(2) To grasp a value presumed to be sensitivity coefficient.

(3) Understanding of the effects of cross section from the previously obtained results of analytical studies.

(4) To extract the problems concerning the previously made calculations.

Here are shown the sensitivity coefficients with regard to K_{eff}, breeding ratio, Na-void effects, and Doppler effects. The following graphs shows the four largest of the sensitivity coefficients obtained by Moorhead,[1] Gandini [6] and V. Rojkov. [7]

As was usually before, the sensitivity coefficients which were obtained by them are the sensitivity coefficients as a quantity integrated in the energy region. Since it is impossible to make comparison of the sensitivity coefficients of different energy regions, here are given the values obtained by dividing them by the lethargy width of the region, that is, the values obtained converting into the sensitivity coefficients per unit lethargy. When obtained lethargy, the lowest group of Moorhead, that is, the lowest limit of energy of the fifth group was taken as 50eV. For, considering the reactivity, the reactivity lower than 50eV was less than 1% compared with the reactivity of 9.1 keV and therefore the effects of reactivity lower than 50eV can be neglected. As for the results except Moorhead, the lowest limit was taken as 0.0252eV which is thermal energy.

The following figures give the percentage changes of the nuclear characteristics when the microscopic cross section is increased 1%, that is, the sensitivity coefficients. Fig. 1 through Fig. 4 show the sensitivity coefficients for K_{eff} and Fig. 5 through Fig. 8 show the sensitivity coefficients for breeding ratio. In these figures, the results obtained by Moorhead [1)] are shown by solid lines and those of V. Rojkov are shown by broken lines. In their analytical studies, Moorhead used a medium-sized reactor and V. Rojkov used a large reactor. As for K_{eff}, their sensitivity coefficients are roughly in agreement with each other but the values obtained by Moorhead, except for $^{238}U\ \sigma c$, are larger than those obtained by V. Rojkov. This is presumably because the critical adjustment was not made in the analysis done by V. Rojkov. This presumption is supported by the fact that the sensitivity coefficients for the breeding ratio of $^{238}U\ \sigma_c$ in Fig. 8 is higher for the values shown by V. Rojkov than those which were given by Moorhead in contrast to other cases. Fig. 9 through Fig. 12 give the sensitivity coefficients for Na-void effect, the results of the analytical study made by Gandini. [6] In these figures, Na-void effect (10% void ratio) has a negative value and therefore the fact that the sensitivity coefficients are positive or negative means that the void effect is more negative or positive. Gandini also uses the same expression for the sensitivity coefficients for Doppler effect in Fig. 13 through Fig. 16.

From these figures, the following things are shown.

(1) Sensitivity coefficients for K_{eff}

In any case from Fig. 1 through Fig. 4, the sensitivity coefficients are very large within the range from 1MeV to 10Kev. As for the cross section, the sensitivity coefficients of $^{239}Pu\ \nu$ and $^{239}Pu\ \sigma_f$ are large and the sensitivity coefficient of $^{238}U\ \sigma_c$ is about 1/2 of them.

(2) Sensitivity coefficients for breeding ratio

(a) The sensitivity coefficient for breeding ratio can be roughly expressed as follows.

$$^{239}U\ \sigma_c \approx \frac{1}{2} \times\ ^{239}Pu\ \sigma_c \approx \frac{1}{2} \times\ ^{239}Pu\ \sigma_f \approx \frac{1}{10} \times\ ^{239}Pu\ \nu$$

(b) The reason why the sensitivity coefficient for $^{239}Pu\ \nu$ is especially large is that the rate of enrichment can be made smaller.

(c) The sensitivity coefficient for $^{239}Pu\ \sigma_c$ is larger than expected (equal to the sensitivity coefficient for

$^{239}Pu\ \sigma_f$) because the ^{239}Pu absorption ratio increases with the increase of σ_c and because it is necessary to increase the rate of enrichment. On the other hand, when $^{239}Pu\ \sigma_f$ is varied, the sensitivity coefficient is not so large as is generally expected because the effect of ^{239}Pu absorption rate due to the variation of σ_f and the effect of the adjustment of critical mass offset each other.

(d) Moorhead has pointed out that the sensitivity coefficients normally vary about two times depending whether the critical mass is adjusted or not.[1)]

(e) $^{238}U\ \sigma_c$ is considered to be quantity which has the largest effect on the breeding ratio. However, the sensitivity coefficient (particularly the results by Moorhead) for this is smaller than that for $^{239}Pu\ \sigma_c$. Such an unexpected result was due to the fact that the adjustment of critical mass has a great effect.

(3) Sensitivity coefficients for Na-void effect and for Doppler effect

As for these coefficients, there are only the results given by Gandini.[6)] It is unknown whether he took into account the variation of the self-shielding factor accompanying Na-void in his analytical study. Judging from the fact that the sensitivity coefficients for $^{238}U\ \sigma_c$ and $^{239}Pu\ \sigma_c$ at low energies are equal, it is presumed that the self-shielding factor was not considered. In any case, however, it can be generally said that the sensitivity coefficient for the cross section of fuel element is large as shown by the results of the study made by Gandini. The sensitivity coefficient of Na itself against the Na-void effect is smaller than that for the fuel element.

What should be noted about the Doppler effect is that the contribution of ^{239}Pu to the Doppler effect of the system is about 1/4 of ^{238}U at most, but the sensitivity coefficients for ^{239}Pu σ_f and ν are equal to the sensitivity coefficient of ^{238}U. This is partly because there are the effects coming in through the neutron importance. In the case of ^{238}U σ_c, when σ_c is varied, particularly below several KeV, the effects on the neutron spectrum is so large that the sensitivity coefficients become considerably smaller than when the variation of the neutron spectrum is ignored.

From the above tabulation of the results of the previously made analytical studies on sensitivity coefficients, it is learned that the results which can be tabulated as sensitivity coefficients are extremely limited.

Table 1 Method and Problem of Sensitivity Analysis up to now

Author	Object	Calculating model	Method and contents of sensitivity analysis	Problem and comment
T.D. Moorhead[1] 1962 (AEEWUK)	Prototype reactor	5-group diffusion Group constants: ANL-11	o As for the breeding ratio, a linear equation of eigen value and breeding ratio is derived to obtain the changes in the breeding ratio when K_{eff} is adjusted to a prescribed value. o As for the sensitivity coefficient for the differential cross section, the macroscopic cross section is varied independently and to the results is applied the relationship between the microscopic cross section and the macroscopic cross section and the interrelation of the microscopic cross section. In this case, the changes in physical quantities for the changes in cross section are all approximated by the relationship of a linear equation.	o It is shown that within the 10% change of the macroscopic cross section, the changes in cross section and the changes in nuclear characteristics are in simple proportion with an accuracy of 2 to 3%, except for the scattering matrix $\Sigma^{i \to j}$. $\Sigma^{i \to j}$ is the worst case in which the deviation is about 10%. ($\Sigma^{i \to j}$ at about 1MeV) o The author thinks it necessary to use a statistical processing of error in establishing a relation between the uncertainty of nuclear data and the uncertainty of nuclear characteristics by using sensitivity coefficients. In the present report, no work including the use of such a method is not done.

Author	Object	Calculating model	Method and contents of sensitivity analysis	Problem and comment
E.D. Pendlebury[2] 1962	Bare reactor and reflector-equipped reactors with U^{235} enrichment from 94% to 30%		o The width of uncertainty of the differential cross section of U^{235} and U^{238} were evaluated at the point of time in 1962 to calculate the effects on the nuclear characteristics.	o Since the objects were small reactors, the results showed a different tendency from large reactors.
F.M. Hech[3] 1966	A core using carbide as fuel of the prototype reactor and commercial class reactor	One dimensional spherical diffusion calculation	o The author made a study only on the changes in nuclear characteristics for the changes in macroscopic cross section of the system. o He studied the breeding ratio by adjusting the critical mass.	o He says that the changes in macroscopic cross section and the changes in nuclear characteristics hold good simple proportional relation with a high degree of accuracy. (No concrete results are given) o Discussion limited to the coefficients for the macroscopic cross section of the system for the nuclear characteristics.
Greebler et al.[4] 1966	Large reactor (practical reactor) Experimental reactor (EBR-II) Medium fast reactor (for military use)	The diffusion equation was used on the bare core and 60-group (for large reactor) was used for the standard group constant.	o A study is made on the present status of the accuracy of nuclear characteristics calculation on the basis of the results of survey on the present status (as of 1966) of	o The interrelations between nuclear data are not shown. o It is not shown whether the adjustment of critical mass was considered with regard to breeding ratio.

Author	Object	Calculating model	Method and contents of sensitivity analysis	Problem and comment
			nuclear data.	o There is no general discussion based on sensitivity coefficients. o No definite relation is given between the target accuracy for nuclear characteristics and the determination of required accuracy of the corresponding nuclear data.
Greebler et al.[5] 1968	Calculations made on commercial fast reactor, low-leakage reactor and high-leakage reactor	ENDF/B-Version-1 used as standard data	Same as above. Further discussion on the effects on cost of fuel.	o The techniques are the same as those used in 1966 but the grasping of the nuclear data as of 1968 was the main purpose. Characteristic is the discussion on the cost of fuel.
A. Gandini et al. [6] 1968	Large fast reactor using oxides and carbides as fuel	Soviet group constants[8]	Generalized perturbation techniques [9] were used for the calculations of sensitivity coefficients.	o No discussion is made on the target accuracy for definite nuclear characteristics.
V.Rojkov[7] 1969	Large reactor using oxides and carbides as fuel	o Soviet group constants contracted to 18 groups o One-dimensional spherical diffusion calculation	o Sensitivity coefficients were calculated by use of perturbation techniques. o The author assumed that the target accuracy for nuclear	o As a preliminary study, the author made calculations on the data of ^{239}Pu and ^{238}U but the results produced unrealistic value for the required accuracy of nuclear constants.

Author	Object	Calculating model	Method and contents of sensitivity analysis	Problem and comment
			data would be given by $d = 1/1X$ where d is target accuracy and X is sensitivity coefficient.	This is largely due to the problem of establishing a relation between sensitivity coefficients and required accuracy of nuclear data. This is a difficult problem and it is necessary to take into account the degree of difficulty of experiments and the accuracy of the presently available data.

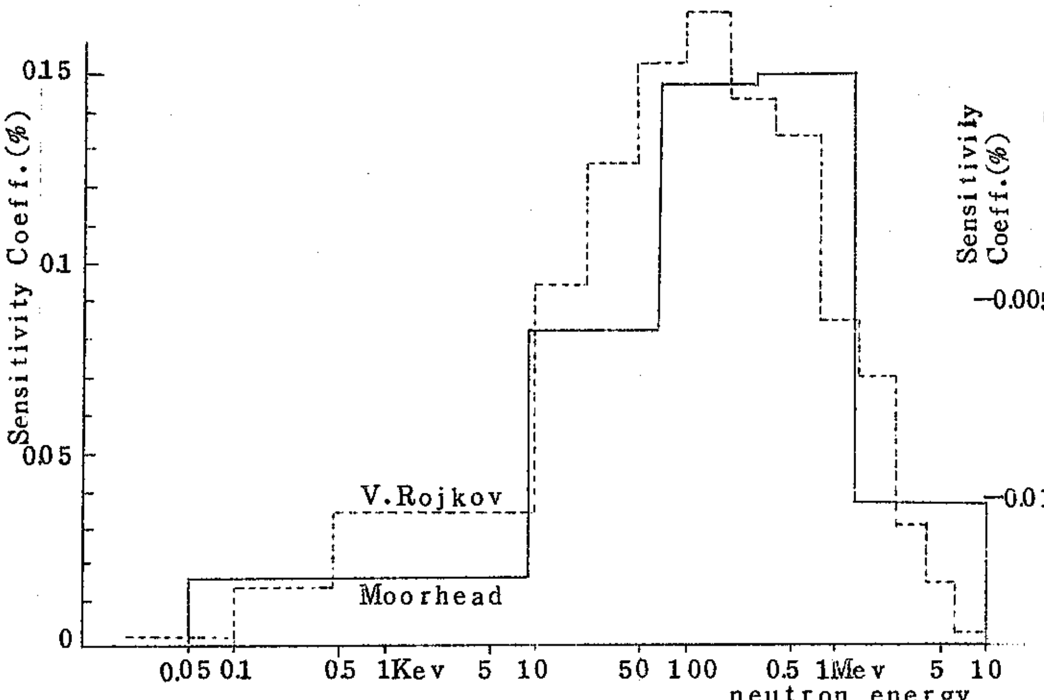


Fig.1. Sensitvity Coeff.of ^{239}Pu ν for keff.

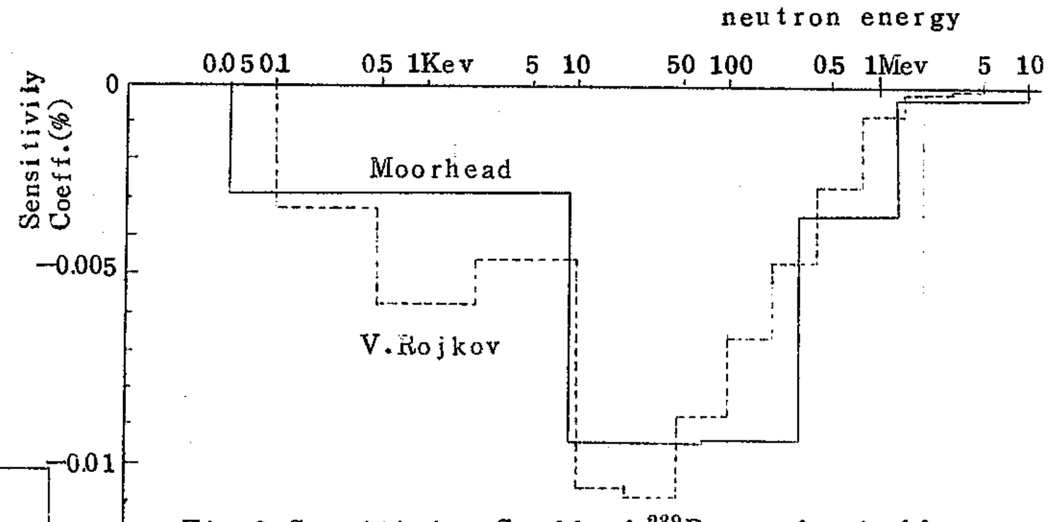


Fig.3. Sensitivity Coeff.of ^{239}Pu σ_c for keff.

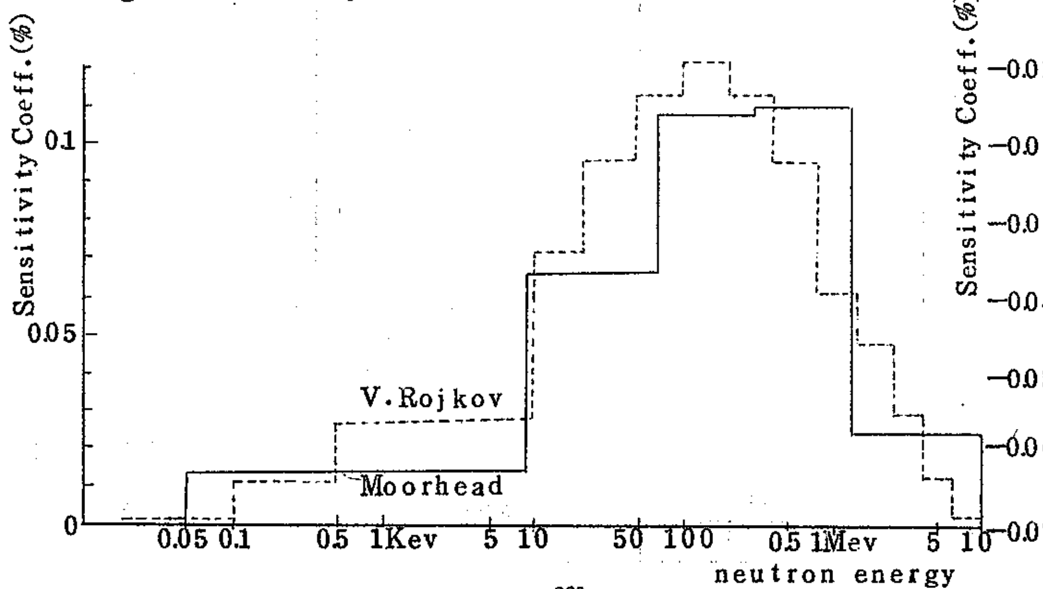


Fig.2. Sensitivity Coeff.of ^{239}Pu σ_c for keff.

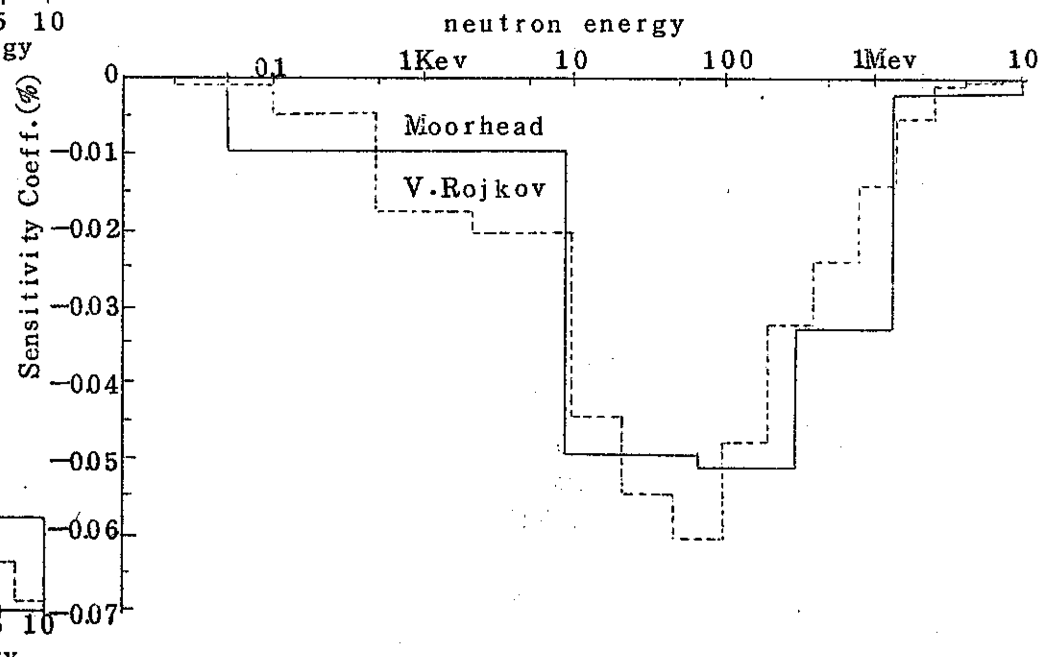


Fig.4. Sensitivity Coeff.of ^{238}U σ_c for keff.

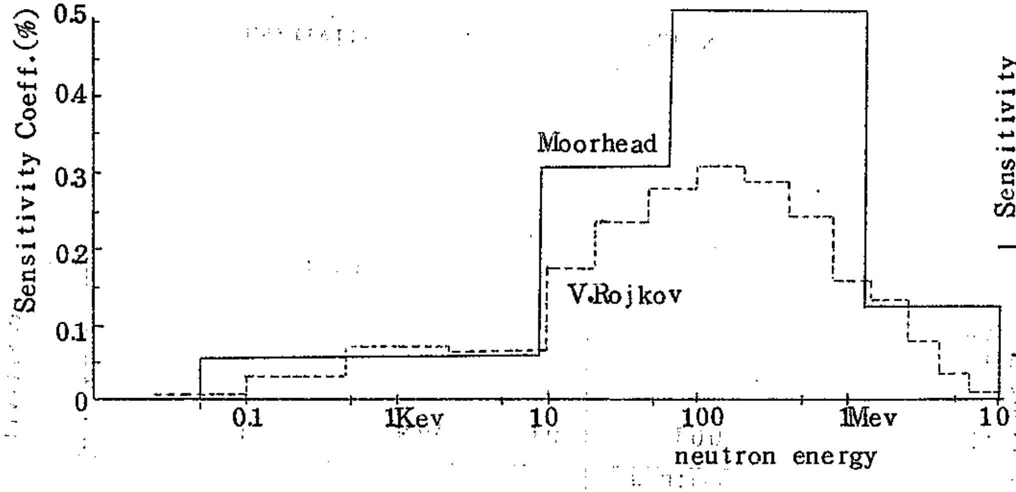


Fig.5. Sensitivity Coeff. of ^{239}Pu ν for Breeding Ratio.

