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Study on Characteristics of Void Reactivity Coefficients for High Conversion Type Core of FLWR for MA Recycling

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The investigation on the characteristics of void reactivity coefficients for the high conversion type core of the FLWR (HC-FLWR) concept for MA recycling has been performed. Void reactivity coefficients are the major restrictions for the core design of HC-FLWR for MA recycling, because the loaded MA makes void reactivity coefficients worse. Therefore, it is important to investigate the characteristics of void reactivity coefficients as a mechanism of reactor physics. Thus, in this study, the investigation of void reactivity coefficients has been performed using the exact perturbation calculations. In the exact perturbation theory, the reactivity is related to the variation in the cross section, and divided into scattering, leakage, absorption and fission terms. Then, it is found that the worsening of the void reactivity coefficient caused by the MA loading mainly via the scattering term. Moreover, the void reactivity coefficient becomes better via the scattering term for the smaller fuel rod diameter, and via the leakage term for the lower core height. In addition, the 100% void reactivity coefficient, which is the restriction for the core design of HC-FLWR for MA recycling, cannot be negative only by using the effect of the scattering

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term through reducing the fuel rod diameter. Therefore, the mechanism of achieving the negative 100% void reactivity coefficient by using the effect of the leakage term through the core height reduction is quantitatively verified.

KEYWORDS: FLWR, high conversion ratio, void reactivity coefficient, exact perturbation, MOX, MA recycling

I. Introduction

In order to ensure sustainable energy supplies in the future based on the well-established light water reactor (LWR) technologies, conceptual design studies on the innovative water reactor for flexible fuel cycle (FLWR) have been performed¹⁻⁶⁾ at Japan Atomic Energy Agency (JAEA). FLWR is an advanced boiling water reactor (BWR) with a tight triangular lattice core of uranium/plutonium mixed oxide (MOX) fuel rods. FLWR consists of two kinds of core concepts. The first is the high conversion type one (HC-FLWR)²⁾ for early introduction of FLWR following the MOX-LWR experience without a serious technical gap from the LWR technologies. The other is a breeder type one called the Reduced-Moderation Water Reactor (RMWR).^{5,6)} HC-FLWR core is designed to use the fuel assemblies with the same shape and size as those of RMWR. Therefore, HC-FLWR can be converted to RMWR by replacing the fuel assemblies with no change of any reactor systems, corresponding flexibly to the future circumstances of the fuel cycle.

The MOX core designs for Minor Actinide (MA) recycling based on the HC-FLWR concept has been performed in the previous study.⁷⁾ Moreover, this study also has been performed, because the void reactivity coefficients were found to be the major restrictions for the core design. The reason is that the loaded MA makes the void reactivity coefficients worse, *i.e.*, reactivity coefficients shift to the positive side. In the previous study of the core design, the characteristics of void reactivity coefficients were investigated as a trend with the fuel rod diameter and the MA contents to find a promising core design specification. However, it was not found why the trend appeared. Therefore, in this study, the void reactivity coefficients were investigated quantitatively as a mechanism of reactor physics. The investigation was performed using the exact perturbation calculations which are suitable to estimate the mechanism of the variations in the void reactivity coefficients quantitatively.

← [Fig. 1]

II. Over-All Core Concept of HC-FLWR for MA Recycling

1. Design Concept of the Core

The reactor concept of FLWR is designed to use the same plant system as in the existing advanced BWR (ABWR) system. HC-FLWR is the first part of the FLWR concept chronologically as shown in **Fig. 1**, and the core design is based on the BWR-type concept. The core design of HC-FLWR for MA recycling⁷⁾ is summarized in **Table 1** and described briefly in the following. ← [**Table 1**]

The electric power output is 1,356MWe as same as ABWR. The core consists of 900 fuel assemblies and 283 Y-shaped control rods. The equivalent core diameter is about 7.4m. The fuel assembly consists of 217 MOX fuel rods, a hexagonal shaped channel box and other components, *e.g.*, grid spacers. The fuel rods are arranged in a triangular array with a pitch of 15mm. The outer diameter of the fuel rod is 9mm and the gap width between them is 6mm. The fuel cladding and the channel box material is Zircaloy. In order to achieve negative void reactivity coefficients, the core is short and flat to utilize the neutron leakage effect. The core has only a MOX region without any blanket regions. The core height is 1,200mm. One control rod is installed among 3 adjoining fuel assemblies except in peripheral regions. A graphite follower is added in the upper side of the control rod to remove coolant water. For the fuel composition, the fissile plutonium (Puf) content is 13wt%, and MA content is 2wt%. The loaded MA is neptunium (Np), americium (Am) or the combination of them. The Pu composition and MA composition are shown in **Table 2**. However, Am gives significantly severer effect on void reactivity coefficients than Np. Therefore, in this paper, only the characteristics with respect to Am contents are presented. The core flow rate of coolant water is 10,000kg/s. And, the coolant temperature at the core inlet is 550K. The flow rate and inlet temperature are the determined values to realize the natural circulation core cooling.⁸⁾ Under this condition, the core average void fraction is less than 50%. The discharge burn-up is about 55GWd/t, and the MA conversion ratio, which is defined as the weight ratio of MA in discharged fuel to that in fresh fuel, is around unity.

The major modification of the core design from the representative core to the MA

recycling core is the fuel rod diameter. The fuel rod diameter had to be reduced from 11.2mm to 9mm, because the loaded MA made the void reactivity coefficients worse. The variation in the fuel rod diameter gives a significant effect to the characteristics of void reactivity coefficients.

← [Table 2]

III. Void Reactivity Coefficient

There considered two types of void reactivity coefficient. For the first one, the coolant flow rate is assumed to decrease to 90% of the nominal value, where it is simply called “the void reactivity coefficient” as a custom for BWR. For the second one, the coolant water is assumed to fully flow out, and the inside of the vessel is filled with saturated steam. In this case, it is defined in the present paper as “the 100% void reactivity coefficient”. We adopted the design criteria that not only void reactivity coefficient but also 100% void reactivity coefficient should be negative value. As FLWR uses a highly enriched plutonium fuel, there is a possibility of a positive reactivity insertion under the highly voided condition, unlike the conventional BWR core using low enriched uranium. Therefore, the 100% void reactivity coefficient was also adopted as a criterion. The definition is written in Eq. (1).

$$VC = \frac{\left(\frac{k_1 - k_0}{k_1 \cdot k_0} \right)}{(V_1 - V_0)} \quad (1)$$

where;

VC: Void reactivity coefficient ($\Delta k/k/\%$ void)

$k_{i(i=0,1)}$: Effective multiplication factor at void fraction of $V_{i(i=0,1)}$

V_0 : Void fraction at nominal condition (%)

V_1 : Void fraction at varied condition (%).