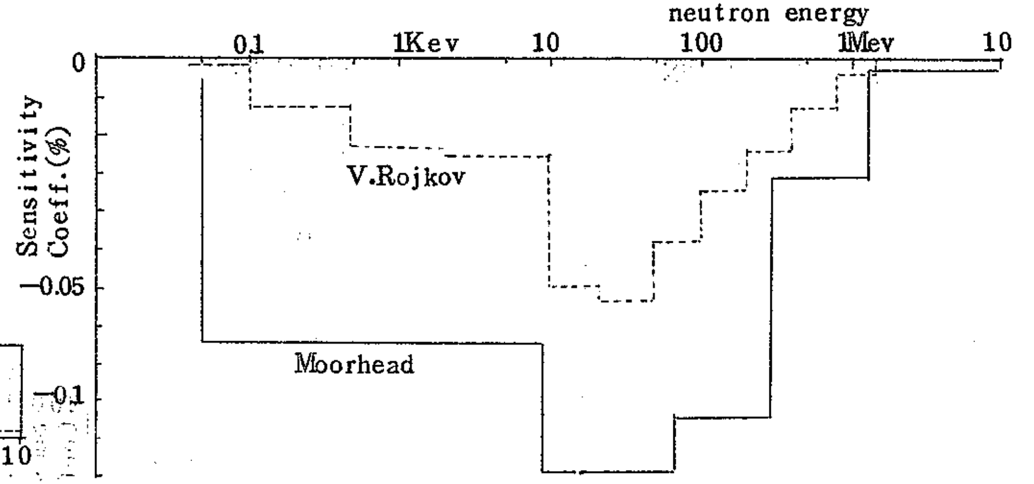


Fig.7. Sensitivity Coeff. of ^{239}Pu σ_c for Breeding Ratio.

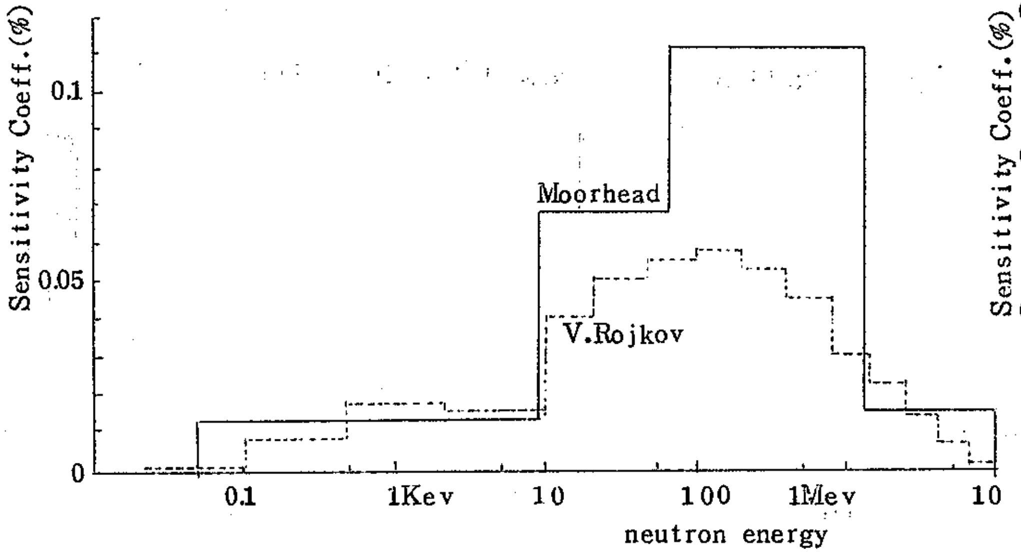


Fig.6. Sensitivity Coeff. of ^{239}Pu σ_f for Breeding Ratio.

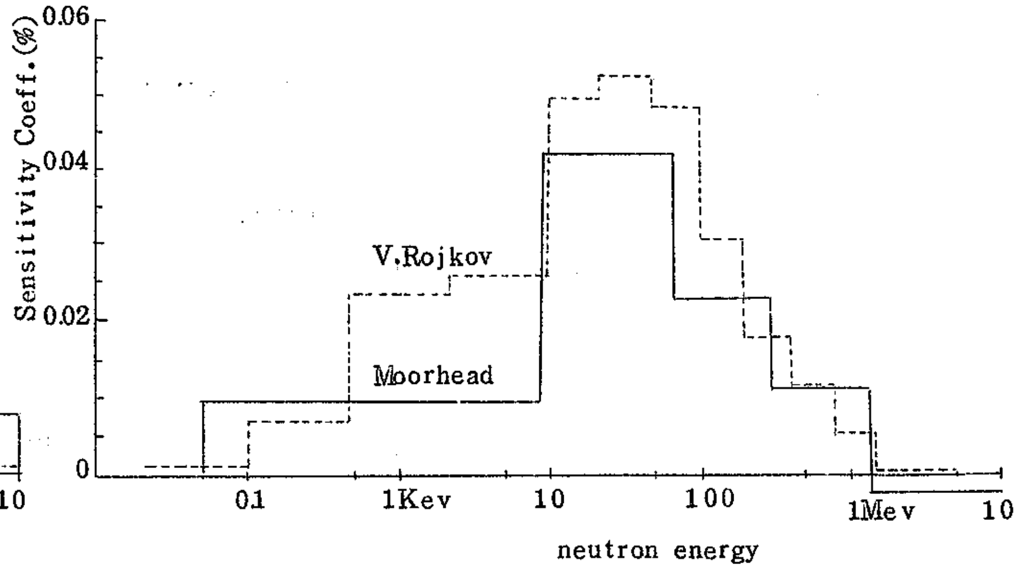


Fig.8. Sensitivity Coeff. of ^{238}U σ_c for Breeding Ratio.

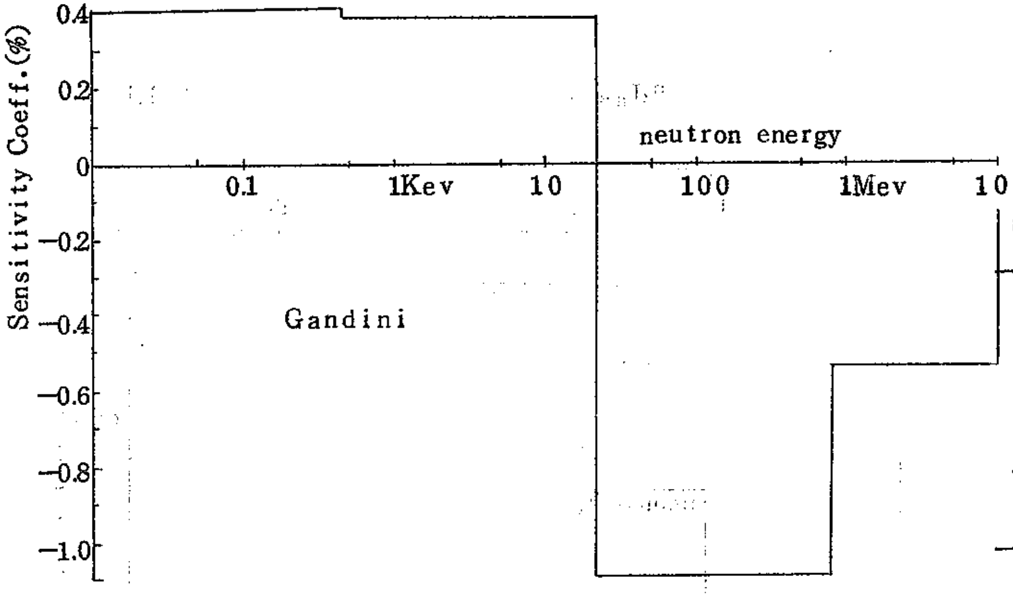


Fig.9. Sensitiviy Coeff.of ^{239}Pu ν for Na-Void Reactivity.

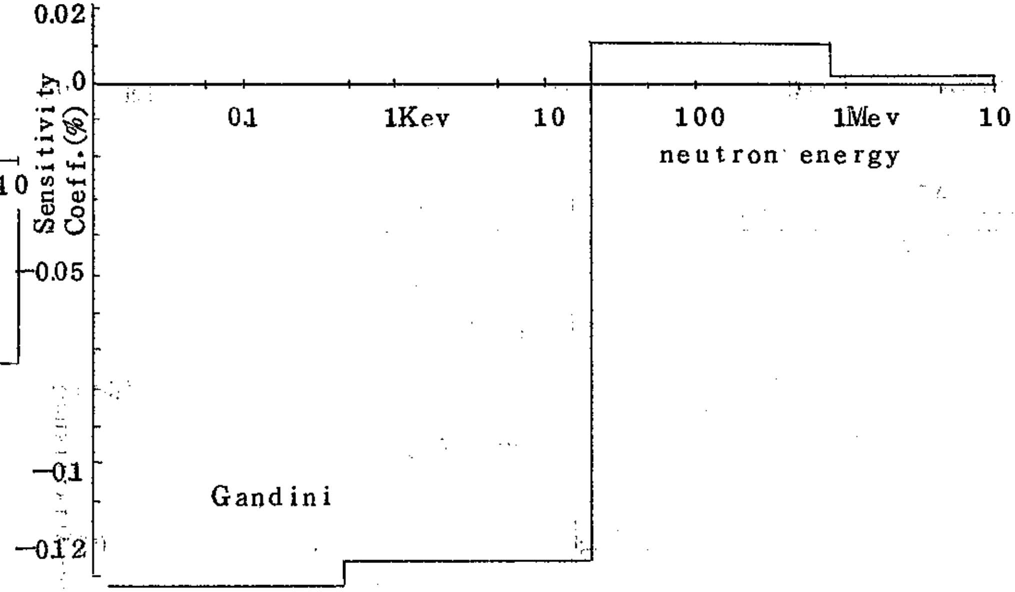


Fig.11. Sensitivity Coeff. ^{239}Pu σ_c for Na-Void Reactivity.

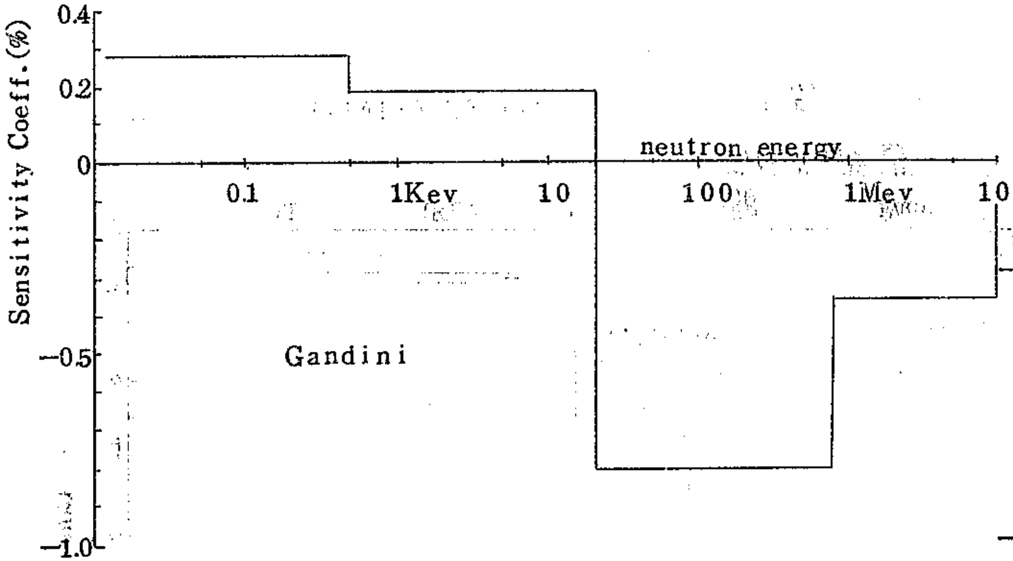


Fig.10. Sensitivity Coeff.of ^{239}Pu σ_f for Na-Void Reactivity.

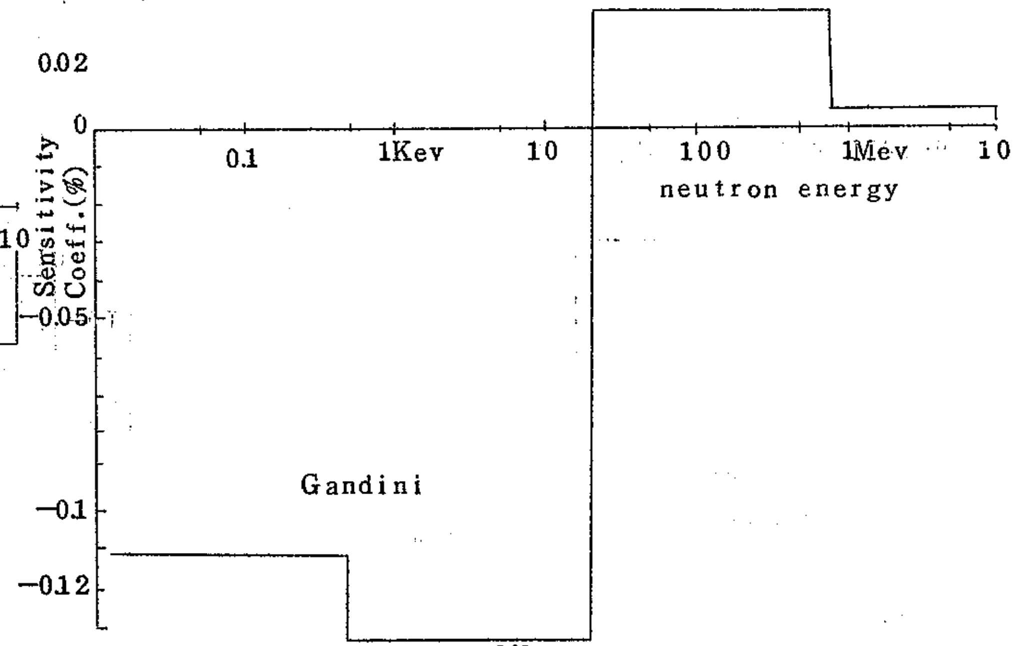


Fig.12. Sensitivity Coeff. ^{238}U σ_c for Na-Void Reactivity.

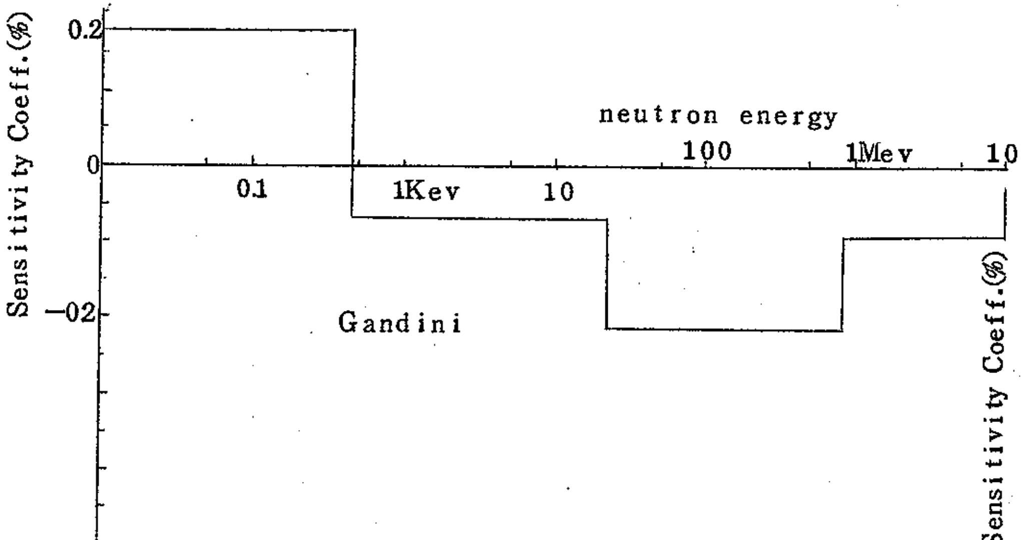


Fig.13. Sensitivity Coeff.of ^{239}Pu ν for Doppler Reactivity.

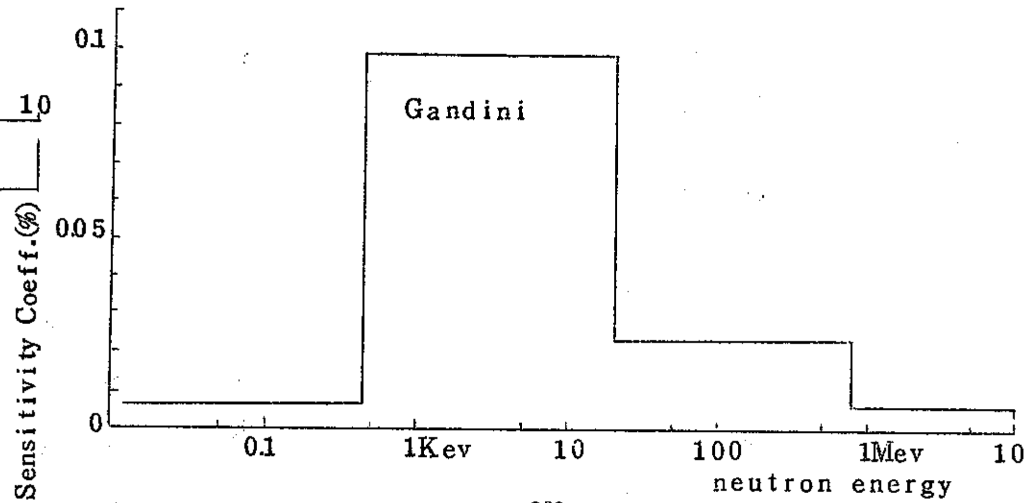


Fig.15. Sensitivity Coeff.of ^{238}U σ_c for Doppler Reactivity.

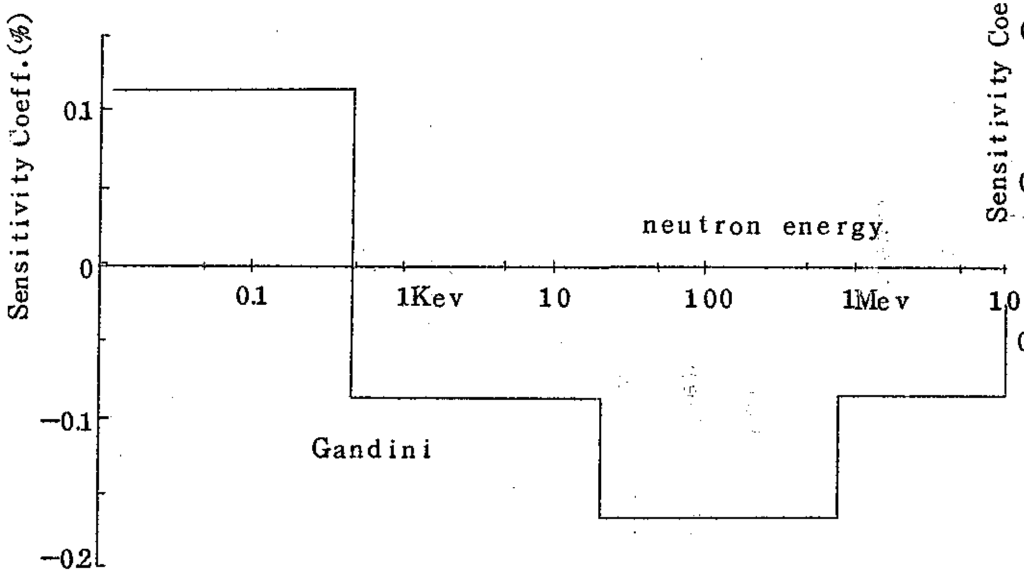


Fig.14. Sensitivity Coeff.of ^{239}Pu σ_f for Doppler Reactivity.

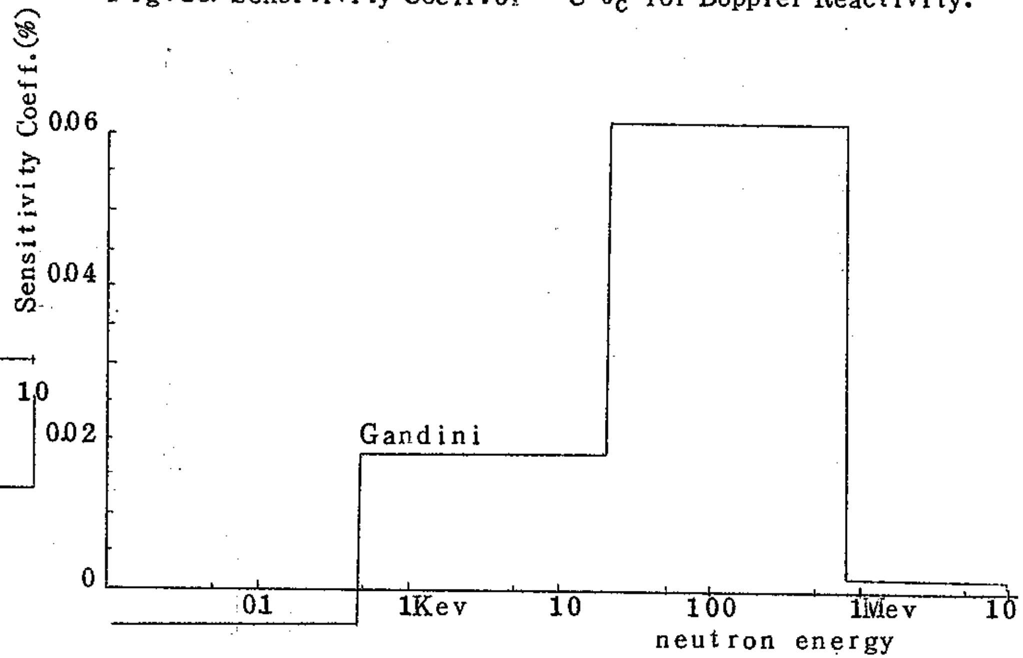


Fig.16. Sensitivity Coeff.of ^{16}O σ_{el} for Doppler Reactivity.

3. Method of sensitivity analysis

From what has been found as a result of the above literature examination, we will discuss the various problems to be solved in making sensitivity analysis and the remedial measures against such problems.

3.1 Choice of standard library

At first we thought of using the group constants obtained from ENDF/B-II as the standard library. ENDF/B-II has been made by making improvements to the consistency of fission cross section, the non-elastic scattering cross section of ^{238}U, the resonance cross section of structural material, and the resonance cross section of ^{240}Pu in ENDF/B-I. However, a study made early 1971 by ENDF/B working group showed that ENDF/B-II underestimated the eigen value by 3% to 5% (ENDF/B-I underestimated the same value by 2%). This was due to such causes as follows.

(i) The imperfection of microscopic data, which had so far been offset, became pronounced as the microscopic data were improved.

(ii) There were some big mistakes somewhere in ENDF/B-II data.

(iii) ENDF/B-I was revised in an attempt to improve it but it was actually made worse than before.

According to the results of the analytical studies made in the United States after the development of ENDF/B-II, they concluded that the trouble with ENDF/B-II was due to the third cause. In the present sensitivity analysis, our policy was to approximate the relationship between the nuclear data variations and the nuclear characteristics by a simple equation and therefore it is undesirable to use such imperfect group constants as the standard.

So, decided to perform our sensitivity analysis by using HIM-1 group constant which was developed by Hitachi so that if any appropriate results were obtain HIM-1 would be used as the standard group constants.

3.2 Method of calculation of sensitivity coefficients

The most basic approximation for obtaining the sensitivity coefficients is the approximation of the relationship between the nuclear data variations and the nuclear characteristics by a linear equation. This approximation is considered to be a sufficient good approximation as shown by the results of the analysis made by Moorhead.[1] When obtaining the sensitivity coefficients, the adjustment of critical mass has a great effect on the breeding ratio. In the present analysis, the relationship between the eigen value variations and the breeding ratio variations when the degree of enrichment was varied.

$$\Delta BR = A \times \Delta k \qquad (3.1)$$

where ΔBR : variation of breeding ratio

Δk : variation of eigen value

A : ratio coefficient

By using this equation, the breeding ratio was compensated as follows.

$$BR = BR^{o} - A \times (K_{eff} - K^{o}_{eff}) \qquad (3.2)$$

where BR^{o} : breeding ratio before compensation

K_{eff} : effective multiplication factor when nuclear constant was varied

K^{o}_{eff} : effective multiplication factor when standard nuclear constants were used

A value of -1.90 was used for A.

The sensitivity coefficient is obtained by varying the group constants of infinite dilution. The sensitivity coefficient is defined as follows.

$$g_{ax}^{iJ} = \frac{\Delta a_x^{iJ}}{a} \bigg/ y_x^{iJ} \qquad (3.3)$$

where Δa_x^{iJ} is the amount of variation of the physical quantity a when σ_x^{iJ} varied by y_x^{iJ} and g_{ax}^{iJ} is the sensitivity coefficient at that time. x is the kind of nuclear constants, σf, σc, σt, σel, σin, ν. J is the energy group of the nuclear constant which is varied, i is nuclide.

Next, the sensitivity coefficient G_{ax}^{iJ} including the interrelation between the nuclear constants will be considered. First, let us consider the interrelation between the nuclear constants.

$$\sigma_t = \sigma_a + \sigma_s \qquad (3.4)$$

$$\sigma_a = \sigma_f + \sigma_c \qquad (3.5)$$

$$\sigma_s = \sigma_{in} + \sigma_{el} \qquad (3.6)$$

Hence

$$\sigma_t = \sigma_f + \sigma_c + \sigma_{in} + \sigma_{el} \qquad (3.7)$$

σf and σc can be related as follows by the value α .

$$\alpha = \frac{\sigma_c}{\sigma_f} \qquad (3.8)$$

ν is independent of other nuclear constants.

Let us consider the interrelation between the nuclear constants by using the equations (3.7) and (3.8). Assuming σ_Z^{iJ} varied by y_x^{iJ} and thereby other nuclear constants $\sigma_Y^{iJ}(Y \neq X)$, σ_Z^{iJ} $(Z \neq X,\ Z \neq Y)$, ..., varied by y_Y^{iJ} , y_Z^{iJ} ..., respectively,

$$\sigma_x^{iJ} \rightarrow \sigma_x^{iJ} \quad (1 + y_x^{iJ}) \tag{3.9}$$

$$\sigma_Y^{iJ} \rightarrow \sigma_Y^{iJ} \quad (1 + y_Y^{iJ}) \tag{3.10}$$

$$\sigma_z^{iJ} \rightarrow \sigma_z^{iJ} \quad (1 + y_z^{iJ}) \tag{3.11}$$

The sensitivity coefficient G_{ax}^{iJ} including the interrelations of the nuclear constants is given by

$$G_{ax}^{iJ} \cdot y_x^{iJ} = g_{ax}^{iJ}\, y_x^{iJ} + g_{aY}^{iJ}\, y_Y^{iJ} + g_{az}^{iJ}\, y_z^{iJ}$$

$$\therefore\ G_{ax}^{iJ} = g_{ax}^{iJ} + g_{aY}^{iJ}\,\frac{y_Y^{iJ}}{y_x^{iJ}} + g_{az}^{iJ}\,\frac{y_z^{iJ}}{y_x^{iJ}} \tag{3.12}$$

If y_Y^{iJ} and y_Z^{iJ} are expressed by y_X^{iJ} by using the equations (3.7) through (3.11) and substituted in (3.12), G_{ax}^{iJ} can be obtained.

4. Improvement of sensitivity coefficient calculation program

In order to make calculations of the sensitivity coefficients discussed in the preceding chapter, improvements have been made to the one-dimensional diffusion code as briefly described below.

The calculation for altering the microscopic cross section σ_x^{iJ} to $\sigma_x^{iJ}(1 + y_x^{iJ})$ was made in "ABAGYAN" which was the previously used library production code. ABAGYAN code and the one-dimensional diffusion code "SUNRISE-4-3" were joined together for the calculations of physical quantities. Finally, using the results of such calculations, the sensitivity coefficients were obtained.

The flow diagrams are shown below. (Fig. 17 through Fig. 19). The previous "ABAGYAN" was used for MAIN-1, SUNRISE-4-3 for MAIN-2, and the sensitivity coefficient calculation section for the subroutine of MAIN-3 and they were connected by the whole MAIN as shown in Fig. 20.

Fig.17. Micro data change routine.

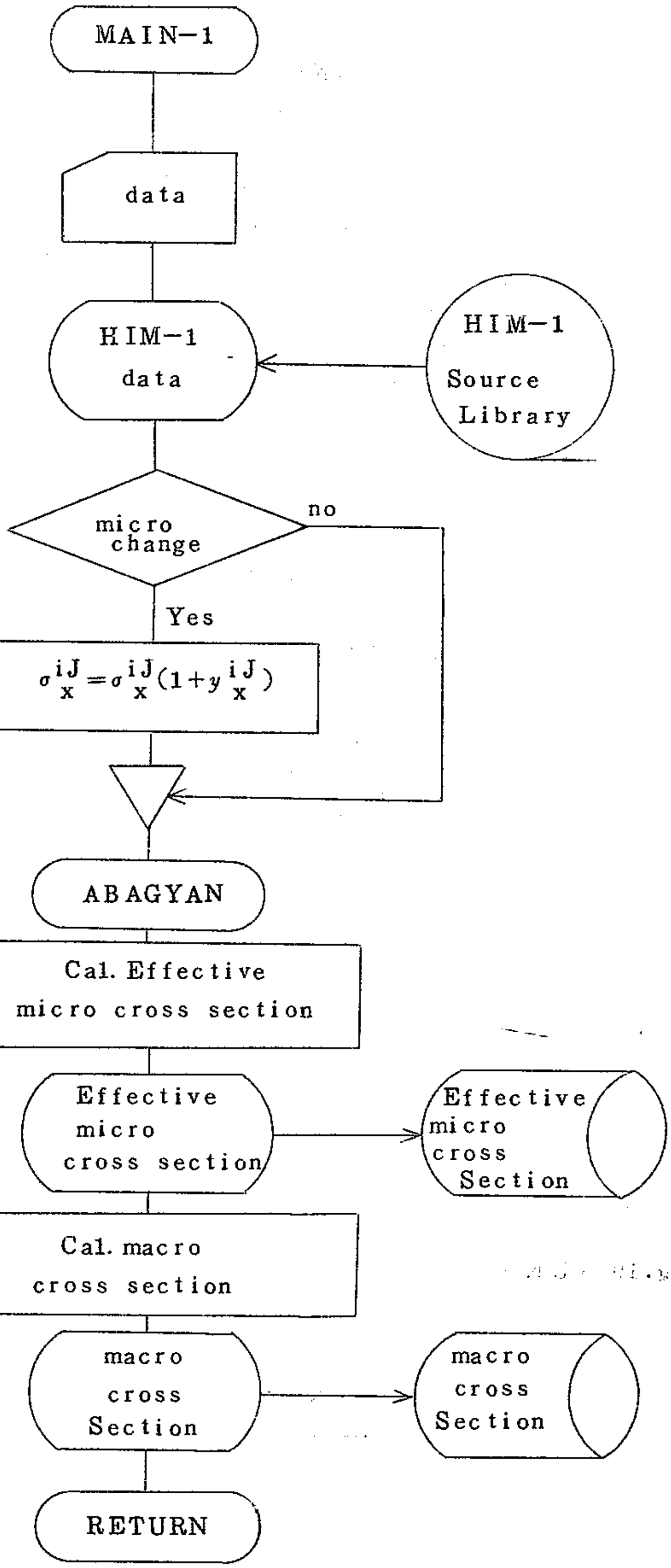


Fig.18. Sensitivity Coefficients Calculation Routine.

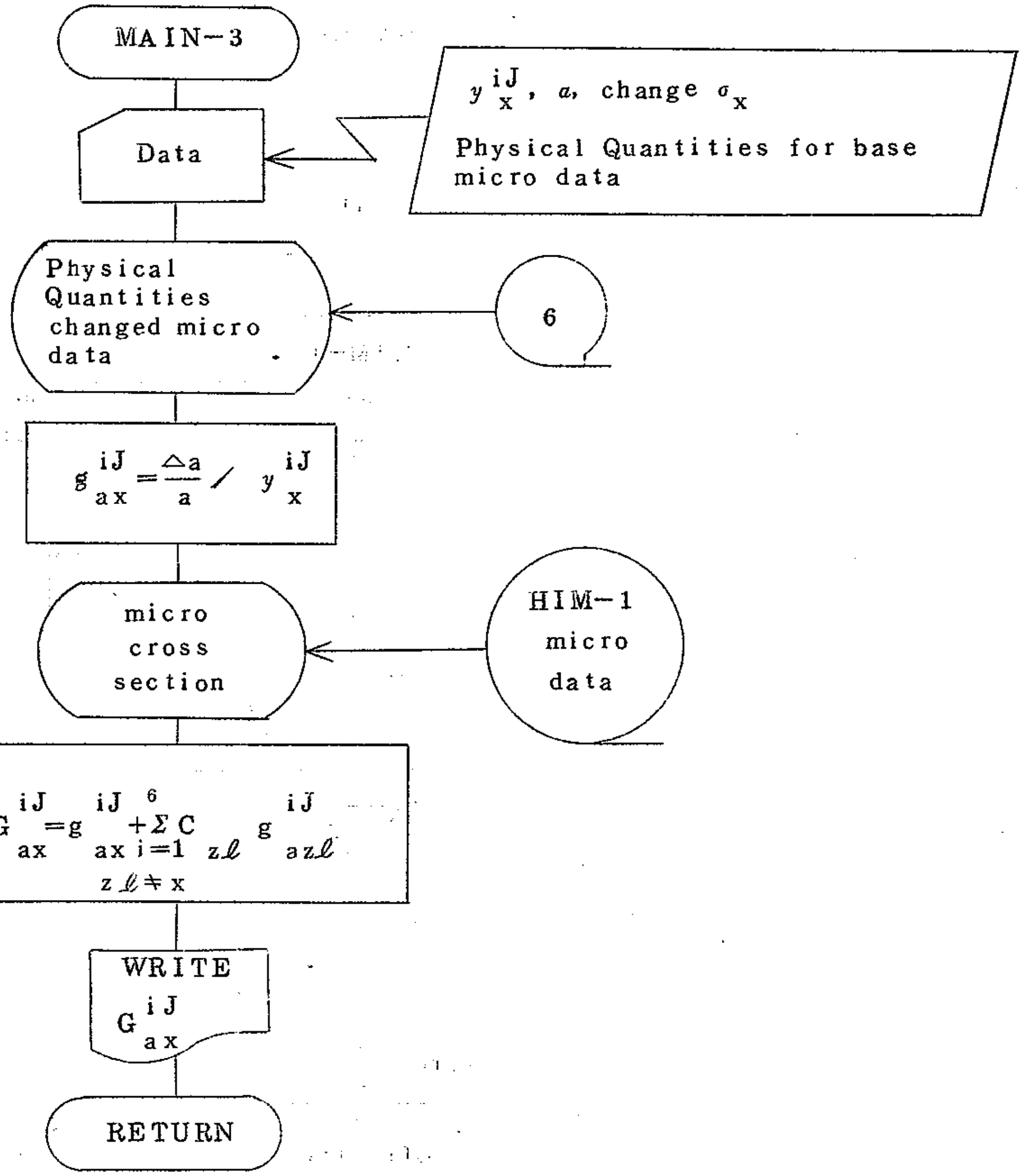
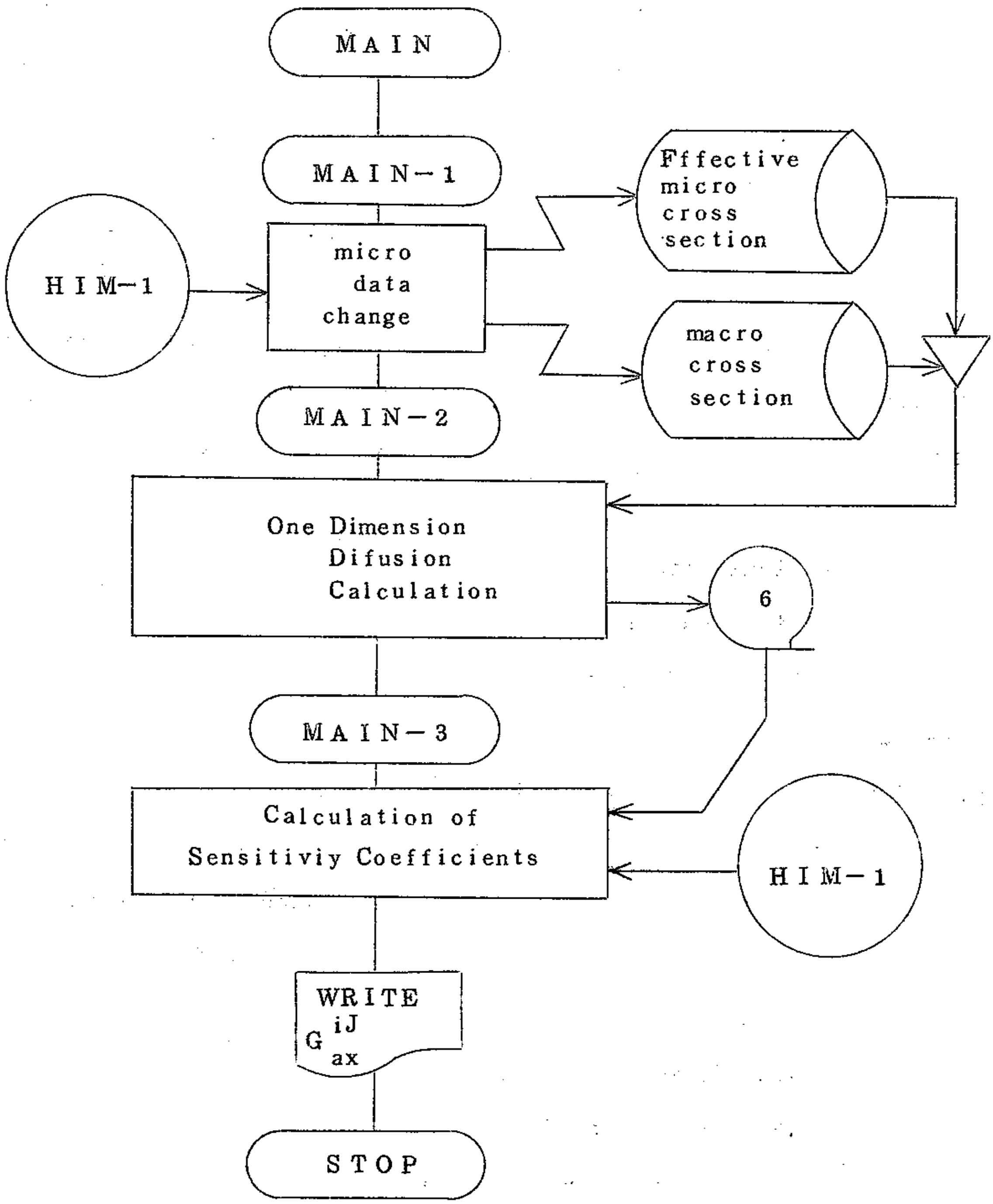


Fig.19. SUNRISE−4−3

Fig.20. Whole Flow Diagram.



5. Test of HIM-1 as standard nuclear constants

In order to study the validity of HIM-1 as the standard nuclear constants, we made analysis the Bench Mark integral experiments. As for the calculation model, we used the Bench Mark analysis model and applied one-dimensional diffusion and one-dimensional transport calculation for the spherical homogeneous model. In the one-dimensional transport calculations, the transport approximation was used for anisotropic diffusion. It is not necessary to correct the effective multiplication factor for the anisotropical effects as far as the Bench Mark analysis model is used. As for the reaction rate ratio, which was equally emphasized as the effective multiplication factor, the anisotropical effects were extremely small. In this report, we will discuss the results of the Bench Mark analysis of the Bench Mark series from No.1 to No.4 with the plutonium core, which is closely related to the "MONJU" core.

5.1 Outline of Bench Mark series No.1 - No.4

The Bench Mark series have their own nuclear characteristics. Table 2 shows the compositions of the Bench Mark series No.1 - No.4. Table 2 shows that these Bench Mark series have the following characteristic features.

No.1: Bare core consisting of only plutonium

No.2: Core consisting of SUS and plutonium, provided with natural uranium reflector

No.3: Core consisting of SUS, sodium, plutonium, carbon, depleted uranium, provided with depleted uranium reflector

No.4: Core consisting of SUS, plutonium, and natural uranium, provided with natural uranium reflector

Such structural features are also clearly seen in the neutron spectrum shown in Fig. 21. The neutron spectrum in Fig. 21 is the spectrum of the core center calculated by the one-dimensional transport calculation code ANISN, in which the integral value of energy is normalized to 100.0. No. 1 is the core with a large leakage and containing no moderator. The neutron spectrum has a peak near 2MeV and has a sharp form similar to the fission neutron spetrum. Therefore, this is particularly suited for studying of the validity of σ_f of ^{239}Pu, particularly above 1MeV through the effective multiplication factor and the ratio of σ_f over 1MeV through the reaction rate ratio. In No.2, since the core is consisted of SUS and carbon and has reflector, the peak energy of the spectrum is about 1.0MeV and shows a wide spectrum form because of the carbon content. The nuclear constants within the energy range of 100KeV to 3MeV have great effects and therefore suit for studying particularly the validity of the nuclear constants of ^{239}Pu in the region. In No.3, the plutonium fissile enrichment is about 20% and SUS, sodium and carbon are contained in the core. Although the plutonium enrichment is somewhat larger than in the case of the core of the prototype reactor class, this core is considerably close to the core of the prototype reactor class in the respect of the neutron spectrum. The peak energy of neutron spectrum is near 350KeV and σ_f of ^{239}Pu and σ_c of ^{238}U within the range of 10KeV to 1.5MeV have great effects on the effective multiplication factor. In No.4, the fissile enrichment is about 10%, relatively small. Since the core does not contain the moderators such as sodium and carbon, the peak energy of the neutron spectrum is ~ 400KeV, and shows a very sharp spectrum form. σ_f of ^{239}Pu and σ_c of ^{238}U within the range of 100keV to 1.0MeV have great effects on the effective multiplication factor.

5.2 Study on the results of analysis

An analytical study was made on the effective multiplication factor and central reaction rate ratio by the one-dimensional transport calculation. One-dimensional diffusion calculation was partially used. In the one-dimensional transport and diffusion methods, the effective groups constants for σ_{tr} were defined as follows.

$$\text{Diffusion calculation} \; \ldots\ldots \; \frac{\Sigma \phi_i}{\Sigma \frac{1}{\sigma^i_{tr}} \phi^i}$$

$$\text{Transport calculation} \; \ldots\ldots \; \frac{\Sigma \phi^i_{tr} \phi^i}{\Sigma \phi^i}$$

where ϕ^i is the spectrum of the i-th group. When diffusion calculations were made by using σ_{tr} which was obtained by the definition in the transport calculations, the effective multiplication factor of ZPR-III Assembly 11 was overestimated by~ 0.1%.