The void reactivity coefficients are major restriction for the core design. Regarding HC-FLWR for MA recycling, the 100% void reactivity coefficient is severer than the void

reactivity coefficient. The type of the limiting coefficient depends on the core design, *i.e.* the Puf content, the MA content, the core height, etc.

In this study, the perturbed state corresponding to the void reactivity coefficient is called “the state of voided”, and the state corresponding to the 100% void reactivity coefficient is called “the state of 100% voided”.

IV. Calculation Method

1. Calculation Formula for Exact Perturbation Theory

The exact perturbation theory is broadly used for reactivity analyses. The perturbation theory is effective to estimate the mechanism of the variation in reactivity, because it can divide the reactivity into the regions of energy and space where cross sections change. In this section, the definition and the calculation method for the exact perturbation theory are described. The definition of the reactivity in the exact perturbation theory is written in Eq. (2).

$$\rho = \frac{\langle \phi^* (-\Delta L + \lambda' \Delta P) \phi' \rangle}{\langle \phi^* P \phi' \rangle} \quad (2)$$

where;

L, P : Net loss and production operators

Δ : Difference between the reference state and perturbed state

λ' : Lambda mode eigenvalue $= 1/k_{eff}$, where k_{eff} is the reactor multiplication constant in the perturbed state

ϕ^* : Adjoint flux in the reference state

ϕ' : Forward flux in the perturbed state ($\text{cm}^{-2}\text{s}^{-1}$).

The bracket notation indicates an inner product which corresponds to an integral over the whole energy and space regions. This equation suggests that the reactivity of the exact perturbation theory consists of the products of the adjoint flux in the reference state, the variation in the cross section and the forward flux in the perturbed state.

Next, the numerical method for the exact perturbation theory employed in this study is described as the following. Regarding Eq. (2), the denominator, which is generally called “the perturbation denominator”, is commonly used for the each term mentioned as follows. The numerator can be divided into several terms. For the loss term, it can be divided into a leakage, absorption and scattering term. For the production term, it is a fission term. The definitions for these terms are written in Eq. (3)-(7).

$$Ip = \sum_g \int_{Reactor} \nu \Sigma_{f,g} \phi'_g \sum_{g'} \chi_{g'} \phi^*_{g'} dV \quad (3)$$

$$\Delta\rho_{g,i}^D = \frac{- \int_{V \in V_i} \Delta D_g \nabla \phi^*_g \cdot \nabla \phi'_g dV}{Ip} \quad (4)$$

$$\Delta\rho_{g,i}^a = \frac{- \int_{V \in V_i} \phi^*_g \Delta \Sigma_{a,g} \phi'_g dV}{Ip} \quad (5)$$

$$\Delta\rho_{g,i}^s = \frac{- \int_{V \in V_i} \phi'_g \sum_{g' \neq g} \Delta \Sigma_{s,g \rightarrow g'} (\phi^*_g - \phi^*_{g'}) dV}{Ip} \quad (6)$$

$$\Delta\rho_{g,i}^f = \frac{\lambda' \int_{V \in V_i} \Delta \nu \Sigma_{f,g} \phi'_g \sum_{g'} \chi_{g'} \phi^*_{g'} dV}{Ip} \quad (7)$$

where;

g : Suffix of energy group

i : Suffix of region

Ip : Perturbation denominator

$\Delta\rho^D$: Reactivity of leakage term

$\Delta\rho^a$: Reactivity of absorption term

$\Delta\rho^s$: Reactivity of scattering term

$\Delta\rho^f$: Reactivity of fission term

$\nu \Sigma_f$: Macroscopic production cross section (cm^{-1})

χ : Fission spectrum

D : Diffusion coefficient (cm)

Σ_a : Macroscopic absorption cross section (cm^{-1})

$\Sigma_{s\ g \rightarrow g'}$: Macroscopic scattering cross section from group g to g' (cm^{-1}).

These definitions are particular for the terms of scattering and fission. The form of the reactivity is different from the form derived directly, and changed to assign the reactivity to the energy group where the cross section changes. By this transformation, the mechanism of the variation in the cross section can be observed easily.

2. Core Calculation with MOSRA

In order to analyze the reactivity with the methods described in the previous section, the cross sections, the flux and the adjoint flux should be prepared in the reference and perturbed states respectively. In this study, the reactivity analyses were performed for the geometry of cell and one dimensional (1-D) core.

In order to prepare the data, the MOSRA¹⁰⁾ system was used. MOSRA is a modular type neutronics and thermal-hydraulics coupled (NTHC) calculation code. It consists of a neutronics calculation module, a thermal-hydraulic calculation module, a fuel temperature calculation module, a feedback cross section generation module and a frame which combines the modules and controls the calculation. The MSRAC code, a cell calculation code, was used to supply macroscopic cross sections to MOSRA. MSRAC has been developed using the PIJ module of SRAC.⁹⁾ For the cross section, the JENDL-3.3 nuclear data set¹¹⁾ was used.

← [Fig. 2 and 3]

To roughly evaluate the effect of the degree of moderation, the cell calculations were performed with varying the fuel rod diameter. For the reactivity analyses with the cell geometry, the cross sections were generated using the cell calculation model of MSRAC shown in Fig. 2. The cell calculations were performed at 30GWd/t which was assumed to be the average burn-up at the end of the equilibrium cycle (EOC) core, because the void reactivity coefficient has the most positive side value under the EOC condition due to the fission product (FP) accumulation through the reactor operation. The void fraction was

assumed to be 50%, which was expected under the coolant flow conditions described in Chapter II. The void fraction in the state of voided is assumed to be 55%. With the cross sections, the flux and the adjoint flux were calculated using the neutronic module of MOSRA system. In this calculation, only neutronic calculations were performed in a 3-D XYZ geometry with reflection boundary conditions to model infinite cell geometry.

For 1-D core calculations, the macroscopic cross sections were generated using MSRAC with the cell calculation model shown in Fig. 2. The number of energy groups used for the cell burn-up calculation is 107. The fine energy group structure of homogenized macroscopic cross section was collapsed into 14 groups for core burn-up calculations. For the NTHC calculation with MOSRA, many cross sections need to be prepared using MSRAC. In the NTHC calculations, the cross sections were interpolated, extrapolated or fitted to a polynomial expression using the pre-calculated values corresponding to 3 historical void fraction conditions. With these cross sections, the NTHC calculations were performed. For the 1-D core calculations, the geometry model is shown in Fig.3. There are 5 regions; top reflector, plenum, MOX, lower tie-plate and bottom reflector. In these calculations, the three dimensional (3-D) XYZ geometry was employed as 1-D axial geometry with the reflection boundaries for the radial directions.