5.2.1 Effective multiplication factor

The number of order of each angle division for the core, N is as follows.

Bench Mark No.	1	2	3	4
SN	S16	S8	S16	S8

The degrees of convergence for N in No.1 and No.3 cores are

	No. 1	No. 3
S2	1.0567	1.0074
S4	1.0242	0.9984
S8	1.0142	0.9978
S16	1.0114	0.9976

Therefore, the effective multiplication factor shown in Table 3 is a difference of about 0.3% ΔK in No.1 core and less than 0.1% ΔK in No.2 through No.4 for S^{∞}.

The results of calculations of the effective multiplication factors in Table 3, show the following things ;

1. HIM-I agrees very well with the experimental results for the effective multiplication factor of No.2 and No.3 cores. This shows that the errors of calculation for the effective multiplication is within 1% for the core of the prototype reactor class. Therefore, we think there is no problem about using HIM-I for the standard group constants from the standpoint of the effective multiplication factor.
2. For No.1 core, HIM-I overestimates the effective multiplication factor by about 1%. This is presumably because σ_f of ^{239}Pu above 1MeV is 1% to 2% too large.
3. For No.4 core, HIM-I underestimates the effective multiplication factor by about 1.5%. This is probably because σ_c of ^{238}U of HIM-I is about 5% to 10% too large within the range of 50KeV to 500KeV.

5.2.2 Central reaction rate ratio

Table 4 shows the results of the one-dimensional transport calculations. The experimental values are so well in agreement with the calculated values that there is no serious problem with HIM-I in view of the reliability of the group constants at the present time. From the results of analysis of the reaction rate ratio, the following problem can be pointed out to be further studied for the improvement of HIM-I in the future. The problems are whether the value of ^{235}U σ_f above 2MeV is too large, whether σ_f of ^{238}U near 1MeV is too large, and whether the moderation of ^{238}U due to the inelastic scattering is too large.

From the above-mentioned results of the test of HIM-I, we reached the conclusion that although there are some points to be studied further in the future, there is no problem about using HIM-I as the standard group constants in the present study.

Table 2. Composition of Bench Mark Core.

Bench Mark Series No.	1	2		3		4	
region	core	core	reflector	core	reflector	core	reflector
Average atom number density of each region (10^{-24}/cc)							
Pu 239	.037483	.007213		.001645		.003465	
Pu 240	.001768	.000370		.000107		.000183	
Pu 241	.000184	.000028		.000011		.000016	
U 235			.000250	.000016	.000083	.000228	.000301
U 238			.034400	.007405	.039976	.031560	.040990
U 234							
U 233							
Fe		.006090	.006460	.010180	.004925	.004559	.003496
Cr		.001580	.001680	.002531	.001196	.000818	.000913
Ni		.000660	.000710	.001119	.000536	.000321	.000360
C		.046200		.020770			
Na				.006231			
Mo				.000206			
Al				.000233	.000060		
Cu		.008050				.004794	
Mn				.000106	.000051		
core radius (cm)	6.284	13.985		46.46		23.67	
reflector thickness (cm)			43.0		30.0		30.50

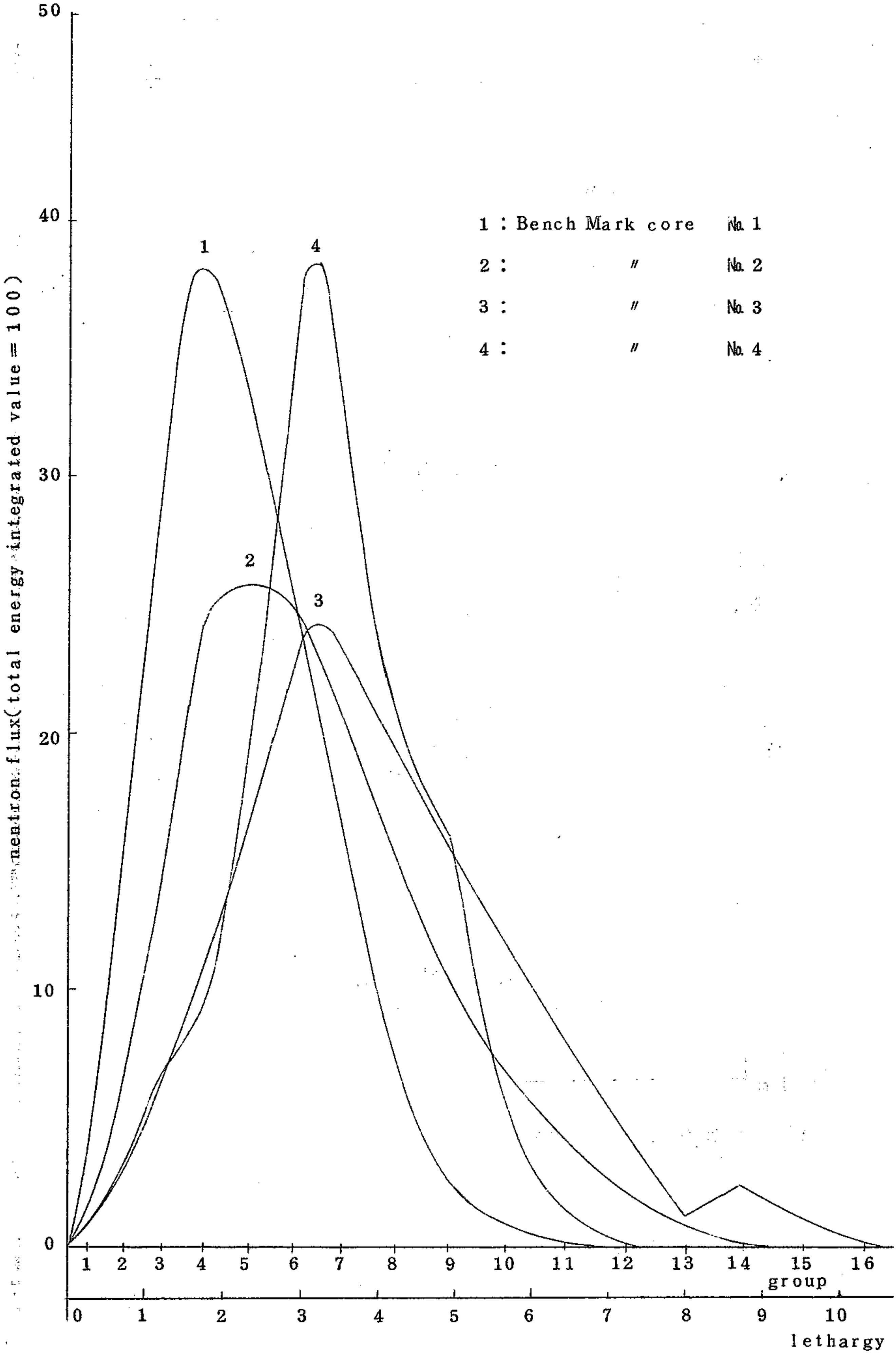


Fig.21 Central spectrums of Bench Mark cores.

Table 3. Comparison of experimental value and calculated value of effective multiplication factor (Bench Mark core).

Problem No.	1	2	3	4
A B B N	1.016	1.017	1.047	1.004
H I M - I	1.011	1.000	0.998	0.986
exp.	1.000 ± .003	1.000 ± .004	1.000 ± .004	1.000 ± .003

Table 4. Comparison of experimental value and calculated value of reaction rate ratio (Bench Mark core).

Problem No.	1			2			3			4		
	exp.	cal.	cal./exp.	exp.	cal.	cal./exp.	exp.	cal.	cal./exp.	exp.	cal.	cal./exp.
$\sigma f^{28} / \sigma f^{25}$	0.205 ±.008	0.1925	0.94	0.077 ±.002	0.0885	1.15	0.0407 ±.0004	0.03157	1.03	0.0462 ±.0008	0.0418	0.91
$\sigma f^{23} / \sigma f^{25}$	1.61 ±.10	1.555	0.97	1.49 ±.03	1.572	1.06	1.480 ±.015	1.5392	1.04	1.542 ±.019	1.6059	1.04
$\sigma f^{49} / \sigma f^{25}$	1.49 ±.03	1.375	0.92	1.07 ±.02	1.129	1.06	0.976 ±010	0.9364	0.96	1.190 ±.114	1.1508	0.97
$\sigma f^{40} / \sigma f^{25}$	—	—	—	0.475 ±.020	0.4982	1.05	0.243 ±.002	0.2462	1.01	0.373 ±.005	0.3743	1.00
$\sigma f^{26} / \sigma f^{25}$	—	—	—	—	—	—	—	—	—	0.099 ±.005	0.0998	1.01
$\sigma c^{28} / \sigma f^{25}$	—	—	—	—	—	—	0.138 ±.004	0.1387	0.98	—	—	—
$\sigma f^{28} / \sigma f^{49}$	0.138	0.1411	1.02	0.072	0.0784	1.09	0.0315	0.03370	1.07	0.0388	0.03632	0.94
$\sigma c^{28} / \sigma f^{49}$	—	—	—	—	—	—	0.141	0.1481	1.05	—	—	—
$\sigma f^{40} / \sigma f^{49}$	—	—	—	0.444	0.4413	0.99	0.249	0.2630	1.06	0.314	0.3252	1.04

6. Calculations of sensitivity coefficients

The calculations of sensitivity coefficients were made on the equilibrium core of the second design of "MONJU". Its composition is shown in Table 5. As for the changing of the nuclear constants, 26 groups were divided into 6 energy groups as shown in Table 6 and the nuclear constants in each group were changed at the same rate.

6.1 Calculation model

The calculations were made by one-dimensional cylindrical diffusion method. The contribution of the axial blanket to the breeding ratio was considered in the following form.

$$(BR)_{Rad}{}^{k}\ \frac{DB^{2}{}_{k}}{L_{Rad}} \times \frac{N^{2'8}_{ax}}{N^{28}_{Rad}} \qquad (6.1)$$

where $(BR)_{Rad}$ is the contribution of the radial blanket to the breeding ratio, and DB_z^2 is

$$DB_z^2 = B_z^2 \sum_{1} \int D^i \phi^i dV \qquad (6.2)$$

B_z^2 is the axial buckling, D^i is the diffusion coefficients of the i-th group, and N^{28}_{ax} and N^{28}_{Rad} are the atomic number density of ^{238}U in the axial and radial blankets. As for the changes in the Doppler reactivity and Na-void reactivity when the nuclear constants were varied, we made calculations by the perturbation method by using the neutron flux and neutron importance obtained by varying the nuclear constants. In the calculation of Na-void reactivity, the effects of the changes in the self-shielding were considered for ^{239}Pu and ^{238}U.

6.2 Determination of the condition of convergence for sensitivity coefficient calculations

As for the nuclear constants, we assumed 10% changes for each energy group. In this case, we made preliminary sensitivity calculations from the viewpoint of obtaining the required calculation accuracy for sensitivity coefficients and the time to calculate. The preliminary calculations were made on ZPR-III — Assembly 48 because of the similarity in the system. We made a study in the case in which the condition of convergence for the effective multiplication factor was 10^{-5}, 5.0×10^{-6} and 5.0×10^{-7}. When judging the convergence by the effective multiplication factor, the problem is the accuracy of calculation of the neutron flux in a region specially far from the center, the neutron flux in a low-energy region, and the neutron importance. Such being the case, we paid special attention to the worth of B-10 in the core center. Tables 7 through 10 show the sensitivity coefficients of nuclear characteristics and the frequency of convergence under the convergence conditions of 1.0×10^{-5}, 5.0×10^{-6}, and 6.0×10^{-7}. From these results, it is known that the convergence condition of 1.0×10^{-5} is sufficient to obtain significant sensitivity coefficient for each nuclear characteristics. To calculate a sensitivity coefficient of more than one effective figure for all cross section changes is not only meaningless but also a waste of time because the convergence frequence becomes very large.

6.3 Sensitivity coefficients not including interrelations

Here we discuss the results of calculation of the sensitivity coefficients g_{ax}^{iJ} not including the interrelations defined by equation (3.3) of Paragraph 3-2 for the effective multiplication factor, breeding ratio, Na-void reactivity (100% void), and Doppler reactivity (1173 °K → 1473 °K). g_{ax}^{iJ} is given by the percentage change for 1% change of nuclear constants.

The effective multiplication factors are shown in Table 11. The first column in this table shows the nuclides and nuclear cross sections when the nuclear constants were changed. The second and following columns show the values of effective multiplication factors in the respective energy regions. These values are the values when the nuclear constants were changed 10% and the value for the standard nuclear constants is K_{eff} = 1.04786. Table 12 shows the sensitivity coefficients for the effective multiplications factors (when the interrelations are not included).

As for the breeding ratio, Table 13 shows the ratios not corrected by the effective multiplication factor and Table 14 shows the corrected ratios. The correction was made by equation (3.2). The sensitivity coefficients (not including the interrelations) for the breeding ratio are shown in Table 15.

The Na-void reactivities are shown in Table 16 and the sensitivity coefficients in Table 17. The Doppler reactivities are shown in Table 18 and the sensitivity coefficients in Table 19.

6.4 Sensitivity coefficients including the interrelations

Table 20 through 23 show the sensitivity coefficient including the interrelations which were obtained on the basis of equation (3.12). These values are graphically shown in Figs. 22 through 30. Since the values given in the tables were equivalent to the integral values in the energy regions, the graphs shown the values obtained by dividing them by the letharge width of the energy region.

6.4.1 Sensitivity coefficients for the effective multiplication factors

The sensitivity coefficients for the effective multiplication factors are shown in Tables 20 and Fig. 22 and Fig. 23. The characteristic features of these sensitivity coefficients are as follows. The values used below are the values from the graphs.

(1) As was naturally expected, the sensitivity coefficients of σf and ν of ^{239}Pu are large. It is particularly notable that the sensitivity coefficient of ν has such a value as ~ 0.12% and that of σf has a value of about ~ 0.08% within the energy region of 1MeV to 100KeV and they are about ~ 0.08% and 0.05%, respectively, even in the region of 100KeV to 10KeV.

(2) The next largest values are shown by σf and ν of ^{238}U in the energy region of above 1.4MeV. They show such values as ~ 0.03% and ~ 0.04%, respectively. σc of ^{238}U shows a value of about ~ -0.03% in the region of 100KeV to 10KeV and about ~ -0.02% even in the region of 1.4MeV to 100KeV.

(3) σc and ν of ^{241}Pu show values of ~ 0.02% and ~ 0.03%, respectively, within the region of 400KeV to 10KeV.

(4) The sensitivity coefficient of σc of Fe is almost sero except that it shows a value of about -0.004% within the region of 100KeV to 10KeV.

6.4.2 Sensitivity coefficients for breeding ratios

The sensitivity coefficients for the breeding ratio are shown in Table 21 and Fig. 24 and 25.

(1) The largest sensitivity coefficient is shown by ν of ^{239}Pu. It is about 0.2% within the region of 1.4MeV to 100KeV and over 0.1% even in the region of 100KeV to 10KeV.

(2) The sensitivity coefficient of ν of ^{238}U shows a value close to 0.1% at over 1.4MeV.

(3) The sensitivity coefficient of ν of ^{241}Pu shows a value of about 0.06% at 400KeV to 10KeV.

(4) Among those which show negative values of sensitivity coefficients, σc of ^{239}Pu shows a relatively large value, about -0.03% at 400KeV to 10KeV.

(5) The sensitivity coefficient of σc of ^{238}U shows so large a value as close to 0.07% at 100KeV to 10KeV. This is predictable because ^{238}U is a fertile nuclide.

6.4.3 Sensitivity coefficients for Na-void reactivity

The sensitivity coefficients for Na-void reactivity are shown in Table 22 and Figs. 26 and 27 and 28.

(1) σf and ν of ^{239}Pu which is a fuel element shows such large sensitivity coefficients as to be more than -1.0% at 1.4MeV to 400KeV. The sensitivity coefficient of σc of ^{239}Pu shows values close to -0.1% at below 10KeV. The sensitivity coefficient of ν of ^{239}Pu shows positive values at below 100KeV, about 0.5%.

(2) The sensitivity coefficient of σf and ν of ^{238}U show the value close to -0.03% above 1.4MeV. The sensitivity

coefficient of σin of ^{238}U showed so large values as -0.14% at 1.4MeV to 100KeV.

(3) Apart of the fuel element, σt of the sodium itself (including the moderating effect) had sensitivity coefficients, close to 0.1% particularly at 400KeV to 10KeV. σt of oxygen has sensitivity coefficients larger than -0.3% at 1.4MeV to 100KeV.

6.4.4 Sensitivity coefficients for Doppler reactivity

The sensitivity coefficients for Doppler reactivity are shown in Table 23 and Figs. 29 and 30.

(1) The sensitivity coefficient of σt of moderated elements (including moderating effect) has a large value. Especially, that of σt of *O* is 0.12 - 0.15% at 400KeV to 10KeV. That of σt of Na has a large value of 0.07 - 0.1% at 400KeV to 10KeV.

(2) Among the moderating elements, σf and ν of ^{239}Pu had the largest sensitivity coefficients, -0.07% to -0.12% at 1.4MeV to 10KeV. ν had such large sensitivity coefficients because ν of ^{239}Pu has the greatest effect to the neutron balance in the core. Its σf has sensitivity coefficients of 0.1 to 0.2% at 1.4MeV to 10KeV.

Table 5. Atomic number density in the middle of equilibrium MONJU core.

region	1	2	3	4	5	6
Pu 239	.0007321	.0010546	.0011052	.0001018	.0001181	
Pu 240	.0003381	.0004930	.0005063	.0000021	.0000078	
Pu 241	.0001457	.0002274	.0002418	.0	.0000005	
Pu 242	.0000577	.0000845	.0000861	.0	.0	
U 235	.0000070	.0000075	.0000081	.0000185	.0000185	
U 236	.0000005	.0000004	.0000003	.0000004	.0000006	
U 238	.0043960	.0044340	.0045809	.0098647	.0100390	
O	.0119180	.0132100	.0135450	.0200090	.0203790	
Na	.0105330	.0095740	.0090925	.0076396	.0076127	.0079285
Fe	.0129050	.0134900	.0137800	.0114630	.0114180	.0094871
Cr	.0034400	.0035970	.0036730	.0030650	.0030433	.0025287
Ni	.0021505	.0022490	.0022980	.0019100	.0019026	.0015809
Mo	.0002741	.0002866	.0002928	.0002435	.0002426	.0002015
C						.0389310
FP(U235)	.0000282	.0000240	.0000179	.0000108	.0000065	
FP(Pu239)	.0002440	.0002654	.0002136	.0000061	.0000086	
Outer radius of region (cm)	70.37	84.18	94.48	105.19	125.29	157.01
Buckling	.000622	.000622	.000622	.000386	.000386	.000386

Table 6. Energy Section in Sensitivity Analysis.