← [Table 3]

← [Fig.4]

V. Calculation Results and Investigation

1. Result of Cell Calculation

The moderation effect on void reactivity coefficients was investigated with varying the fuel rod diameter. The cell was assumed to be infinite geometry without buckling. The Puf content is 13wt% which is the core design specification. For the MA loading, there are two cases, namely the case without MA and with 2wt% of Am. The burn-up is 30GWd/t corresponding to EOC condition. The burn-up of EOC was assumed with batch number of 4 and discharge burn-up of about 50GWd/t. **Figure 4** shows the void reactivity coefficients and the 100% void reactivity coefficients calculated using the exact perturbation theory. The

total values are also shown in **Table 3**. These values accurately coincide with those of the direct method which calculates the reactivity directly from the multiplication factors in the two states. These void reactivity coefficients were evaluated in the range of the fuel rod diameter between 7 to 14mm. This range includes the range investigated in the previous study⁷⁾ for the core design where the fuel rod diameter was changed from the representative core's value of 11.2mm to the final design value of 9mm. The void reactivity coefficient decreases significantly toward negative along with the decreasing fuel rod diameter under 11mm. The 100% void reactivity coefficient shows the similar tendency, but the degree is relaxed. On the other hand, the void reactivity coefficient becomes negative under 9mm, but the 100% void reactivity coefficient is large positive value and positive at even 7mm. The characteristics of the variation in both of the void reactivity coefficients when the fuel rod diameter is reduced to less than 11mm are discussed as follows. In addition, the core design of HC-FLWR for MA recycling was performed taking advantage of these characteristics in the previous study.

For each reactivity effect, the absorption term is positive, and the fission term is negative. These values cancel out each other, and the variation are small. Contrarily, the scattering term shows a wide variation. Moreover, the loaded MA significantly changes the value of the scattering term. Therefore, the net characteristics of void reactivity coefficients depend on the characteristics of the scattering term.

← [Fig. 5 and 6]

The energy distributions of the void reactivity coefficient and the 100% void reactivity coefficient with the fuel rod diameters of 7, 9 and 11mm are shown in **Figs. 5 and 6**, respectively. The reactivity is assigned to the energy group where the cross section changes as mentioned in Section IV-1. In infinite geometry, there exist only three terms, namely the scattering, absorption and fission term.

First, the characteristics of the scattering term are discussed. Considering the meaning of Eq. (6), the factors determining the characteristics of the scattering term are as follows. First, it is proportional to the flux level in the same energy region. Next, it is proportional to the

convolution of the cross section variation and the difference of the adjoint flux level between the energy region of departure and arrival during the scattering process. In other words, the reactivity may change via the difference of the adjoint flux level, even if the neutron population did not change. The scattering term can be divided into three parts with considering the characteristics. First part is the negative reactivity peak around 1eV. Second part is the positive and negative peaks distributing in the resonance region from 2eV to 40keV. Third part is the peak of positive reactivity over 40keV.

The negative peak around 1eV corresponding to the large resonance absorption peak of ^{240}Pu is very important, and the absolute value of the peak becomes larger with the decreasing fuel rod diameter. Because of this characteristic, the net void reactivity shifts significantly toward negative for the smaller fuel rod diameter. This effect is almost solely due to the flux level. This can be verified by comparing the flux levels around 1eV shown in **Figs. 7 and 8** with the reactivity shown in Figs. 5 and 6, respectively. The spectra become softer for the smaller fuel rod diameter, and become larger around 1eV.

← **[Fig. 7 and 8]**

For the positive and negative peaks in the resonance range from 2eV to 40keV, the reactivity amplitude becomes also larger for the smaller fuel rod diameter. Strictly speaking, for the void reactivity coefficient, the energy range where this tendency appears is from 2eV to 400eV. The reason is also the increase in the flux level. In the state of 100% voided, the flux levels increase with increasing fuel rod diameters. On the other hand, in the state of voided the flux levels increase only under 400eV. The effect of slimed fuel rod is not only the increase in the reactivity amplitude but also the shift of the average value toward negative. The reactivity distributed in this energy range also plays important role to shift the total reactivity toward negative.

For the peak of positive reactivity over 40keV, the effect of the difference of the adjoint flux is significant comparing with that of the flux level. The gradient of the adjoint flux around 10^6eV shown in **Fig. 9** becomes less for the smaller fuel rod diameter. Also, the almost constant values distributed from 1 to 100keV become larger. These effects reduce

the positive reactivity with the smaller fuel rod diameter, because the peak of positive reactivity over 40keV reduces with the reducing difference of the adjoint flux level between the energy region of departure and arrival during the scattering process. On the other hand, for the flux distribution over 1MeV, the distribution becomes harder for the smaller fuel rod diameter. This effect reduces the positive reactivity of the peak over 40keV for the smaller fuel rod diameter. These three negative reactivity effects give the characteristics where the reactivity of the scattering term reduces linearly toward negative with the reduced fuel rod diameter. In a current discussion, the effect on the variation of the scattering cross section is not yet discussed. However, the variation in the scattering cross section, which is caused by the reduction in the coolant density, is negative value, and the effect on the reactivity is small for the variation in the fuel rod diameter comparing with that of the variation in the adjoint flux distribution. This was confirmed numerically. For the 100% void reactivity coefficient shown in Fig. 6, the reactivity distribution can be also divided into three regions similarly. However, different characteristics appear. The absolute value of the peak around 1eV is very small, and the peak over 40keV is very large. Therefore, the value is distributed significantly over positive region as shown in Fig. 4 comparing with the void reactivity coefficient.

← [Fig. 9]

Next, the characteristics of the absorption and fission terms are discussed. These two kinds of the reactivity coefficient are generated by similar mechanisms. The reason why the absorption and fission terms were distributed almost symmetrically with the positive and negative value is that the reduction in the absorption cross section generates positive reactivity, whereas the reduction in the production cross section generates negative reactivity. The cause of the reactivity generation is considered as the variation in the cross section, the flux and the adjoint flux. For the variation in the cross section, two causes can be considered.

First is the effect of the variation in the homogenized macroscopic cross section due to the variation in flux distribution. The variation in the flux distribution changes the weight of the each cell region for the cross sections. And the variation in the weight changes the

homogenized macroscopic cross section. This effect appears mainly under 1eV and over 100keV. Generally speaking, when the void fraction increases, the absorption cross section reduces due to the reduced density of the coolant. However, the effect can be ignored in this case, because most of the cross section variations occur in the pellet region not only for the production cross section but also for the absorption cross section. This can be confirmed by observing the reactivity distribution where the absorption and fission terms are distributed almost symmetrically. On the contrary, if the variation of the absorption cross section due to the reduced density of the coolant cannot be ignored, the symmetry breaks because of the different mechanism of the cross section variation. Therefore, the contribution of the variation in the coolant density to the variation in the absorption cross section is small. These decreases in the cross sections occur due to the relative shift of flux distribution from the pellet region to the coolant region.

Second is the effect of the variation in resonance cross section in pellet region. The reactivity from 1eV to 1keV is due to this effect. The mechanism is considered as follows. First, the scattering reaction out of the pellet region is reduced due to the reduction in the coolant density along with the void fraction. This effect can be qualitatively explained by discussing the Dancoff coefficients shown in **Table 4**. The physical meaning of the Dancoff coefficient can be interpreted as the probability of the neutron escaping from the pellet region to come back to the pellet region again without scattering in the coolant region. This probability increases along with the void fraction. The effect of the decrease in the scattering reaction in the coolant region appears as the decrease in the effective background cross section. As a result, the energy self-shielding effect is strengthened, so the resonance cross section decreases.

Next, the effect of the absolute value of the flux and the adjoint flux is discussed. The forward spectra in the state of voided and 100% voided are shown in Fig. 7 and 8, respectively. Also, the adjoint spectra in the reference state are shown in Fig. 9. These values are normalized under the condition as follows.

$$\sum_g v\Sigma_{f,g}\phi'_g = 1 \quad (8)$$

$$\sum_{g'} \chi_{g'}\phi^*_{g'} = 1 \quad (9)$$

By these normalizations, the perturbation denominator described in Eq. (2) becomes unity. Therefore, the absolute value of the flux and the adjoint flux determine the absolute value of the reactivity directly. In the state of voided, the absolute value of the flux is small despite the significant variation in the shape with different fuel rod diameters. In the state of 100% voided, the value increases with the decreasing fuel rod diameter. Two reasons can be considered for the variation in the absolute value of the flux. First is the effect of decrease in the production cross section due to the decrease in the area of the pellet region by reduction in the fuel rod diameter. The reason is that the absolute value of the flux is inversely proportional to the production cross section in the relation of Eq. (8). The other is the effect of the variation in the fission reaction rate distribution due to the variation in the spectrum shape. This is also due to the normalization by Eq. (8). The thermal and fast energy regions play important roles to this effect. In the thermal energy region, the production cross section is very large in the $1/v$ manner. In the fast energy region, the value is also large due to the threshold reaction and increase in the fission neutron yield. In the state of voided, there are two effects for increase in the flux level and one effect for decrease. For the effects for the increase in the flux level, the cross section becomes smaller with decreasing fuel rod diameter. Also, the softer spectrum with the smaller fuel rod diameter reduces the fission reaction rate in fast energy region. For the effect for the decrease in the flux level, the fission reaction rate in thermal energy region increases because of the softer spectrum. These three effects cancel out. As a result, the absolute value of the flux changes little. In the state of 100% voided, there exist similar effects. Generally, the spectrum is hard, and the flux level in the thermal energy range is very small. Therefore, the effect for the decrease in the flux level due to increasing the fission reaction rate in the thermal energy cannot be

expected. As a result, the flux level becomes larger for the smaller fuel rod diameter. Because of this tendency, the absolute value of the reactivity of the absorption and fission term increase with the reducing fuel rod diameter for the 100% void reactivity coefficient as shown in Fig. 4. On the other hand, the effect of the variation in the adjoint flux for the absorption and fission term is little.

← [Fig. 10]

Finally, the effect of the loaded MA on void reactivity coefficients is discussed. As shown in Fig. 4, the main effect is the increase in the absolute value of the scattering term. This tendency is more significant for the 100% void reactivity coefficient. **Figure 10** shows the comparison for the scattering term between the case without MA and the case with 2wt% of Am at the fuel rod diameter of 11mm. The figure shows the value in each energy region and the cumulative value of the difference between the reactivity without MA and the reactivity with 2wt% of Am for the energy from the lower energy region. As the effect of the loaded MA, the values shift toward positive in all energy regions. Especially for the positive reactivity peak over 10^5 eV, the increase in the reactivity is significant, and the contribution is about two thirds of the increase in the total reactivity. As a result, the positive reactivity is inserted by the MA loading. This tendency is more significant for the 100% void reactivity coefficient. The effect is mainly due to the variation in the adjoint flux with MA loading as shown in **Fig. 11**. The loaded MA shifts the adjoint flux toward negative constantly under 10^5 eV and increase the gradient over 10^5 eV. This causes the increase in the reactivity over 10^5 eV. Furthermore, for the effect of variation in the flux due to the MA loading, the loaded MA, whose absorption cross section is large in the thermal energy, makes the spectrum harder, and makes the absolute value larger around 10^6 eV in the state of voided as shown in **Fig. 12**. It also contributes to the increase in the reactivity. On the other hand, in the state of 100% voided, the variation in the spectrum due to the loaded MA is small because the spectrum is originally hard as shown in **Fig. 13**. As described above, the variation in the flux also contribute to the reactivity generation, but almost all of the contribution is due to the variation in the adjoint flux. For the variation of the scattering

cross section, the effect by loaded MA can be ignored, because the variation of the scattering is mainly due to the variation of hydrogen atoms of the coolant. Therefore, in order to consider the mechanism of the reactivity generation, the characteristics of the adjoint flux should be understood. The adjoint flux is also called “the neutron importance”, and used as the barometer which indicates the contribution of the absorbed neutrons to the reactivity. Generally, it is said that the neutron importance is related to the η -value which is the ratio of the production to absorption cross section¹²⁾. **Fig. 14** shows the homogenized macroscopic cross section of the production and absorption, and the η -value without MA and with 2wt% of Am. Comparing the η -value with the adjoint flux, the same tendency by the MA loading appears in the both values. For example, the values shift constantly toward negative under 10^5 eV. And, the gradient increases over 10^5 eV. The reason is considered that these tendencies appear due to the difference of cross sections between the loaded Am, mainly ^{241}Am and ^{243}Am , and ^{238}U which is replaced by the Am nuclides. For the constant decrease in the adjoint flux under 10^5 eV, it is due to the larger absorption cross section of the Am nuclides than that of ^{238}U . Moreover, for the increased gradient over 10^5 eV, it is mainly due to the larger production cross section of the Am nuclides than that of ^{238}U . As a matter of course, both of ^{238}U and the Am nuclides, specifically ^{241}Am and ^{243}Am , are the threshold reaction nuclides. The fission cross section increases rapidly from 10^5 to 10^6 eV, and is distributed constantly from 10^6 to 10^7 eV. In this energy range, the fission cross section of the Am nuclides is about ten times larger than that of ^{238}U . Therefore, the gradient of the adjoint flux is increased by the Am loading. In addition, this tendency is similar to ^{237}Np . Thus the mechanism of worsening in void reactivity coefficients by the Np loading is also similar to the case of the Am loading.