Group in HIM-1	Energy	Section in Sens. Ana.
1	6.5 - 10.5 MeV	1
2	4.0 - 6.5 MeV	
3	2.5 - 4.0 MeV	
4	1.4 - 2.5 MeV	
5	0.8 - 1.4 MeV	2
6	0.4 - 0.8 MeV	
7	0.2 - 0.4 MeV	3
8	0.1 - 0.2 MeV	
9	46.5 - 100 KeV	4
10	21.5 - 46.5 KeV	
11	10.0 - 21.5 KeV	
12	46.5 - 10.0 KeV	5
13	2.15 - 4.65KeV	
14	1.0 - 2.15KeV	
15	46.5 - 1000 eV	

Table 7. Sensivity Coeff.in Conversion Conditon 1.0×10^{-5}.

case / 10% change	Buckling	Neutron Life Time	keff		B10 Worth		Breeding ratio		Peaking Factor	
			keff	keff/keff(%)	A	△A/A(%)	A	△A/A(%)	A	△A/A(%)
0 no change	2.4900-3	2.5589-7	0.98820		−1.36725-1		1.57766		1.82685	
1 U25 σa 1~4 group	2.4900 〃	2.5590 〃	0.98817	−0.003	−1.36725	0.0	1.57758	−0.005	1.82685	0.0
2 〃 ν 〃	2.4900 〃	2.5586 〃	0.98825	+0.005	−1.36720	+0.004	1.57765	−0.001	1.82686	+0.0005
3 〃 σf 〃	2.4900 〃	2.5586 〃	0.98825	+0.005	−1.36720	+0.004	1.57765	−0.001	1.82687	+0.001
4 〃 σtr 〃	2.4900 〃	2.5589 〃	0.98820	0.0	−1.36726	−0.001	1.57766	0.0	1.82685	0.0
5 〃 σs 〃	2.4900 〃	2.5589 〃	0.98819	−0.001	−1.36727	−0.002	1.57766	0.0	1.82685	0.0
6 Pu49 σa 9~11	2.4835 〃	2.5257 〃	0.98109	−0.719	−1.33673	+2.232	1.53972	−2.405	1.82524	−0.088
7 〃 ν 〃	2.4974 〃	2.5186 〃	1.00920	+2.125	−1.36872	−0.108	1.57524	−0.153	1.82656	−0.016
8 〃 σf 〃	2.4974 〃	2.5186 〃	1.00920	+2.125	−1.36871	−0.107	1.57524	−0.153	1.82376	−0.169
9 〃 σtr 〃	2.4686 〃	2.5506 〃	0.98627	−0.195	−1.34579	+1.570	1.58542	+0.492	1.82896	−0.432
10 〃 σs 〃	2.4897 〃	2.5595 〃	0.98823	+0.001	−1.36799	−0.054	1.57729	−0.023	1.82778	+0.051
11 Fe σa 5~6	2.4900 〃	2.5590 〃	0.98811	−0.009	−1.36720	+0.004	1.57766	0.0	1.82684	−0.0005
12 〃 σtr	2.4949 〃	2.5571 〃	0.98911	+0.092	−1.37029	−0.222	1.57534	−0.147	1.82922	+0.130
13 〃 σs	2.4906 〃	2.5637 〃	0.98802	−0.018	−1.37059	−0.244	1.57738	−0.018	1.82725	+0.022

Table 8. Sensitivity Coeff. in Conversion Condition 5.0×10^{-7}.

case \ 10% change	keff		B10 Worth		Breeding ratio		Peaking Factor	
	keff	△A/A(%)	A	△A/A(%)	A	△A/A(%)	A	△A/A (%)
0 no change	0.98820		−1.36725-3		1.57766		1.82685	
1 U25 σ_a 1~4 group	0.98817	−0.003	−1.36725	0.0	1.57758	−0.005	1.82684	+0.0005
2 〃 ν 〃	0.98825	+0.005	−1.36720	+0.004	1.57765	−0.001	1.82686	+0.0005
3 〃 σ_f 〃	0.98825	+0.005						
4 〃 σ_{tr} 〃	0.98820	0.0						
5 〃 σ_s 〃	0.98819	−0.001						
6 Pu49 σ_a 9~11	0.98109	−0.719	−1.38673	+2.232	1.53972	−2.405	1.82525	−0.088
7 〃 ν 〃	1.00920	+2.125						
8 〃 σ_f 〃	1.00920	+2.125	−1.36872	−0.108	1.57524	−0.153	1.82376	−0.169
9 〃 σ_{tr} 〃	0.98627	−0.095						
10 〃 σ_s 〃	0.98819	−0.001						
11 Fe σ_a 5~6	0.98811	−0.009	−1.36720	+0.004	1.57766	0.0	1.82684	−0.0005
12 〃〃 σ_{tr} 〃	0.98911	+0.092	−1.37029	−0.222	1.57535	−0.147	1.82921	+0.022
13 〃 σ_s 〃	0.98801	−0.018						
14 U28 σ_a 1~4	0.98188	−0.640	−1.36596	+0.094	1.59563	+1.139	1.82543	−0.078
15 〃 ν 〃	0.99903	+1.096	−1.35739	+0.721	1.57529	−0.150	1.82947	+0.143
16 〃 σ_f 〃	0.99903	+0.096						
17 〃 σ_{tr} 〃	0.98926	+0.107						
18 〃 σ_s 〃	0.98487	−0.337	−1.38125	−1.024	1.57588	−0.113	1.82789	+0.057

Table 9. Sensitivity Coeff. in Conversion Condition 5.0×10^{-6}

case / 10% change	keff		B10 Worth		Breeding ratio		Peaking Factor	
	keff	△A／A(%)	A	△A／A(%)	A	△A／A(%)	A	△A／A(%)
0 no change	0.98820		−1.36725−3		1.57766		1.82685	
1 U235 σ_a 1∼4 group	0.98817	−0.003	−1.36725	0.0	1.57758	−0.005	1.82684	−0.0005
2 〃 ν 〃	0.98825	+0.005	−1.36720	+0.004	1.57765	−0.001	1.82686	+0.0005
3 〃 σ_f 〃	0.98825	+0.005	−1.36720	+0.004	1.57765	−0.001	1.82687	+0.001
4 〃 σ_{tr} 〃	0.98820	0.0	−1.36726	−0.001	1.57766	0.0	1.82685	0.0
5 〃 σ_s 〃	0.98819	−0.001	−1.36727	−0.002	1.57766	0.0	1.82685	0.0
6 Pu239 σ_a 9∼11	0.98109	−0.719	−1.33673	+2.232	1.53972	−2.405	1.82524	−0.088
7 〃 ν 〃	1.00920	+2.125	−1.36871	−0.107	1.57524	−0.153	1.82656	−0.016
8 〃 σ_f 〃	1.00920	+2.125	−1.36871	−0.107	1.57524	−0.153	1.82376	−0.169
9 〃 σ_{tr} 〃	0.98627	−0.095	−1.34579	+1.570	1.58542	+0.492	1.81896	−0.432
10 〃 σ_s 〃	0.98819	−0.001	−1.36766	−0.030	1.57751	−0.010	1.82686	+0.0005
11 Fe σ_a 5∼6	0.98811	−0.009	−1.36720	+0.004	1.57766	0.0	1.82684	−0.0005
12 〃 σ_{tr} 〃	0.98911	+0.092	−1.37029	−0.222	1.57534	−0.147	1.82921	+0.129
13 〃 σ_s 〃	0.98801	−0.019	−1.37059	−0.244	1.57788	−0.018	1.82724	+0.021
14 U238 σ_a 1∼4	0.98188	−0.640	−1.36595	+0.094	1.59563	+0.139	1.82543	−0.078
15 〃 ν 〃	0.99903	+1.096	−1.35739	+0.721	1.57529	−0.150	1.82947	+0.143
16 〃 σ_f 〃	0.99903	+1.096	−1.35739	+0.721	1.56464	−0.825	1.83097	+0.226
17 〃 σ_{tr} 〃	0.98926	+0.107	−1.37102	−0.276	1.57416	−0.222	1.83096	+0.225
18 〃 σ_s 〃	0.98487	−0.337	−1.38125	−1.024	1.57588	−0.113	1.82789	+0.057

Table 10. The number of iteration in each conversion condition

case \ 10% change \ FLUX \ conversion condition	1.0×10^{-5}				5.0×10^{-6}				5.0×10^{-7}			
	Normal		Adjoint		Normal		Adjoint		Normal		Adjoint	
	keff	iteration	keff	iteration	keff	iteration	keff	iteration	keff	iteration	keff	iteration
0 NO change	0.98820	23	0.98820	13	0.98820	23	0.98820	14	0.98820	39	0.98820	19
1 U235 σ_a 1~4 group	0.98817	1	0.98817	2	0.98817	2	0.98817	2	0.98817	5	0.98817	7
2 〃 ν 〃	0.98825	23	0.98825	13	0.98825	23	0.98825	14	0.98825	26	0.98825	21
3 〃 σ_f 〃	0.98825	23	0.98825	13	0.98825	23	0.98825	14	0.98825	37		100 ~
4 〃 σ_{tr} 〃	0.98820	23	0.98820	13	0.98820	23	0.98820	14	0.98820	30		〃
5 〃 σ_s 〃	0.98819	23	0.98819	13	0.98819	23	0.98819	14	0.98819	32		〃
6 Pu239 σ_a 9~11	0.98109	23	0.98109	13	0.98109	23	0.98109	14	0.98109	29	0.98109	18
7 〃 ν 〃	1.00920	23	1.00920	18	1.00920	23	1.00920	13	1.00920	75		100 ~
8 〃 σ_f 〃	1.00920	24	1.00920	13	1.00920	23	1.00920	13	1.00920	32	1.00920	20
9 〃 σ_{tr} 〃	0.98627	23	0.98627	13	0.98627	23	0.98627	14	0.98627	28		100 ~
10 〃 σ_s 〃	0.98823	7	0.98819	22	0.98819	23	0.98819	14	0.98819	30		〃
11 Fe σ_a 5~6	0.98811	23	0.98811	21	0.98811	23	0.98811	14	0.98811	32	0.98811	45
12 〃 σ_{tr} 〃	0.98911	15	0.98911	13	0.98911	35	0.98911	14	0.98911	31	0.98911	19
13 〃 σ_s 〃	0.98802	15	0.98802	13	0.98801	23	0.98801	14	0.98801	31		100 ~
14 U238 σ_a 1~4					0.98188	23	0.98188	14	0.98188	32	0.98188	32
15 〃 ν 〃					0.99903	23	0.99903	14	0.99903	31	0.99903	21
16 〃 σ_f 〃					0.99903	34	0.99903	14	0.99903	32		100 ~
17 〃 σ_{tr} 〃					0.98926	23	0.98926	14	0.98926	30		〃
18 〃 σ_s 〃					0.98487	23	0.98487	14	0.98487	34	0.98487	94

Table 11. Effective Multiplication Factor keff
(for 10% changed nuclear constants).

energy / nuclide / cross secton		10.5~1.4 MeV	1.4~0.4 MeV	400~100 KeV	100~10 KeV	10~0.465 KeV
U238	σ_t	1.04843	1.04881	1.04973	1.04973	1.04796
	σ_f	1.05345	1.04802			
	ν	1.05704	1.04812			
	σ_c		1.04583	1.04453	1.03960	1.04329
	σ_{in}	1.04596	1.04751	1.04752	1.04781	
Pu239	σ_t	1.04793	1.04799	1.04811	1.04807	1.04788
	σ_f	1.05223	1.05655	1.06058	1.06112	1.05325
	ν	1.05446	1.06076	1.06649	1.06679	1.05571
	σ_c		1.04765	1.04717	1.04620	1.04591
Pu240	σ_t	1.04789	1.04792	1.04798	1.04795	1.04786
	σ_f	1.04947	1.04991			
	ν	1.05032	1.05094			
	σ_c		1.04769	1.04757	1.04718	1.04729
Pu241	σ_t	1.04787	1.04788	1.04791	1.04790	1.04786
	ν_f	1.04854	1.04927	1.05103	1.05407	1.05106
	σ	1.04886	1.04991	1.05242	1.05660	1.05246
	σ_c		1.04782	1.04770	1.04756	1.04755
Na	σ_t	1.04849	1.04907	1.04923	1.04881	1.04778
	σ_{in}	1.04745	1.04760			
	σ_{el}	1.04761	1.04735	1.04719	1.04751	1.04808
O	σ_t	1.04855	1.04972	1.04968	1.04892	1.04777
	σ_{el}	1.04743	1.04674	1.04651	1.04728	1.04806
Fe	σ_c				1.04690	

NO change keff = 1.04786

Table 12. Sensitivity Coefficients for keff (no interrelation).

(%)

nuclide / cross section \ energy		10.5~1.4 MeV	1.4~0.4 MeV	400~100 KeV	100~10 KeV	10~0.465 KeV
U238	σ_t	5.33×10^{-3}	9.07×10^{-3}	1.77×10^{-2}	1.42×10^{-2}	7.49×10^{-4}
	σ_f	5.33×10^{-2}	1.35×10^{-3}			
	ν	8.76×10^{-2}	2.29×10^{-3}			
	σ_c		-1.95×10^{-2}	-3.20×10^{-2}	-7.90×10^{-2}	-4.73×10^{-2}
	σ_{in}	-1.83×10^{-2}	-3.50×10^{-3}	-3.35×10^{-3}	-6.92×10^{-4}	
Pu239	σ_t	5.69×10^{-4}	1.12×10^{-3}	2.25×10^{-3}	1.87×10^{-3}	1.82×10^{-5}
	σ_f	4.16×10^{-2}	8.28×10^{-2}	1.21×10^{-1}	1.26×10^{-1}	5.12×10^{-2}
	ν	6.29×10^{-2}	1.23×10^{-1}	1.78×10^{-1}	1.80×10^{-1}	7.47×10^{-2}
	σ_c		-2.17×10^{-3}	-6.76×10^{-3}	-1.60×10^{-2}	-1.87×10^{-2}
Pu240	σ_t	1.41×10^{-4}	3.82×10^{-4}	9.53×10^{-4}	7.28×10^{-4}	-1.21×10^{-4}
	σ_f	1.52×10^{-2}	1.94×10^{-2}			
	ν	2.33×10^{-2}	2.93×10^{-2}			
	σ_c		-1.78×10^{-3}	-2.92×10^{-3}	-6.61×10^{-3}	-5.61×10^{-3}
Pu241	σ_t	-3.41×10^{-5}	7.28×10^{-5}	3.14×10^{-4}	2.59×10^{-4}	-1.37×10^{-4}
	σ_f	6.37×10^{-3}	1.33×10^{-2}	3.01×10^{-2}	5.91×10^{-2}	3.04×10^{-2}
	ν	9.56×10^{-3}	4.34×10^{-2}	4.34×10^{-2}	8.32×10^{-2}	4.37×10^{-2}
	σ_c		-5.71×10^{-4}	-1.70×10^{-3}	-3.98×10^{-3}	-3.14×10^{-2}
Na	σ_t	5.83×10^{-3}	1.14×10^{-2}	1.29×10^{-2}	8.87×10^{-3}	-9.42×10^{-4}
	σ_{in}	-4.10×10^{-3}	-2.63×10^{-4}			
	σ_{el}	-2.55×10^{-5}	-5.04×10^{-3}	-6.54×10^{-3}	-3.43×10^{-3}	1.88×10^{-3}
Fe	σ_c				-9.09×10^{-3}	
O	σ_t	6.42×10^{-3}	1.76×10^{-2}	1.72×10^{-2}	9.93×10^{-3}	-1.01×10^{-3}
	σ_{el}	-4.26×10^{-3}	-1.08×10^{-2}	-1.31×10^{-2}	-5.72×10^{-3}	1.70×10^{-3}

Table 13. Breeding Ratio
(for 10% changed nuclear constants).

nuclide	cross section \ energy	10.5~1.4 MeV	1.4~0.4 MeV	400~100 KeV	100~10 KeV	10~0.465 KeV
U238	σ_t	1.11062	1.11024	1.10924	1.10985	1.11121
	σ_f	1.11305	1.11136			
	ν	1.11442	1.11140			
	σ_c		1.11790	1.12306	1.14389	1.13155
	σ_{in}	1.11034	1.11154	1.11205	1.11137	
Pu239	σ_t	1.11118	1.11108	1.11085	1.11089	1.11125
	σ_f	1.11480	1.09783	1.09161	1.09129	1.10417
	ν	1.11087	1.11054	1.11043	1.11095	1.11151
	σ_c		1.11065	1.10903	1.10529	1.10523
Pu240	σ_t	1.11124	1.11120	1.11108	1.11110	1.11128
	σ_f	1.11111	1.11108			
	ν	1.11107	1.11100			
	σ_c		1.11178	1.11216	1.11350	1.11335
Pu241	σ_t	1.11127	1.11125	1.11120	1.11120	1.11129
	σ_f	1.11030	1.10914	1.10643	1.10202	1.10706
	ν	1.11122	1.11112	1.11090	1.11060	1.11089
	σ_c		1.11118	1.11079	1.10992	1.11042
Na	σ_t	1.11044	1.10962	1.10933	1.11010	1.11194
	σ_{in}	1.11116	1.11136			
	σ_{el}	1.11129	1.11149	1.11214	1.11024	1.11002
O	σ_t	1.11043	1.10905	1.10901	1.11007	1.11187
	σ_{el}	1.11119	1.11195	1.11378	1.11063	1.11025
Fe	σ_c				1.11070	

NO change 1.11130

Table 14. Breeding Ratio (for 10% changed nuclear constants) Corrected by Effective Multiplication Factor.

nuclide \ energy / cross section		10.5～1.4 MeV	1.4～0.4 MeV	400～100 KeV	100～10 KeV	10～0.465 KeV
U238	σ_t	1.11170	1.11204	1.11279	1.11340	1.11140
	σ_f	1.12366	1.11166			
	ν	1.13184	1.11191			
	σ_c		1.11405	1.11675	1.12820	1.12288
	σ_{in}	1.10674	1.11088	1.11141	1.11128	
Pu239	σ_t	1.11131	1.11133	1.11132	1.11129	1.11129
	σ_f	1.11314	1.11432	1.11575	1.11645	1.11439
	ν	1.11311	1.13501	1.14577	1.14686	1.12640
	σ_c		1.11025	1.10772	1.10214	1.10153
Pu240	σ_t	1.11130	1.11131	1.11131	1.11127	1.11128
	σ_f	1.11416	1.11496			
	ν	1.11574	1.11684			
	σ_c		1.11146	1.11161	1.11221	1.11227
Pu241	σ_t	1.11129	1.11129	1.11130	1.11128	1.11129
	σ_f	1.11159	1.11181	1.11244	1.11380	1.11313
	ν	1.11312	1.11501	1.11955	1.12718	1.11962
	σ_c		1.11110	1.11049	1.10935	1.10983
Na	σ_t	1.11164	1.11192	1.11193	1.11190	1.11179
	σ_{in}	1.11038	1.11087			
	σ_{el}	1.11082	1.11052	1.11087	1.10958	1.11044
O	σ_t	1.11174	1.11258	1.11246	1.11208	1.11170
	σ_{el}	1.11037	1.10983	1.11122	1.10953	1.11063
Fe	σ_c				1.10888	

Table 15. Sensitivity Coefficients for Breeding Ratio (no interrelation).

nuclide	cross section \ energy	10.5～1.4 MeV	1.4～0.4 MeV	400～100 KeV	100～10 KeV	10～0.465 KeV
U238	σ_t	3.42×10^{-3}	6.75×10^{-3}	1.31×10^{-2}	1.24×10^{-2}	6.22×10^{-4}
	σ_f	1.11×10^{-1}	2.97×10^{-3}			
	ν	1.85×10^{-1}	5.02×10^{-3}			
	σ_c		2.45×10^{-2}	4.86×10^{-2}	1.52×10^{-1}	1.04×10^{-1}
	σ_{in}	-4.14×10^{-2}	-4.13×10^{-3}	7.51×10^{-4}	-5.94×10^{-4}	
Pu239	σ_t	-7.29×10^{-5}	3.65×10^{-5}	-1.72×10^{-5}	-3.73×10^{-5}	-3.80×10^{-4}
	σ_f	1.59×10^{-2}	2.70×10^{-2}	3.98×10^{-2}	4.60×10^{-2}	2.75×10^{-2}
	ν	1.09×10^{-1}	2.13×10^{-1}	3.10×10^{-1}	3.20×10^{-1}	1.36×10^{-1}
	σ_c		-9.74×10^{-3}	-3.25×10^{-2}	-8.26×10^{-2}	-8.81×10^{-2}
Pu240	σ_t	-2.53×10^{-4}	-2.23×10^{-4}	-2.42×10^{-4}	-4.48×10^{-4}	-3.86×10^{-4}
	σ_f	2.56×10^{-2}	3.28×10^{-2}			
	ν	3.96×10^{-2}	4.97×10^{-2}			
	σ_c		1.12×10^{-3}	2.56×10^{-3}	8.04×10^{-3}	8.40×10^{-3}
Pu241	σ_t	-2.98×10^{-4}	-2.85×10^{-4}	-3.11×10^{-4}	-4.01×10^{-4}	-3.60×10^{-4}
	σ_f	2.38×10^{-3}	4.39×10^{-3}	9.98×10^{-3}	2.22×10^{-2}	1.62×10^{-2}
	ν	1.64×10^{-2}	3.34×10^{-2}	7.40×10^{-2}	1.43×10^{-1}	7.45×10^{-2}
	σ_c		-2.12×10^{-3}	-7.62×10^{-3}	-1.95×10^{-2}	-1.35×10^{-2}
Na	σ_t	2.67×10^{-3}	5.41×10^{-3}	5.39×10^{-3}	5.04×10^{-3}	4.05×10^{-3}
	σ_{in}	-8.55×10^{-3}	-4.12×10^{-3}			
	σ_{el}	-4.66×10^{-3}	-7.28×10^{-3}	-4.17×10^{-3}	-1.57×10^{-2}	-8.17×10^{-3}
Fe	σ_c				-2.16×10^{-2}	
O	σ_t	3.67×10^{-3}	1.11×10^{-2}	1.02×10^{-2}	6.69×10^{-3}	3.35×10^{-3}
	σ_{el}	-8.60×10^{-3}	-1.35×10^{-2}	-1.05×10^{-2}	-1.63×10^{-2}	-6.40×10^{-3}

Table 16. Void Reactivity
(for 10% changed nuclear constants and 100% Void).

nuclide \ cross section \ energy		10.0～1.4MeV	1.4～0.4 MeV	400～100KeV	100～10KeV	10～0.465KeV
U238	σ_t	-1.3065×10^{-2}	-1.2842×10^{-2}	-1.2670×10^{-2}	-1.2939×10^{-2}	-1.3287×10^{-2}
	σ_f	−1.2622	−1.3233			
	ν	−1.2302	−1.3222			
	σ_c		−1.3536	−1.3482	−1.2888	−1.1601
	σ_{in}	−1.3457	−1.3264	−1.3261	−1.3262	
Pu239	σ_t	−1.3228	−1.3190	−1.3169	−1.3204	−1.3262
	σ_f	−1.2806	−1.1890	−1.2244	−1.3496	−1.5271
	ν	−1.2626	−1.1346	−1.1900	−1.3689	−1.6211
	σ_c		−1.3284	−1.3293	−1.3137	−1.2453
Pu240	σ_t	−1.3243	−1.3226	−1.3414	−1.3232	−1.3258
	σ_f	−1.3089	−1.2948			
	ν	−1.3021	−1.2823			
	σ_c		−1.3277	−1.2785	−1.3212	−1.3022
Pu241	σ_t	−1.3250	−1.3242	−1.3237	−1.3244	−1.3257
	σ_f	−1.3184	−1.3029	−1.3008	−1.3458	−1.4429
	ν	−1.3157	−1.2944	−1.2930	−1.3587	−1.4945
	σ_c		−1.3261	−1.3264	−1.3231	−1.3134
Na	σ_t	−1.3546	−1.3677	−1.3905	−1.3811	−1.3130
	σ_{in}	−1.2915	−1.3055			
	σ_{el}	−1.3063	−1.2875	−1.2703	−1.3007	−1.2861
O	σ_t	−1.3022	−1.2460	−1.2667	−1.3010	−1.3228
	σ_{el}	−1.3316	−1.3425	−1.3286	−1.3240	−1.3285
Fe	σ_c				−1.3226	

base value -1.3231×10^{-2}

Table 17. Sensitivity Coefficients for Reactivity (no interrelation).