← [Fig. 11, 12, 13 and 14]

2. Result of Core Calculation with Finite Geometry

The characteristics of the absorption, fission and scattering term discussed in Section V.1 are also common to the result of core calculation. However, to investigate the characteristics

of a leakage term, it is necessary to calculate the core model with finite core height geometry. In this section, the effect of the leakage term, especially for the effect of the core height, is discussed with 1-D core calculations. There are two leakage effects, axial one and radial one. In this core concept, the axial leakage effect is effective due to the short and flat core configuration. In this section, the axial leakage effect is estimated by 1-D calculation for axial direction. On the other hand, the radial leakage is taken into account by the geometrical buckling. Moreover, the 3-D core calculations were also performed. However, the result is similar to that of the 1-D calculations. Also, the result of the 1-D calculations indicates the pure characteristics without the effect of shuffling patterns. Therefore, only the result of the 1-D calculations is discussed. Moreover, to examine the precise characteristics of the void reactivity coefficients, the calculation accuracy of MOSRA, which is based on diffusion theory, for the geometry with the large neutron leakage was investigated by comparing with the results of MVP, which is the Monte Carlo code for neutron transport, as shown in **Table 5**. For the void reactivity, the 100% voided state was employed as the perturbed state, because the neutron leakage is the largest at the state. The geometry condition of the MVP calculations is the same as shown in Figs. 2 and 3. As a result, it was found that the values are in good agreement. Especially, the difference of void reactivity between MOSRA and MVP is merely about $0.5\% \Delta k/k'$ at any core heights. Namely, the accuracy of the MOSRA calculation is high enough to evaluate the void reactivity coefficients in this core concept.

← [Table 5 and 6]

← [Fig. 15]

The void reactivity coefficient and the 100% void reactivity coefficient with the fuel rod diameter of 9mm are shown in **Fig. 15**. These values are in the case with the core height of 80, 100 and 120cm. Each of the cases is performed without MA and with 2wt% of Am. The void reactivity coefficients are at the burn-up corresponding to the EOC condition. However, because of the difference of the calculation conditions for the core height and the MA content, the burn-ups are different. The reason is that the core design with higher burn-up can be established if the core height is higher, or the MA content is less. **Table 6**

shows the detail. In order to consider the leakage effect, it is important to compare the 1-D calculation result of Fig. 15 in finite geometry and the cell calculation results of Fig. 4 in infinite geometry.

By comparing the values shown in Fig. 15, the effect of the core height doesn't appear in the absorption and fission term, but it appears in the scattering and leakage term significantly. Especially in the case of 100% void reactivity coefficient, the effect is significant for the leakage term. The important point for the core design here is that the reactivity of scattering term plays an important role to determine whether void reactivity coefficients are negative or positive as shown in Fig. 4. For the void reactivity coefficient it contributes significantly to the negative reactivity. However, for the 100% void reactivity coefficient it doesn't contribute because of the positive value. In order to make the 100% void reactivity coefficient negative, in this study, it is quantitatively found that the reactivity of the leakage term works to make the 100% void reactivity coefficient negative successfully by the decrease in the core height. Observing the 100% void reactivity coefficient shown in Fig. 15, which is restriction of the core design, the reactivity of the scattering term decreases in proportion to the core height. The reactivity of the scattering term without MA shows the positive value over 100cm despite the fact that the value is widely lower toward negative than the value with infinite geometry at the fuel rod diameter of 9mm shown in Fig. 4. The effect of the MA loading widely shifts the reactivity of the scattering term toward positive. On the other hand, the leakage term gives large contribution to the negative reactivity in spite of the slight increase in the reactivity by the MA loading. This contribution increases inversely proportional to the core height. The mechanism to achieve the negative 100% void reactivity coefficient via the leakage term due to the reduction in the core height as a means of the core design is quantitatively confirmed. As a result, even with MA loading, the 100% void reactivity coefficient is negative if the core height is lower than 120cm. Moreover, the reason why the contribution of the leakage term to the negative reactivity is more significant for the 100% void reactivity coefficient than for the void reactivity coefficient is that the

neutron is easier to leak in the state of 100% voided, because of the lesser scattering reaction, and the lower core height promotes the neutron leakage.

VI. Conclusions

For MA loading to the MOX fuel of HC-FLWR core, the characteristics of void reactivity coefficients are investigated in detail using the exact perturbation calculations, and the factors to achieve the negative void reactivity coefficients are found. There exists the tendency to make the void reactivity coefficients worse due to the loaded MA, and it is found that the tendency is due to the variation in the reactivity of the scattering term in the exact perturbation theory. In addition, as the measure of the core design to achieve the negative void reactivity coefficients, the reduction in the fuel rod diameter and/or the core height is effective. The former is based on the negative reactivity effect of the scattering term with the reduction in the fuel rod diameter. The later is based on the negative reactivity effect of the leakage term with the reduction in the core height. Moreover, the several important characteristics were found as follows:

1. The scattering term deeply depends on the gradient of the adjoint flux over 10^5eV . The loaded MA increases the gradient, and makes the void reactivity coefficients worse.
2. The void reactivity coefficient estimated around the nominal operating condition, simply called “the void reactivity coefficient”, and that evaluated from the nominal operation condition to the state of 100% voided, called “the 100% void reactivity coefficient”, shows individual characteristics. Especially, the reactivity of the scattering term changes widely, so it makes the 100% void reactivity coefficients positive. In order to achieve the negative 100% void reactivity coefficients by controlling this tendency, only the negative reactivity effect of scattering term with reduction in the fuel rod diameter is not enough, so the large negative reactivity effect of leakage term obtained by the reduction in the core height needs to be utilized.
3. The effect of the core height to the reactivity is more significant for the 100% void

reactivity coefficient than for the void reactivity coefficient. The reason is considered that the neutron is easier to leak in the state of 100% voided, because of the less scattering reaction. Moreover, the lower core height promotes the neutron leakage.

Acknowledgements

We appreciate Dr. T. Hazama, Dr. T. Kugo and Dr. G. Chiba for technical comments on the exact perturbation theory.

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Figure captions

Fig. 1 Changes in core design from LWR to FLWR

Fig. 2 Cell calculation model

Fig. 3 Core calculation model

Fig. 4 Void reactivity coefficient and 100% void reactivity coefficient (with Puf content of 13wt% , void fraction of 50% and burn-up of 30GWd/t)

Fig. 5 Void reactivity coefficient without MA

Fig. 6 100% void reactivity coefficient without MA

Fig. 7 Forward spectra in state of voided without MA

Fig. 8 Forward spectra in state of 100% voided without MA

Fig. 9 Adjoint spectra in reference state without MA

Fig. 10 Effect on loaded MA to scatter term at fuel rod diameter of 11mm

Fig. 11 Adjoint spectra in state of 50% voided at fuel rod diameter of 11mm

Fig. 12 Spectra in the state of voided at fuel rod diameter of 11mm

Fig. 13 Spectra in the state of 100% voided at fuel rod diameter of 11mm

Fig. 14 Macroscopic cross sections and η -value

Fig. 15 Void reactivity coefficient and 100% void reactivity coefficient at fuel rod diameter of 9mm

Table 1

Design value of core concept for HC-FLWR for MA recycling

	Am Core
Electric power (MWe)	1,356
Thermal power (MWt)	3,926
Number of fuel assemblies	900
Number of fuel rods per assembly	217
Equivalent core diameter (m)	7.4
Puf content (wt%)	13.0
Fuel rod diameter (mm)	9.0
Gap between fuel rods (mm)	6.0
Core height (mm)	1,200
MA content (wt%)	2.0
Discharge burn-up (GWd/t)	54.9
Cycle length (Month)	13.8
Number of batch	3.45
MA conversion ratio	1.03
Loaded Am conversion ratio	0.81
Puf conversion ratio	0.78
Coolant core inlet temperature (K)	550
Coolant flow rate (kg/s)	10,000
Core average void fraction (%)	45.9
Void reactivity coefficient ($\Delta k/k/\%$ void)	-1.10×10^{-3}
100% void reactivity coefficient ($\Delta k/k/\%$ void)	-2.39×10^{-5}
Doppler reactivity coefficient ($\Delta k/k/K$)	-2.21×10^{-5}
Maximum radial power peaking (EOC)	1.27

Table 2 Pu and MA composition (1/3)

Nuclide	Content (wt%)
^{238}Pu	2.6
^{239}Pu	50.1
^{240}Pu	28.0
^{241}Pu	10.1
^{242}Pu	8.2
^{241}Am	1.0

Puf	60.2

Table 2 Pu and MA composition (2/3)

Nuclide	Content (wt%)
^{237}Np	100.0

Table 2 Pu and MA composition (3/3)

Nuclide	Content (wt%)
^{241}Am	68.6
$^{242\text{m}}\text{Am}$	0.2
^{243}Am	31.3

Table 3

Void reactivity coefficient of exact perturbation theory and direct method (without MA) (1/2)

Rod diameter (mm)	7	8	9	10	11	12	13	14
Perturbation	-1.68×10^{-3}	-1.15×10^{-3}	-4.83×10^{-4}	1.82×10^{-4}	7.09×10^{-4}	1.00×10^{-3}	1.04×10^{-3}	8.51×10^{-4}
Direct	-1.68×10^{-3}	-1.15×10^{-3}	-4.85×10^{-4}	1.80×10^{-4}	7.07×10^{-4}	1.00×10^{-3}	1.04×10^{-3}	8.50×10^{-4}

Table 3

Void reactivity coefficient of exact perturbation theory and direct method

(with 2wt% of Am) (2/2)

Rod diameter (mm)	7	8	9	10	11	12	13	14
Perturbation	-1.77×10^{-3}	-1.07×10^{-3}	-2.73×10^{-4}	4.67×10^{-4}	1.01×10^{-3}	1.27×10^{-3}	1.25×10^{-3}	1.01×10^{-3}
Direct	-1.77×10^{-3}	-1.08×10^{-3}	-2.76×10^{-4}	4.65×10^{-4}	1.01×10^{-3}	1.27×10^{-3}	1.25×10^{-3}	1.01×10^{-3}

Table 4

Relation between void fraction and Dancoff coefficient

Rod diameter (mm)	50% voided (reference)	55% voided	100% voided
7	0.25495	0.27640	0.72480
9	0.35234	0.37518	0.76789
11	0.46423	0.48561	0.79946

Table 5

Verification of multiplication factor estimated by MOSRA

	H:80cm	H:100cm	H:120cm
MOSRA ref	1.12905	1.15332	1.16885
MVP ref	1.13167	1.15333	1.16850
MOSRA 100%	1.02116	1.08840	1.13631
MVP 100%	1.01720	1.08282	1.13003
$\Delta k/kk\%$			
MOSRA	-9.36	-5.17	-2.45
MVP	-9.94	-5.65	-2.91

Table 6

Condition of 1-D core calculation

Core Type	1	2	3	4	5	6
Core Height (cm)	80.0	100.0	120.0	80.0	100.0	120.0
Am Content (wt%)	0.0	0.0	0.0	2.0	2.0	2.0
Cycle Length (day)	365.0	365.0	365.0	284.5	365.0	365.0
Number of Batch	2.84	4.90	6.80	1.00	2.58	4.34
EOC Burn-up (GWd/t)	40.4	49.7	54.7	16.4	30.1	37.5