(%)

energy / nuclide / cross section		105～1.4 MeV	1.4～0.4 MeV	400～100 KeV	100～10 KeV	10～0.465 KeV
U238	σ_t	-1.25×10^{-1}	-2.94×10^{-1}	-4.24×10^{-1}	-2.27×10^{-1}	4.22×10^{-2}
	σ_f	-4.60×10^{-2}	1.33×10^{-3}			
	ν	-7.02×10^{-2}	-7.00×10^{-3}			
	σ_c		2.31×10^{-1}	1.90×10^{-1}	-2.59×10^{-1}	-1.23
	σ_{in}	-1.71×10^{-1}	2.51×10^{-2}	2.29×10^{-2}	2.34×10^{-2}	
Pu239	σ_t	-2.51×10^{-3}	-3.07×10^{-2}	-4.81×10^{-2}	-2.02×10^{-2}	2.36×10^{-2}
	σ_f	-3.21×10^{-1}	-1.01	-7.46×10^{-1}	2.01×10^{-1}	1.54×10^{-0}
	ν	-4.56×10^{-1}	-1.42	-1.01	3.46×10^{-1}	2.25
	σ_c		4.02×10^{-2}	4.71×10^{-2}	-7.12×10^{-2}	-5.88×10^{-1}
Pu240	σ_t	8.94×10^{-3}	-3.64×10^{-3}	-1.28×10^{-2}	7.81×10^{-4}	2.03×10^{-2}
	σ_f	-1.07×10^{-1}	-2.14×10^{-1}			
	ν	-1.59×10^{-1}	-3.08×10^{-1}			
	σ_c		3.48×10^{-2}	3.04×10^{-2}	-1.46×10^{-2}	-1.58×10^{-1}
Pu241	σ_t	1.42×10^{-2}	8.45×10^{-3}	4.66×10^{-3}	1.01×10^{-2}	1.99×10^{-2}
	σ_f	-3.53×10^{-2}	-1.53×10^{-1}	-1.69×10^{-1}	1.72×10^{-1}	9.05×10^{-1}
	ν	-5.60×10^{-2}	-2.17×10^{-1}	-2.27×10^{-1}	2.69×10^{-1}	1.30
	σ_c		2.26×10^{-2}	2.50×10^{-2}	2.71×10^{-4}	-7.30×10^{-2}
Na	σ_t	2.38×10^{-1}	3.37×10^{-1}	5.09×10^{-1}	4.39×10^{-1}	-7.61×10^{-2}
	σ_{in}	-2.38×10^{-1}	-1.33×10^{-1}			
	σ_{el}	-1.27×10^{-1}	-2.69×10^{-1}	-3.99×10^{-1}	-1.69×10^{-1}	1.95×10^{-1}
O	σ_t	-1.58×10^{-1}	-5.84×10^{-1}	-4.27×10^{-1}	-1.67×10^{-1}	-1.95×10^{-3}
	σ_{el}	6.43×10^{-2}	1.47×10^{-1}	4.20×10^{-2}	6.85×10^{-3}	4.08×10^{-2}
Fe	σ_c				-3.83×10^{-3}	

Table 18. Doppler Reactivity
(for 10% changed nuclear constants).

nuclide / cross section \ energy		10.5～1.4 MeV	1.4～0.4 MeV	400～100 KeV	100～10 KeV	10～0.465 KeV
U238	σ_t	-2.5605×10^{-3}	-2.5609×10^{-3}	-2.5635×10^{-3}	-2.5700×10^{-3}	-2.5645×10^{-3}
	σ_f	−2.5400	−2.5604			
	ν	−2.5385	−2.5604			
	σ_c		−2.5603	−2.5554	−2.5347	−2.6044
	σ_{in}	−2.5774	−2.5688	−2.5716	−2.5640	
Pu239	σ_t	−2.5610	−2.5611	−2.5616	−2.5625	−2.5622
	σ_f	−2.5455	−2.5283	−2.5075	−2.4913	−2.5530
	ν	−2.5446	−2.5296	−2.5166	−2.5228	−2.6246
	σ_c		−2.5610	−2.5599	−2.5493	−2.5050
Pu240	σ_t	−2.5862	−2.5611	−2.5613	−2.5617	−2.5614
	σ_f	−2.5553	−2.5532			
	ν	−2.5549	−2.5535			
	σ_c		−2.5610	−2.5606	−2.5565	−2.5473
Pu241	σ_t	−2.5611	−2.5611	−2.5612	−2.5614	−2.5614
	σ_f	−2.5586	−2.5557	−2.5476	−2.5287	−2.5769
	ν	−2.5684	−2.5559	−2.5499	−2.5445	−2.6271
	σ_c		−2.5611	−2.5618	−2.5584	−2.5493
Na	σ_t	−2.5608	−2.5616	−2.5636	−2.5638	−2.5420
	σ_{in}	−2.5637	−2.5623			
	σ_{el}	−2.5622	−2.5693	−2.5823	−2.6213	−2.5999
O	σ_t	−2.5605	−2.5610	−2.5637	−2.5642	−2.5469
	σ_{el}	−2.5631	−2.5771	−2.6005	−2.6415	−2.5860
Fe	σ_c				−2.5556	

base value -2.5606×10^{-3}

Table 19. Sensitivity Coefficients for Doppler Reactivity (no interrelation).

nuclide / cross section \ energy		10.5～1.4 MeV	1.4～0.4 MeV	400～100KeV	100～10KeV	10～0.465KeV
U238	σ_t	-4.84×10^{-4}	1.15×10^{-3}	1.14×10^{-2}	3.64×10^{-2}	1.50×10^{-2}
	σ_f	-8.06×10^{-3}	-7.53×10^{-4}			
	ν	-8.64×10^{-3}	-6.90×10^{-4}			
	σ_c		-1.09×10^{-3}	-2.05×10^{-2}	-1.01×10^{-1}	1.71×10^{-1}
	σ_{in}	6.54×10^{-2}	3.19×10^{-2}	4.26×10^{-2}	1.30×10^{-2}	
Pu239	σ_t	1.70×10^{-3}	2.03×10^{-3}	3.70×10^{-3}	7.39×10^{-3}	6.15×10^{-3}
	σ_f	-5.89×10^{-2}	-1.26×10^{-1}	-2.08×10^{-1}	-2.70×10^{-1}	-2.98×10^{-2}
	ν	-6.25×10^{-2}	-1.21×10^{-1}	-1.72×10^{-1}	-1.48×10^{-1}	2.50×10^{-1}
	σ_c		1.48×10^{-3}	-2.75×10^{-3}	-4.42×10^{-2}	-2.17×10^{-1}
Pu240	σ_t	1.76×10^{-3}	1.91×10^{-3}	2.70×10^{-3}	4.35×10^{-3}	3.06×10^{-3}
	σ_f	-2.08×10^{-2}	-2.89×10^{-2}			
	ν	-2.22×10^{-2}	-2.78×10^{-2}			
	σ_c		1.60×10^{-3}	-7.63×10^{-5}	-1.62×10^{-2}	-5.20×10^{-2}
Pu241	σ_t	1.77×10^{-3}	1.84×10^{-3}	2.18×10^{-3}	3.05×10^{-3}	3.00×10^{-3}
	σ_f	-7.79×10^{-3}	-1.92×10^{-2}	-5.08×10^{-2}	-1.25×10^{-1}	6.35×10^{-2}
	ν	-8.40×10^{-3}	-1.84×10^{-2}	-4.19×10^{-2}	-6.29×10^{-2}	2.60×10^{-1}
	σ_c		1.77×10^{-3}	7.74×10^{-4}	-8.57×10^{-3}	-4.42×10^{-2}
Na	σ_t	9.08×10^{-4}	4.04×10^{-3}	1.18×10^{-2}	1.24×10^{-2}	-7.26×10^{-2}
	σ_{in}	1.20×10^{-2}	1.83×10^{-2}			
	σ_{el}	6.23×10^{-3}	3.38×10^{-2}	8.48×10^{-2}	2.37×10^{-1}	1.53×10^{-1}
O	σ_t	-5.78×10^{-4}	1.59×10^{-3}	1.22×10^{-2}	1.41×10^{-2}	-5.35×10^{-2}
	σ_{el}	9.72×10^{-3}	6.46×10^{-2}	1.56×10^{-1}	3.16×10^{-1}	9.90×10^{-2}
Fe	σ_c				-1.97×10^{-2}	

Table 20. Sensitivity Coefficients for keff (contained interrelation).

energy / nuclide / cross section		10.5 ~ 1.4 MeV	1.4 ~ 0.4 MeV	400 ~ 100 KeV	100 ~ 10 KeV	10 ~ 0.465 KeV
U238	σ_f	5.69×10^{-2}	1.4×10^{-3}	0.0	0.0	0.0
	σ_c	0.0	-1.95×10^{-2}	-3.18×10^{-2}	-7.85×10^{-2}	-4.73×10^{-2}
	σ_{in}	-1.64×10^{-2}	-1.2×10^{-3}	-1.6×10^{-3}	0.0	0.0
	ν	8.76×10	2.3×10^{-3}	0.0	0.0	0.0
Pu239	σ_f	4.17×10^{-2}	8.09×10^{-2}	1.15×10^{-1}	1.10×10^{-1}	3.25×10^{-2}
	σ_c	0.0	-2.2×10^{-3}	-6.8×10^{-3}	-1.60×10^{-2}	-1.87×10^{-2}
	ν	6.29×10^{-2}	1.23×10^{-1}	1.78×10^{-1}	1.80×10^{-1}	7.47×10^{-2}
Pu240	σ_f	1.52×10^{-2}	1.94×10^{-2}	0.0	0.0	0.0
	σ_c	0.0	-1.8×10^{-3}	-2.9×10^{-3}	-6.6×10^{-3}	-5.6×10^{-3}
	ν	2.33×10^{-2}	2.93×10^{-2}	0.0	0.0	0.0
Pu241	σ	6.4×10^{-3}	1.27×10^{-2}	2.85×10^{-2}	5.52×10^{-2}	2.73×10^{-2}
	σ	0.0	0.0	-1.7×10^{-3}	-4.4×10^{-3}	-3.1×10^{-3}
	ν	$9.6\times\times10^{-3}$	1.95×10^{-2}	4.34×10^{-2}	8.32×10^{-2}	4.37×10^{-2}
Fe	σ	0.0	0.0	0.0	-9.1×10^{-3}	0.0

Table 21. Sensitivity Coefficients for Breeding Ratio (contained interrelation).

(%)

nuclide / cross section \ energy		10.5～1.4 MeV	1.4～0.4 MeV	400～100 KeV	100～10 KeV	10～0.465 KeV
U238	σ_f	1.11×10^{-1}	3.0×10^{-3}	0.0	0.0	0.0
	σ_c	0.0	2.45×10^{-2}	4.86×10^{-2}	1.52×10^{-1}	1.04×10^{-1}
	σ_{in}	-1.64×10^{-2}	-1.2×10^{-3}	-1.6×10^{-3}	0.0	0.0
	ν	1.85×10^{-1}	5.0×10^{-3}	0.0	0.0	0.0
Pu239	σ_f	1.59×10^{-2}	1.73×10^{-2}	7.3×10^{-3}	-3.66×10^{-2}	6.10×10^{-2}
	σ_c	0.0	-9.7×10^{-3}	-3.25×10^{-2}	-8.26×10^{-2}	8.81×10^{-2}
	ν	1.09×10^{-1}	2.13×10^{-1}	3.10×10^{-1}	3.20×10^{-1}	1.36×10^{-1}
Pu240	σ_f	1.52×10^{-2}	1.94×10^{-2}	0.0	0.0	0.0
	σ_c	0.0	1.1×10^{-3}	2.6×10^{-3}	8.0×10^{-3}	8.4×10^{-3}
	ν	3.96×10^{-2}	4.97×10^{-2}	0.0	0.0	0.0
Pu241	σ_f	2.3×10^{-3}	2.2×10^{-3}	2.3×10^{-3}	2.6×10^{-3}	2.7×10^{-3}
	σ_c	0.0	-2.1×10^{-3}	-7.6×10^{-3}	-1.95×10^{-2}	1.35×10^{-2}
	ν	1.64×10^{-2}	3.34×10^{-2}	7.40×10^{-2}	1.43×10^{-1}	7.45×10^{-2}
Na	σ_t	-3.3×10^{-3}	-2.3×10^{-3}	1.2×10^{-3}	-1.07×10^{-2}	4.1×10^{-3}
O	σ_t	-5.0×10^{-3}	-2.4×10^{-3}	9.9×10^{-3}	-9.6×10^{-3}	3.1×10^{-3}
Fe	σ_c	0.0	0.0	2.0	-2.16×10^{-2}	1.0

Table 22. Sensitivity Coefficients for Void Reactivity (contained interrelation).

(%)

nuclide	cross section (energy)	10.5~1.4 MeV	1.4~0.4 MeV	400~100 KeV	100~10 KeV	10~0.465 KeV
U238	σ_f	-5.48×10^{-2}	1.07×10^{-3}			
	σ_c		2.31×10^{-1}	1.90×10^{-1}	-2.59×10^{-1}	-1.23
	σ_{in}	1.27×10^{-1}	-5.09×10^{-2}	-1.98×10^{-2}	2.20×10^{-2}	
	ν	-7.02×10^{-2}	-7.00×10^{-3}			
Pu239	σ_f	-3.22×10^{-1}	-9.77×10^{-1}	-7.07×10^{-1}	1.26×10^{-1}	9.60×10^{-1}
	σ_c		4.02×10^{-2}	4.71×10^{-2}	-7.12×10^{-2}	-5.88×10^{-1}
	ν	-4.56×10^{-1}	-1.42	-1.01	3.46×10^{-1}	2.25
Pu240	σ_f	-1.05×10^{-1}	-2.14×10^{-1}			
	σ_c		3.48×10^{-2}	3.04×10^{-2}	-1.46×10^{-2}	-1.58×10^{-1}
	ν	-1.59×10^{-1}	-3.08×10^{-1}			
Pu241	σ_f	-3.25×10^{-2}	-1.29×10^{-1}	-1.43×10^{-1}	1.75×10^{-1}	8.32×10^{-1}
	σ_c		2.26×10^{-2}	2.50×10^{-2}	2.71×10^{-4}	-7.30×10^{-2}
	ν	-5.60×10^{-2}	-2.17×10^{-1}	-2.27×10^{-1}	2.69×10^{-1}	1.30
Na	σ_t	7.53×10^{-2}	5.13×10^{-2}	1.10×10^{-1}	2.70×10^{-1}	1.19×10^{-1}
	σ_{in}	-1.86×10^{-1}	-1.13×10^{-1}			
O	σ_t	-9.31×10^{-2}	-4.37×10^{-1}	-3.85×10^{-1}	-1.60×10^{-1}	3.89×10^{-2}
Fe	σ_c				-3.83×10^{-3}	

Table 23. Sensitivity Coefficients for Doppler Reactivity (contained interrelation). (%)

nuclide / cross section \ energy		10.5～1.4 MeV	1.4～0.4 MeV	400～100 KeV	100～10 KeV	10～0.465 KeV
U238	σ_f	-8.09×10^{-3}	-7.5×10^{-4}			
	σ_c		-1.09×10^{-3}	-2.05×10^{-2}	-1.01×10^{-1}	1.71×10^{-1}
	σ_{in}	6.52×10^{-2}	3.22×10^{-2}	-4.37×10^{-2}	1.32×10^{-2}	
	ν	-8.64×10^{-3}	-6.9×10^{-4}			
Pu239	σ_f	-5.85×10^{-2}	-1.24×10^{-1}	-2.10×10^{-1}	-3.13×10^{-1}	-2.45×10^{-1}
	σ_c		1.48×10^{-3}	-2.75×10^{-3}	-4.42×10^{-2}	-2.17×10^{-1}
	ν	-6.25×10^{-2}	-1.21×10^{-1}	-1.72×10^{-1}	-1.48×10^{-1}	2.50×10^{-1}
Pu240	σ_f	-2.04×10^{-2}	-2.87×10^{-2}			
	σ_c		1.60×10^{-3}	-7.6×10^{-5}	-1.62×10^{-2}	-5.20×10^{-2}
	ν	-2.22×10^{-2}	-2.78×10^{-2}			
Pu241	σ_f	-7.45×10^{-3}	-1.71×10^{-2}	-4.95×10^{-2}	-1.33×10^{-1}	1.93×10^{-2}
	σ_c		1.77×10^{-3}	7.7×10^{-4}	-8.57×10^{-3}	-4.42×10^{-2}
	ν	-8.40×10^{-3}	-1.84×10^{-2}	-4.19×10^{-2}	-6.29×10^{-2}	2.60×10^{-1}
Na	σ_t	8.89×10^{-3}	3.99×10^{-2}	9.66×10^{-2}	2.49×10^{-1}	8.06×10^{-2}
	σ_{in}	1.22×10^{-2}	1.85×10^{-2}			
O	σ_t	9.23×10^{-3}	6.62×10^{-2}	1.68×10^{-1}	3.30×10^{-1}	4.55×10^{-2}
Fe	σ_c				-1.97×10^{-2}	

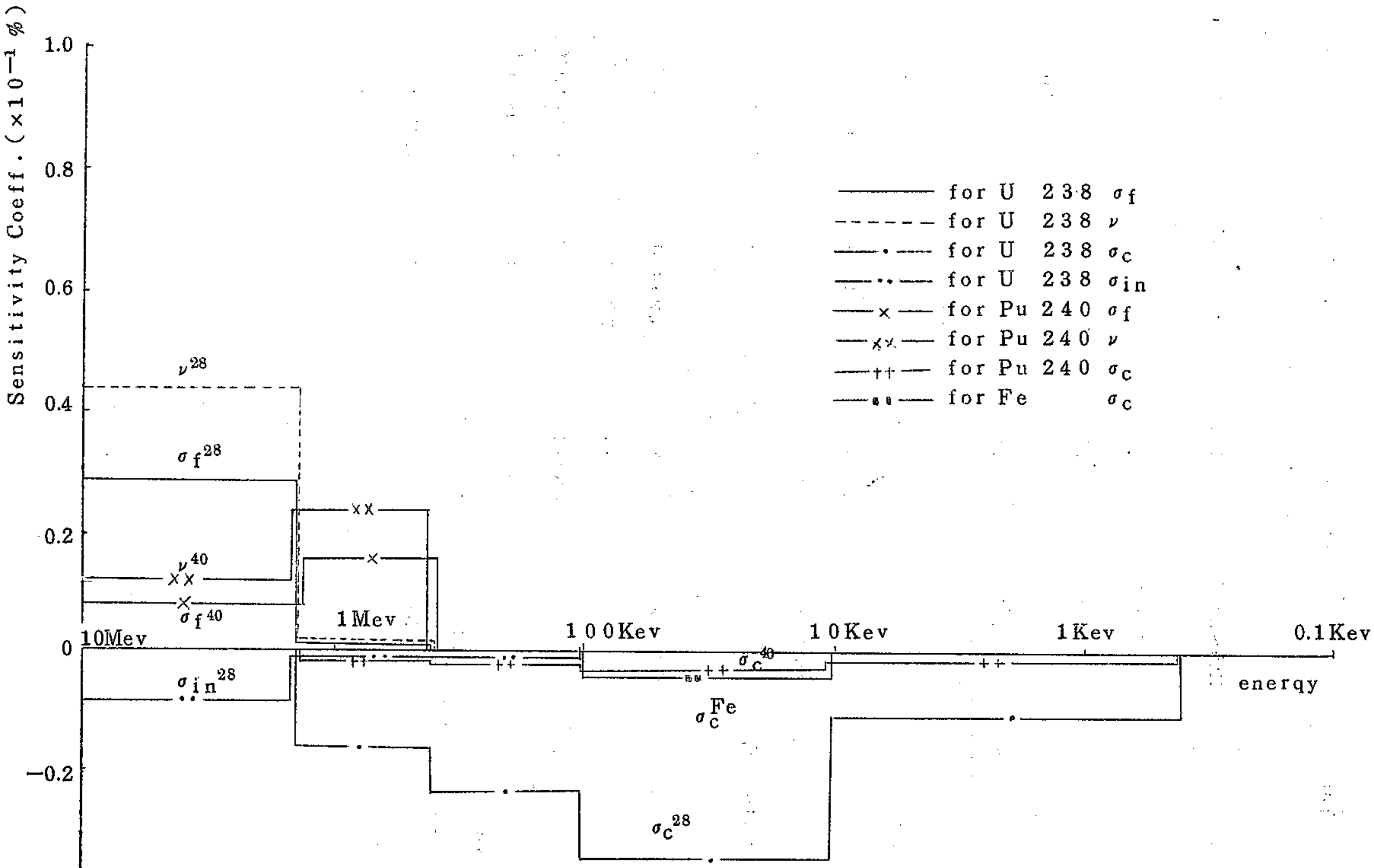


Fig.22. Sensitivity Coefficients for keff (№1).

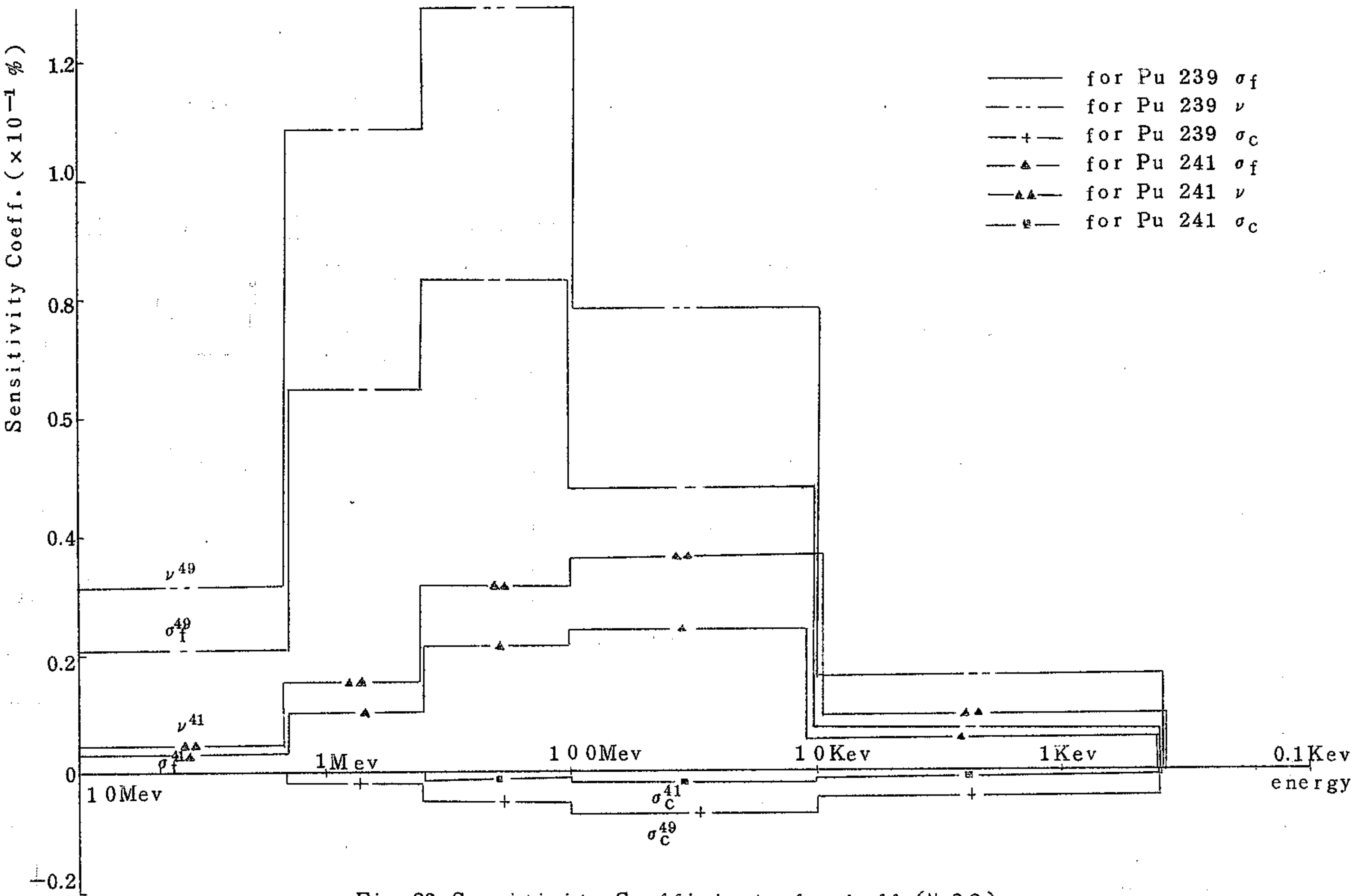


Fig. 23. Sensitivity Coefficients for keff (№ 22).

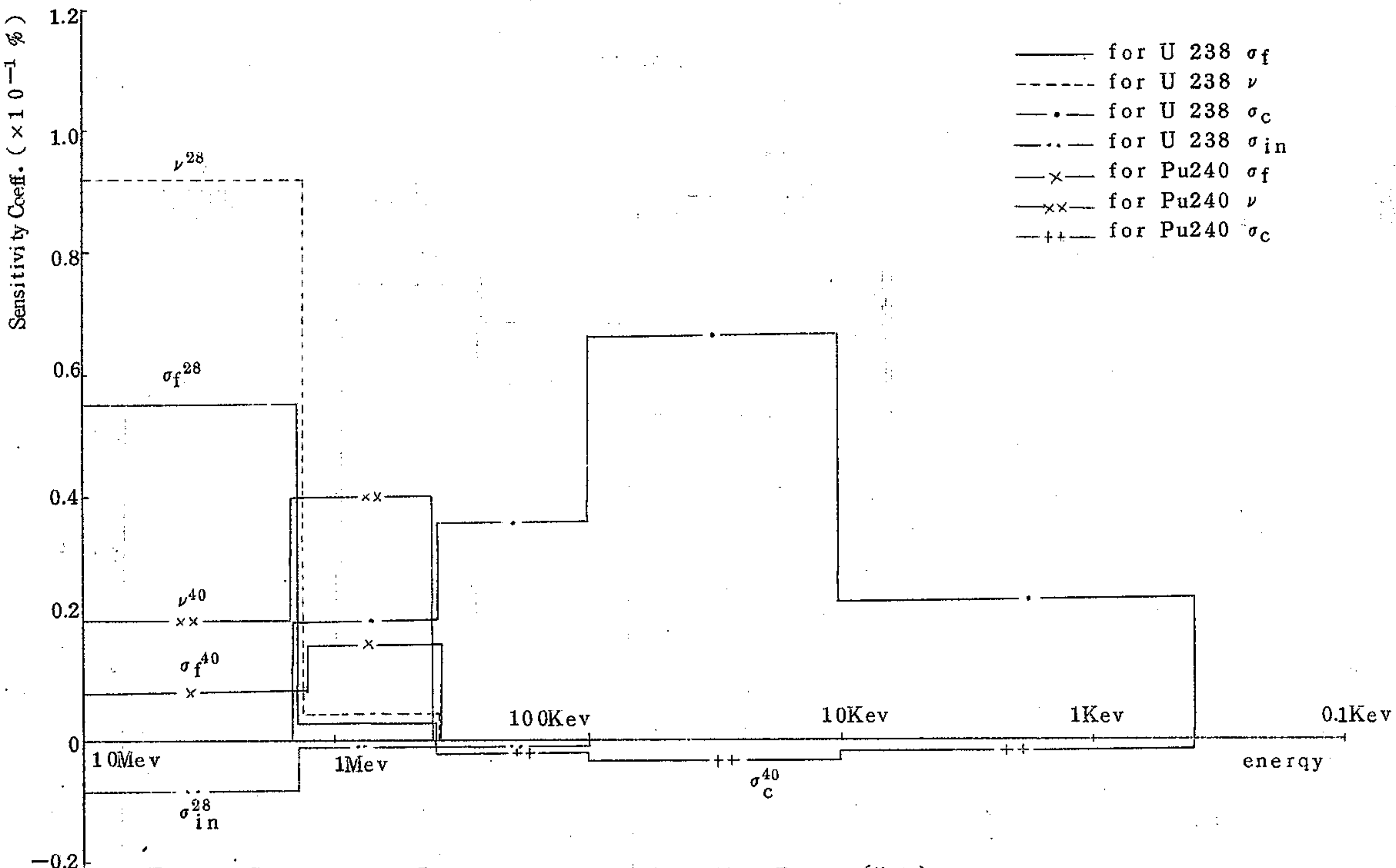


Fig. 24. Sensitivity Coefficients for Breedinq Ratio (No.1)

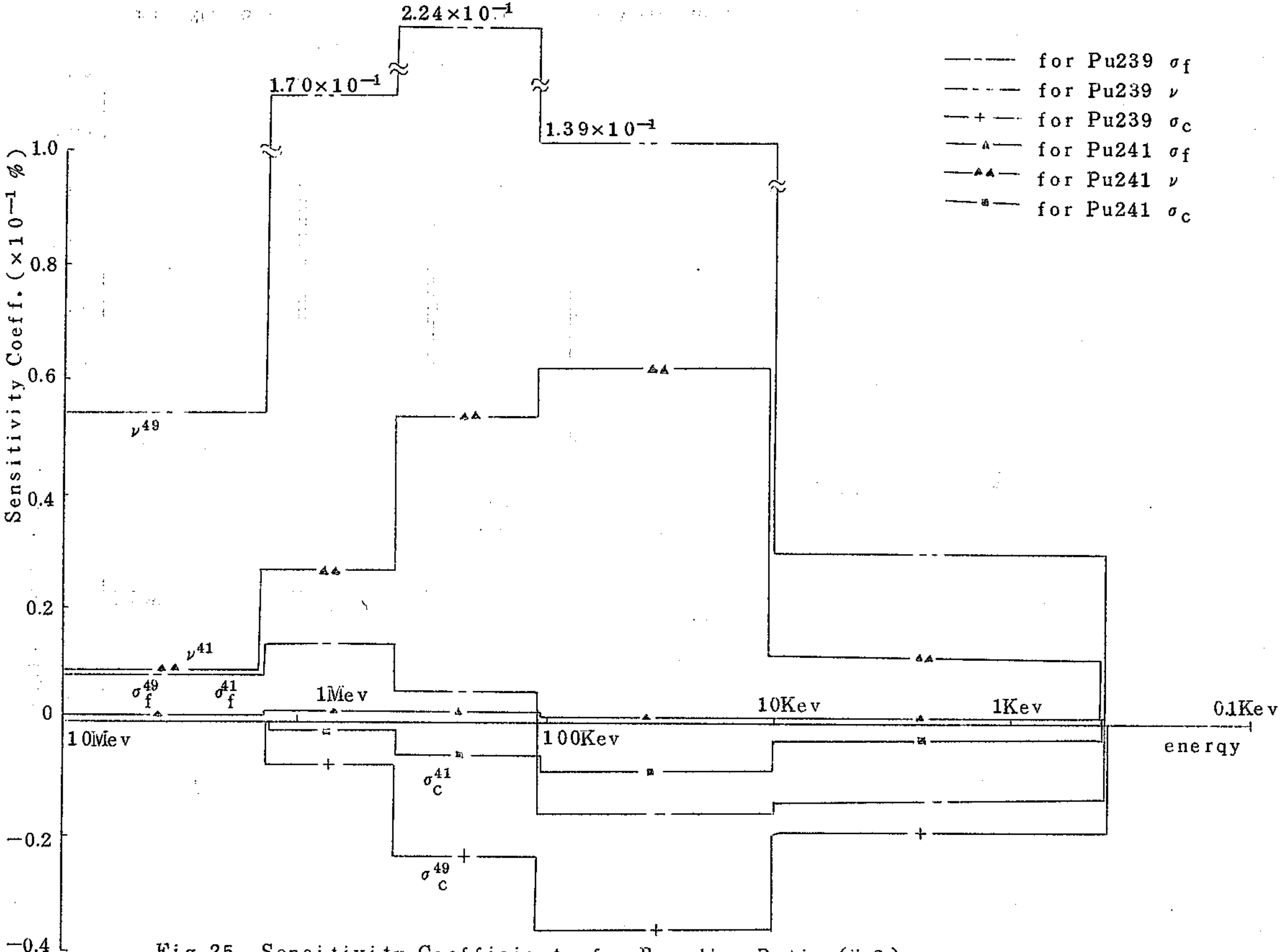


Fig.25. Sensitivity Coefficients for Breeding Ratio (№.2).

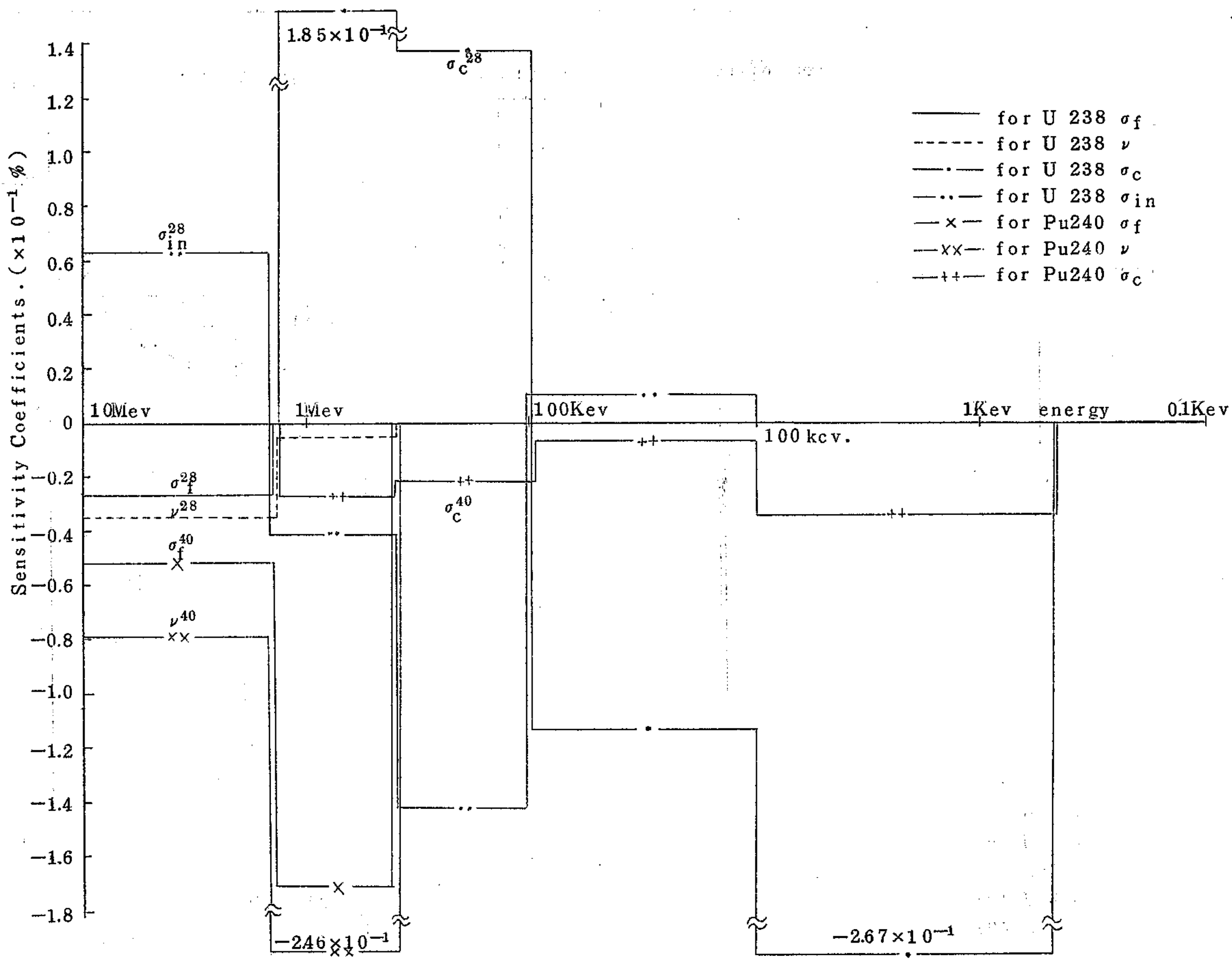


Fig.26. Sensitivity Coefficients for Void Reactivity (№1).

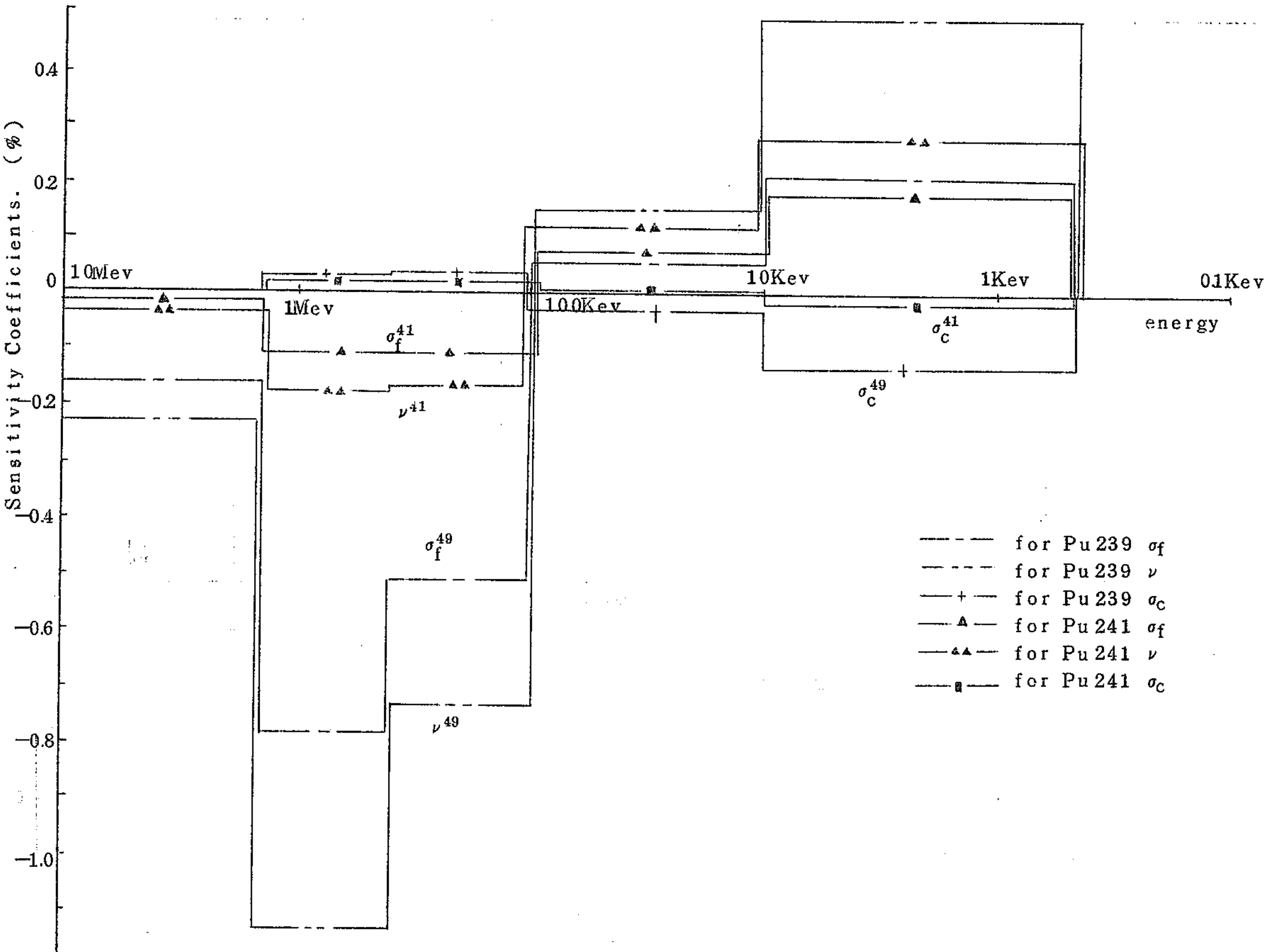


Fig. 27. Sensitivity Coefficients for Void Reoctivity (№2).