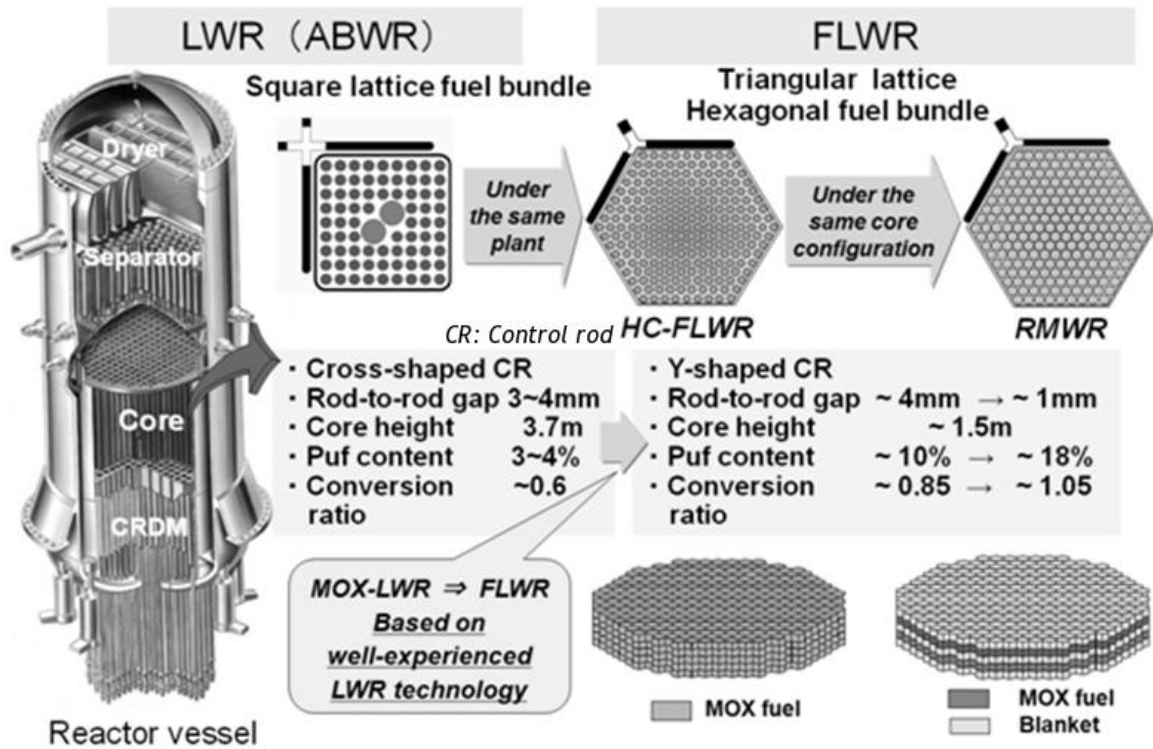


Fig. 1 Changes in core design from LWR to FLWR

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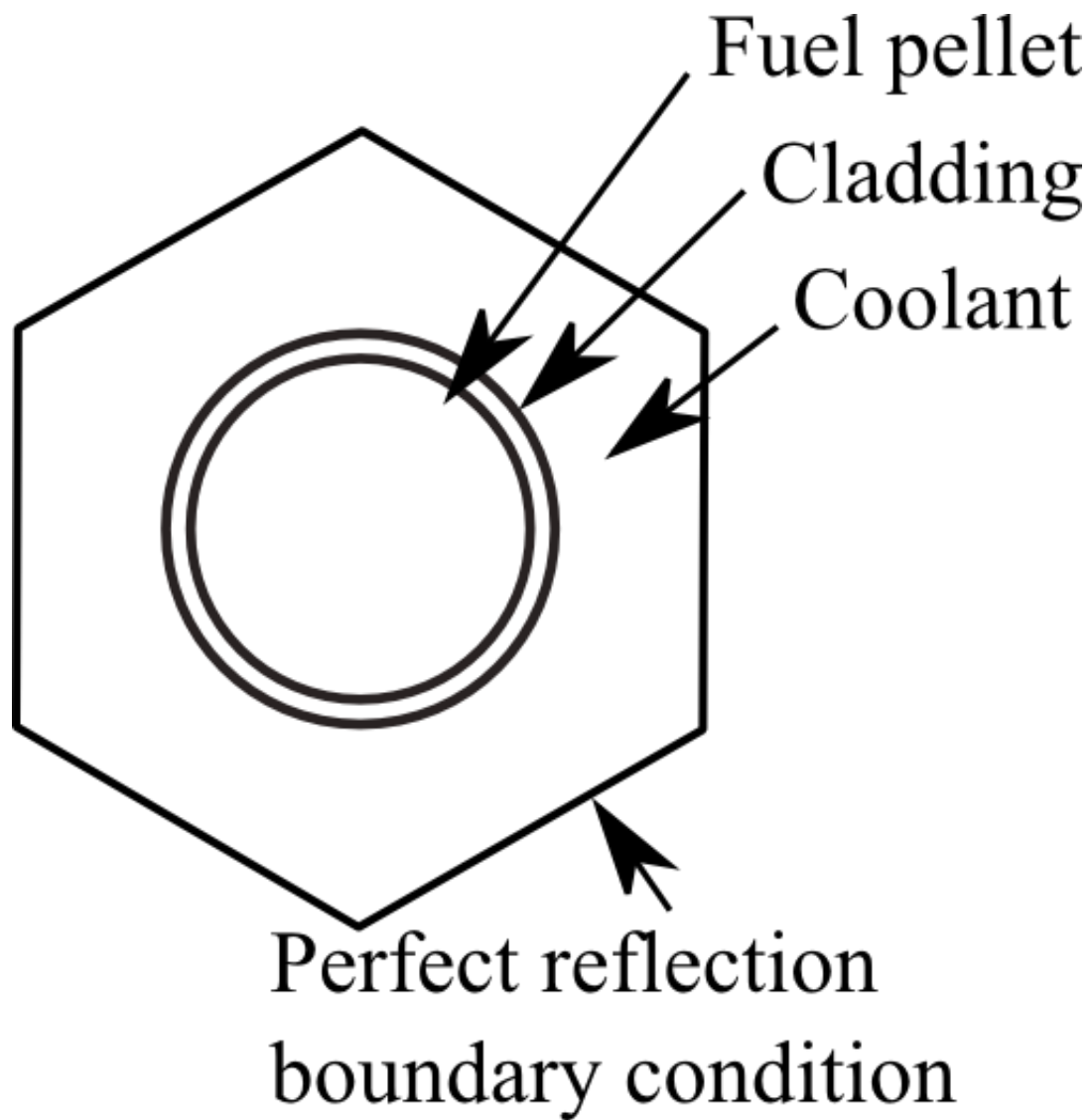