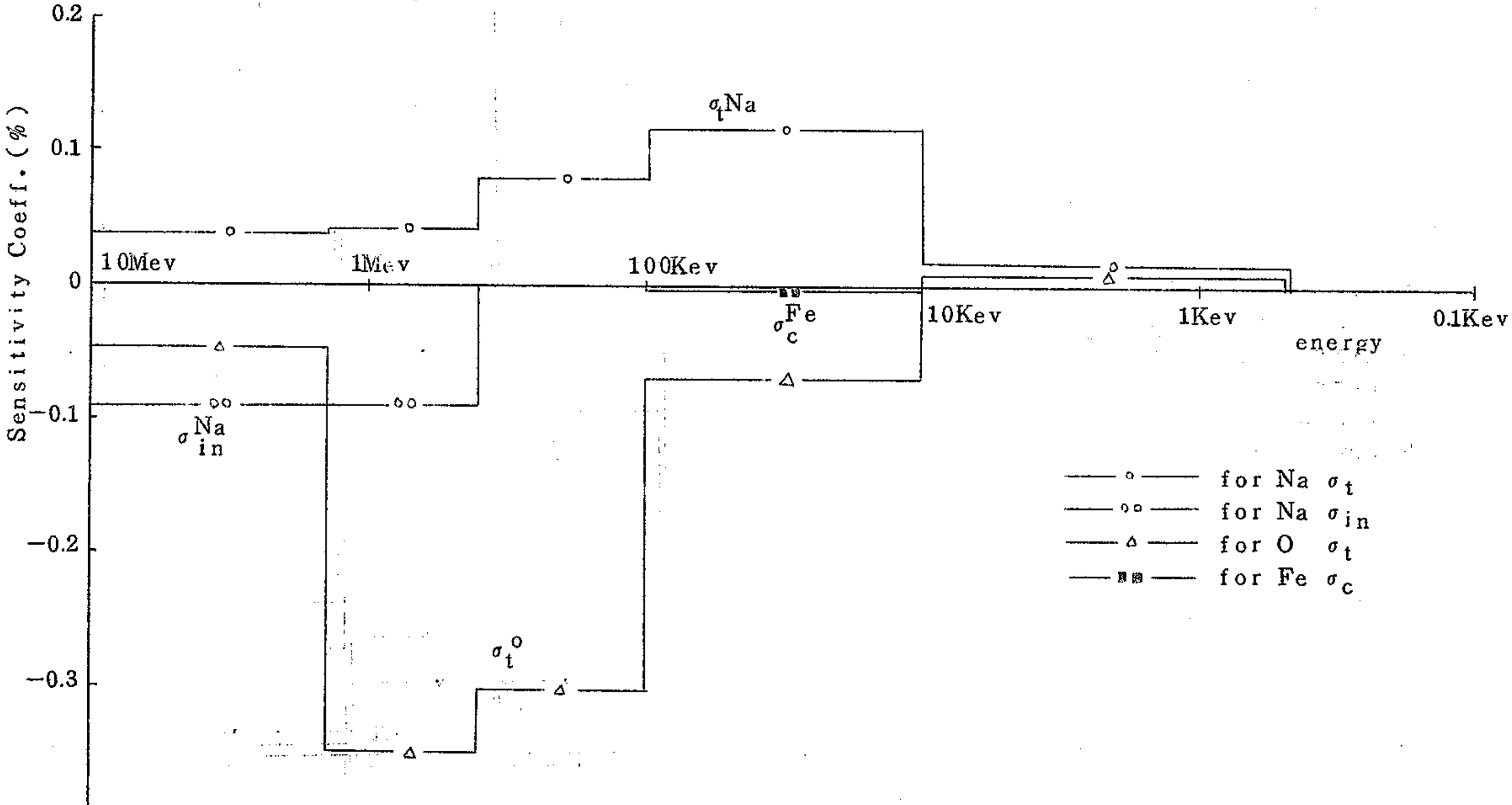


Fig.28. Sensitivity Coefficients for Void Reactivity (No.3).

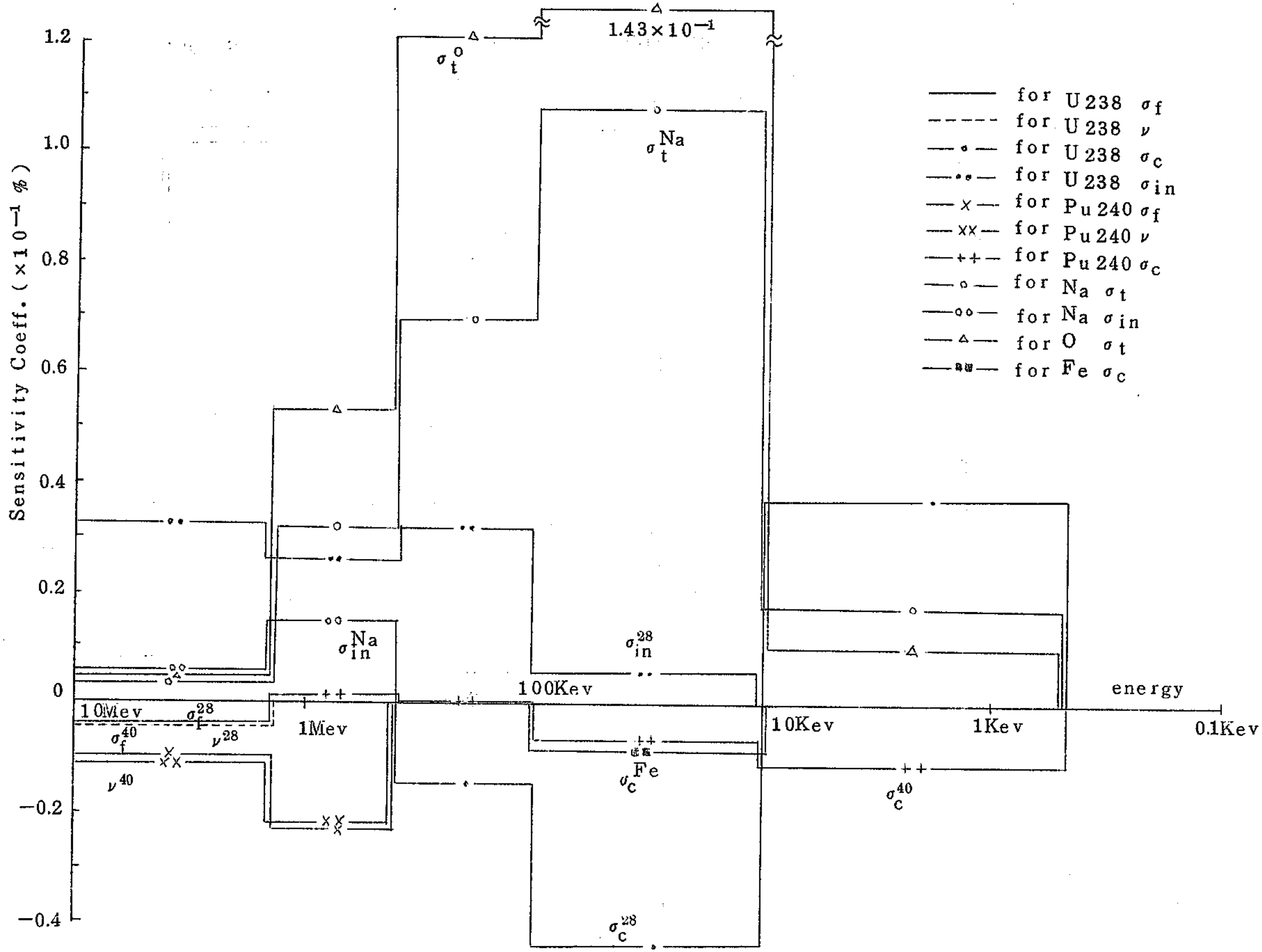


Fig.29. Sensitivity Coefficients for Doppler Reactivity (No.1).

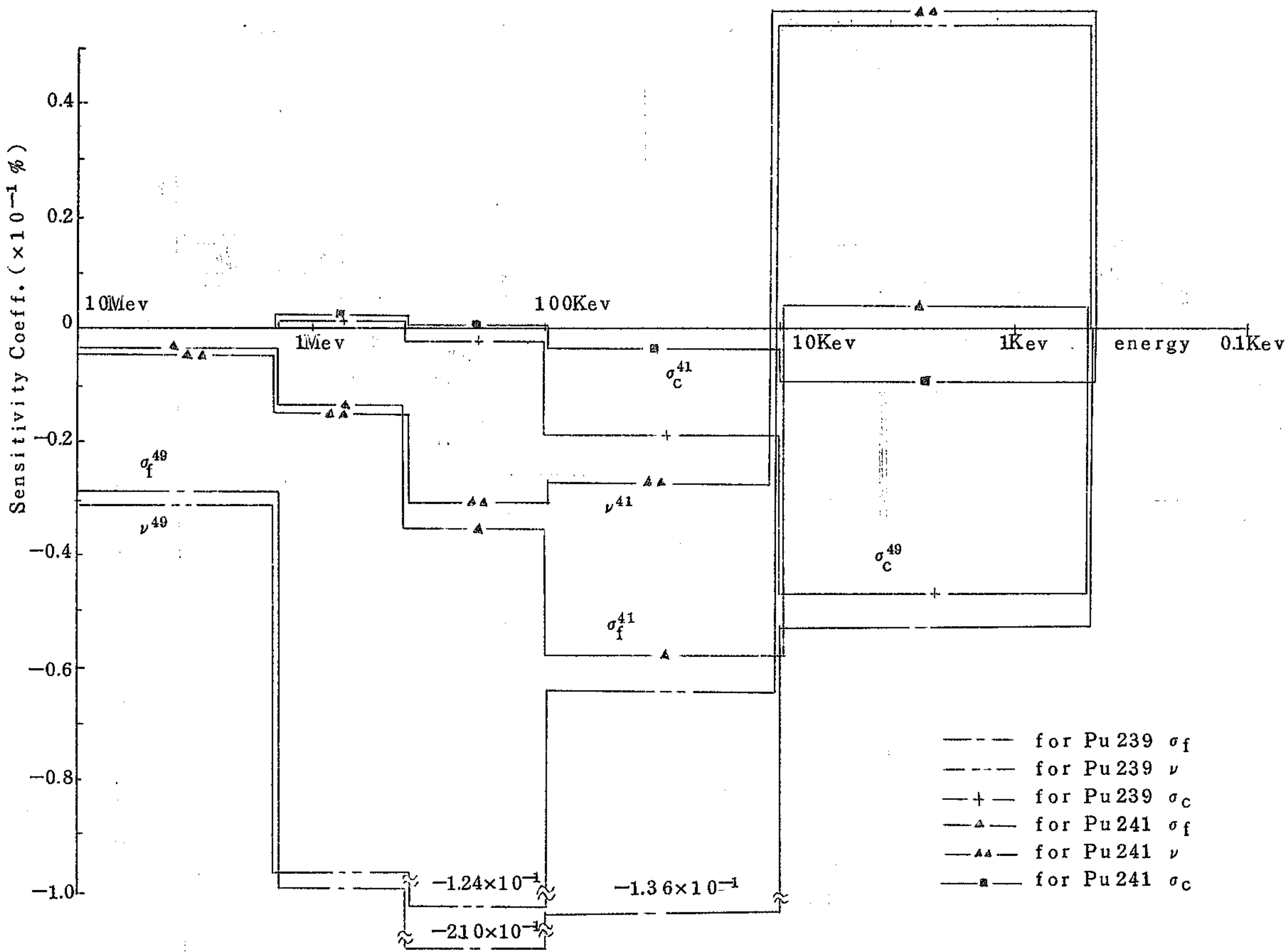


Fig.30. Sensitivity Coefficients for Doppler Reactivity (№2).

7. Study on the required accuracy for nuclear constants

7.1 Method of determining the required accuracy

It is quite natural that the target accuracy for the design values of the core characteristics and the sensitivity coefficients obtained in Chapter 6 become important factor in determining the required accuracy for nuclear constants. The studies on nuclear constants, which have hitherto been made in Japan and abroad were aimed mainly at the nuclear constants with large sensitivity coefficients. However, if the required accuracy is determined by paying attention only to sensitivity coefficients, it would result in imposing unrealistically severe accuracy requirements on the nuclear constants with large sensitivity coefficients.

Such being the case, we studied the required accuracy by taking into consideration the uncertainties of nuclear constants at the present time.

If the sensitivity coefficient G_{ax}^{iJ} which was defined by equation (3.12) in Chapter 3 is used, the total uncertainty D_a of the core physical quantity a which shows the core characteristics is determined as follows.

$$D_a = \sqrt{\sum_{xiJ} \left(G_{ax}^{iJ} \right)^2 \times \left(d_x^{iJ} \right)^2} \qquad (7.1)$$

where d_x^{iJ} : uncertainty for nuclear constant X of element i with neutron energy J. Our object is to obtain d_x^{iJ} by giving D_a according to equation (7.1).

Therefore

$$d_x^{iJ} = \frac{K}{\Delta_x^{iJ} \quad G_{ax}^{iJ}} \qquad (7.2)$$

Δ_x^{iJ} : neutron energy J of element i, uncertainty presently possessed by nuclear constant X of element i with neutron energy J. If K is obtained from (7.1) and (7.2), the required accuracy for nuclear constants becomes

$$d_x^{iJ} = \frac{D_a}{\sum_{xiJ} \left(\frac{1}{\Delta_x^{iJ}} \right)^2} \frac{1}{\Delta_x^{iJ} \quad G_{ax}^{iJ}} \qquad (7.3)$$

The ratio of required accuracy to the present uncertainty is evaluated in order to give the degree of importance of the study in the future,

$$\frac{d_x^{iJ}}{\Delta_x^{iJ}} = \frac{D_a}{\sum_{xiJ} \left(\frac{1}{\Delta_x^{iJ}} \right)^2} \frac{1}{{\Delta_x^{iJ}}^2 \quad G_{ax}^{iJ}} \qquad (7.4)$$

7.2 Target accuracy for design values of core characteristics

It is extremely difficult to clearly define the target value for the design accuracy as a target for the development and research of the design of fast reactor cores.

An accuracy which is considered appropriate from the following viewpoint was used as a target accuracy of a physical quantity showing the core characteristics.

"In the stage where a fast reactor is put to practical use, an economical and safe design can be made without making engineering mockup experiments".

The target accuries for the core characteristics design values from this viewpoint are given in Table 24.

7.3 Required accuracy for nuclear constants

The uncertainties of nuclear constants up to now are given in Table 25. The required accuracy for nuclear constants to satisfy the results in Chapter 6 and the accuracy requirements in Table 24 was obtained by use the equation (7.3) and the results are shown in Table 26. The most severe of the accuracy requirements is the effective multiplication factor due to the uncertainty of nuclear constants up to now. The accuracy requirements for the nuclear constants of fuel elements come from the accuracy requirements for effective multiplication factors. However, the accuracy requirements for σc of ^{238}U at below 400KeV are held down by the breeding ratio and the accuracy requirements for σt of Na and O by Doppler reactivity.

7.4 Comparison between accuracy requirements and uncertainties of nuclear constants up to now

If the ratio of the accuracy requirements to the uncertainties of nuclear constants up to now is obtained by equation (7.4) from the results given in Tables 25 and 26, we obtain the results as shown in Table 27. Studies made with emphasis on those lower than 0.1, that is, the present uncertainty is more than ten times the required accuracy and those ranging from 0.3 to 0.1, that is the present uncertainty is 3 to 10 times the required accuracy are most important for the improvement of nuclear constants in the future. Such uncertainties are summarized below.

Those which are more than 10 times:

^{238}U σc (100~10KeV), ^{238}U σin (10~1.4MeV)

^{239}Pu σf (400~10KeV), ^{239}Pu σc (400~0.4KeV)

^{241}Pu σf (400~0.4KeV), ^{241}Pu σc (100~0.4KeV)

Na σ_{in} (10～0.4KeV), ^{16}O σ_t (400～100KeV)

Fe σ_c (100～10KeV)

3 to 10 times:

^{238}U σ_f (more than 1.4MeV), ^{238}U σ_c (lower than 1.4MeV ～100KeV, 10KeV), ^{239}Pu σ_f (lower than 1.4～0.4MeV, 10KeV), ^{239}Pu σ_c (1.4～0.4MeV), ^{240}Pu σ_f (more than 0.4MeV), ^{240}Pu σ_c (lower than 1.4MeV), ^{241}Pu σ_f (more than 1.4MeV), ^{241}Pu σ_c (400～100KeV), ^{16}O σ_t (100～10KeV)

Table 24. Target Accuracy of Core Nuclear Design.

Nuclear Properties of Core	Target Accuracy (%)
effective multiplication factor	1.0
breeding ratio	2.0
Doppler reactivity	10.0
void reactivity	30.0

Table 25. Uncertainties of Nuclear Constants up to now.

±△(%)

energy / nuclide cross section		10.5~1.4 MeV	1.4~0.4 MeV	400 ~ 100 MeV	100 ~ 10 KeV	10 ~ 0.465 KeV
U238	σ_f	6	6			
	σ_c	10	10	10	10	10
	σ_{in}	20	15	15	15	
	ν	3	3			
Pu239	σ_f	6	6	10	10	10
	σ_c	20	20	20	20	20
	ν	2	2	2	2	2
Pu240	σ_f	15	15	30	30	30
	σ_c	40	40	40	30	30
	ν	3	3			
Pu241	σ_f	25	25	25	25	25
	σ_c	40	40	40	40	40
	ν	3	3	3	3	3
Na	σ_t	10	10	7	10	10
	σ_{in}	50	50			
O	σ_t	10	10	20	10	5
Fe	σ_c	35	35	35	25	25

Table 26. Requared Accuracy for Nuclear Constants.

(%)

nuclide / cross section \ energy		10.5～1.4MeV	1.4～0.4MeV	400～100KeV	100～10KeV	10～0.1KeV
U238	σ_f	1.86	68.79	—	—	—
	σ_c		3.26	2.00	0.81	1.19
	σ_{in}	1.74	12.81	9.44	31.24	—
	ν	2.23	82.55	—	—	—
Pu239	σ_f	2.54	1.31	0.55	0.58	1.93
	σ_c	—	6.38	1.90	0.75	0.70
	ν	3.79	2.58	1.79	1.77	4.12
Pu240	σ_f	2.79	2.18	—	—	—
	σ_c	—	8.83	5.48	3.21	3.78
	ν	9.09	7.23	—	—	—
Pu241	σ_f	3.97	2.00	0.89	0.46	0.89
	σ_c	—	14.74	4.07	1.59	2.29
	ν	22.07	10.86	4.88	2.55	4.76
Na	σ_t	24.64	15.50	9.47	2.48	7.67
	σ_{in}	2.00	3.28	—	—	—
O	σ_t	19.93	4.25	1.84	1.87	27.19
Fe	σ_c	—	—	—	2.29	—

Table 27. Ratio of Requared Accuracy to Uncertainty of Nuclear Constants $d_x^{ij} / \triangle_x^{ij}$

nuclide	cross section \ energy	10.5～1.4MeV	1.4～0.4MeV	400～100KeV	100～10 KeV	10～0.465KeV
U238	σ_f	0.310				
	σ_c		0.326	0.200	0.081	0.119
	σ_{in}	0.087	0.854	0.629		
	ν	0.743				
Pu239	σ_f	0.423	0.218	0.055	0.058	0.193
	σ_c		0.319	0.095	0.038	0.035
	ν			0.895	0.885	
Pu240	σ_f	0.186	0.145			
	σ_c		0.221	0.137	0.107	0.126
	ν					
Pu241	σ_f	0.159	0.080	0.036	0.018	0.036
	σ_c		0.369	0.102	0.040	0.057
	ν				0.850	
Na	σ_t				0.248	0.767
	σ_{in}	0.040	0.066			
O	σ_t		0.425	0.092	0.187	
Fe	σ_c				0.092	

Note: Values are shown only in the case of d_x^{iJ} / $_x^{iJ}$ 1

8. Postscript

Finally, we will briefly discuss the direction sensitivity analysis and the improvement of nuclear constants in the future.

As for sensitivity analysis, present study was made on the reactor core of "Monju", but in the future we would proceed with the analysis for large-size reactors.

With regard to the nuclear constants, precise, studies may be required further on the basis of experimental data of those whose uncertainties are 10 times the required accuracies and the theoretical nuclear considerations.

For those whose uncertainties are 3 to 10 times the required accuracies, we think it advisable to study them by comparing them with the nuclear constants which have been studies in Japan and abroad (mainly abroad, perhaps). As for other nuclear constants, if would be necessary to make judgement of them by revaluating the importance of nuclear constants after studying the nuclear constants of higher degrees of importance.

Acknowledgement

We are grateful to Mr. Katsuya Kinjo of the Fast Breeder Reactor Development Headquarters of the Power Reactor and Nuclear Fuel Development Corporation for his hearty cooperation in carrying out the present experiments.

References

1) T.D.Moorhead : The Effects of Errors in Cross-Section Data on Calculations for a Large Dilute Fast Reactor : Physics of Fast and Intermediate Reactors. 2 111~145(1962).

2) E.D.Pendlebury : The Sensitivity of Calculated Critical Masses of Small Fast Systems to Changes in the U^{235} and U^{238} Neutron-Scattering Data : Physics of Fast and Intermediate Reactors 2 97~110(1962).

3) F.M.Heck : Preliminary Fast Reactor Cross Section Sensitivity Analysis : ANL-7320 263-269(1966).

4) Greebler et al. : User Requirements for Cross Section in the Energy Range from 100eV to 100KeV : Neutron Cross Section Technology 357~380(1966).

5) Greebler et al. : Significance of Neutron Data to Fast Reactor Power Plant Design : Neutron Cross Section and Technology 291~310 (1968-3).

6) Grandini et al. : Sensitivity Study of Fast Reactor Using Generalized Perturbation Techniques : Fast Reactor Physics 1 241~253(1968).

7) V.Rojkov : Evaluation of the Accuracy Requirements for Cross Sections in Calculations for Fast Power Reactor : The Physics of Fast Reactor Operation and Design. 309~314(1969).

8) L.P.Abagyan et al. : Group Constants for Nuclear Reactor Calculations (1964).

9) Ganclini : A Generalized Perturbation Method for Bilinear Functions of the Real and Adjoint Neutron Fluxes : J. Nucl. Enegy 21 755~765(1967).

10) W.G.Davey and A.L.Hess : Additional Fast Reactor Bench Marks for Phase Data Testing of ENDF/B : CSWG Memo. (1969-2).

11) A.R.Baker : Comparative Studies of the Criticality of Fast Critical Assemblies : ANL-7320(1966-8).