Fig. 2 Cell calculation model

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Recycling

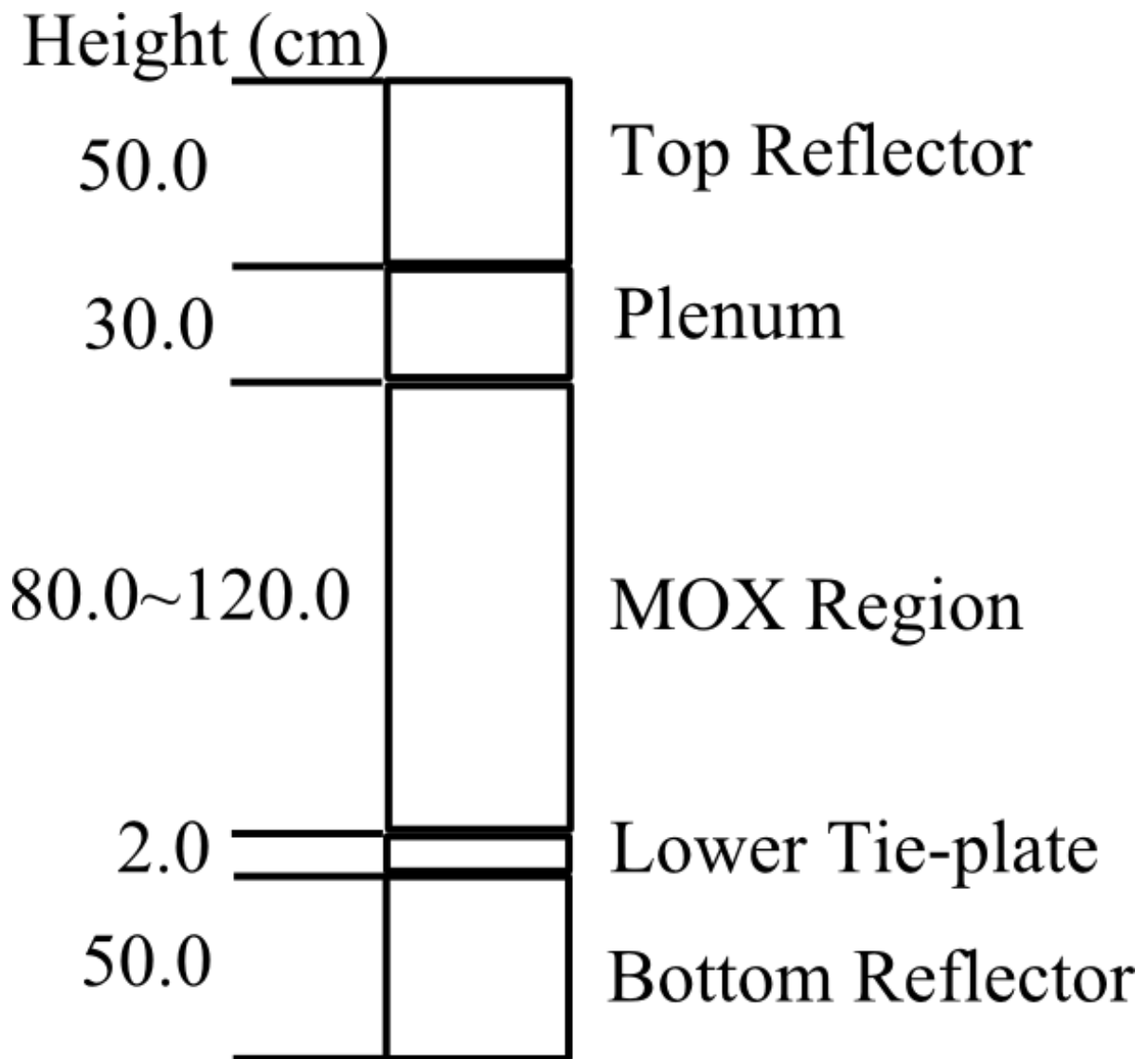


Fig. 3 Core calculation model

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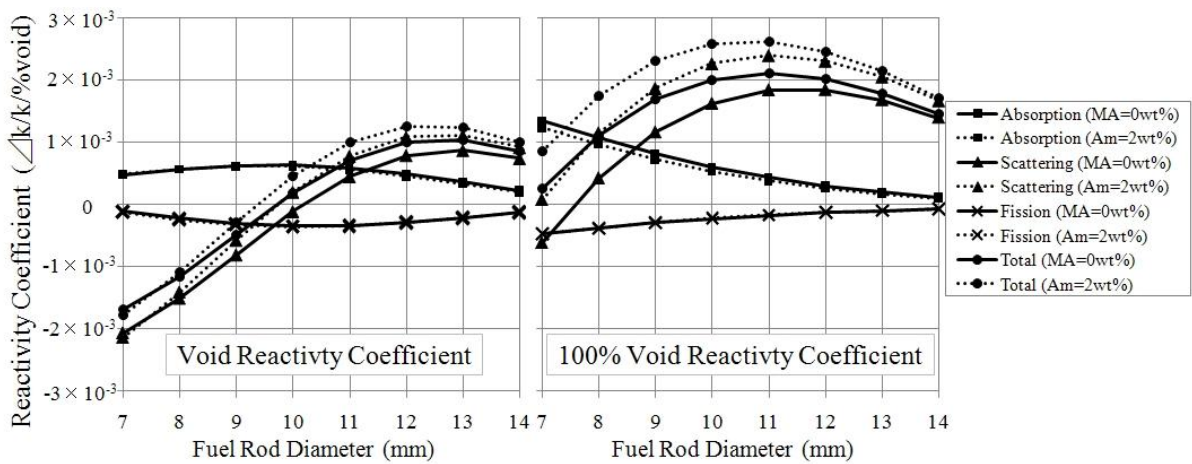


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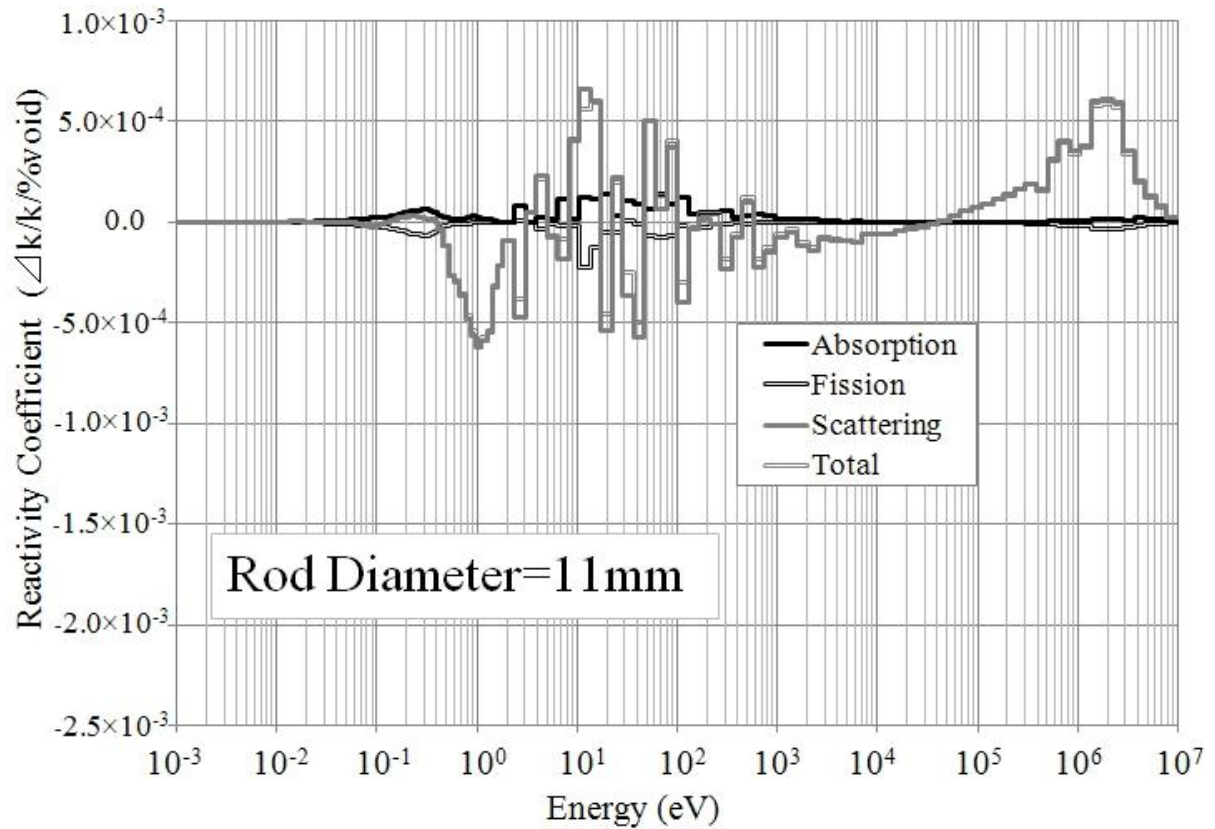


Fig. 5 Void reactivity coefficient without MA(1/3)

(at 11mm of fuel rod diameter)

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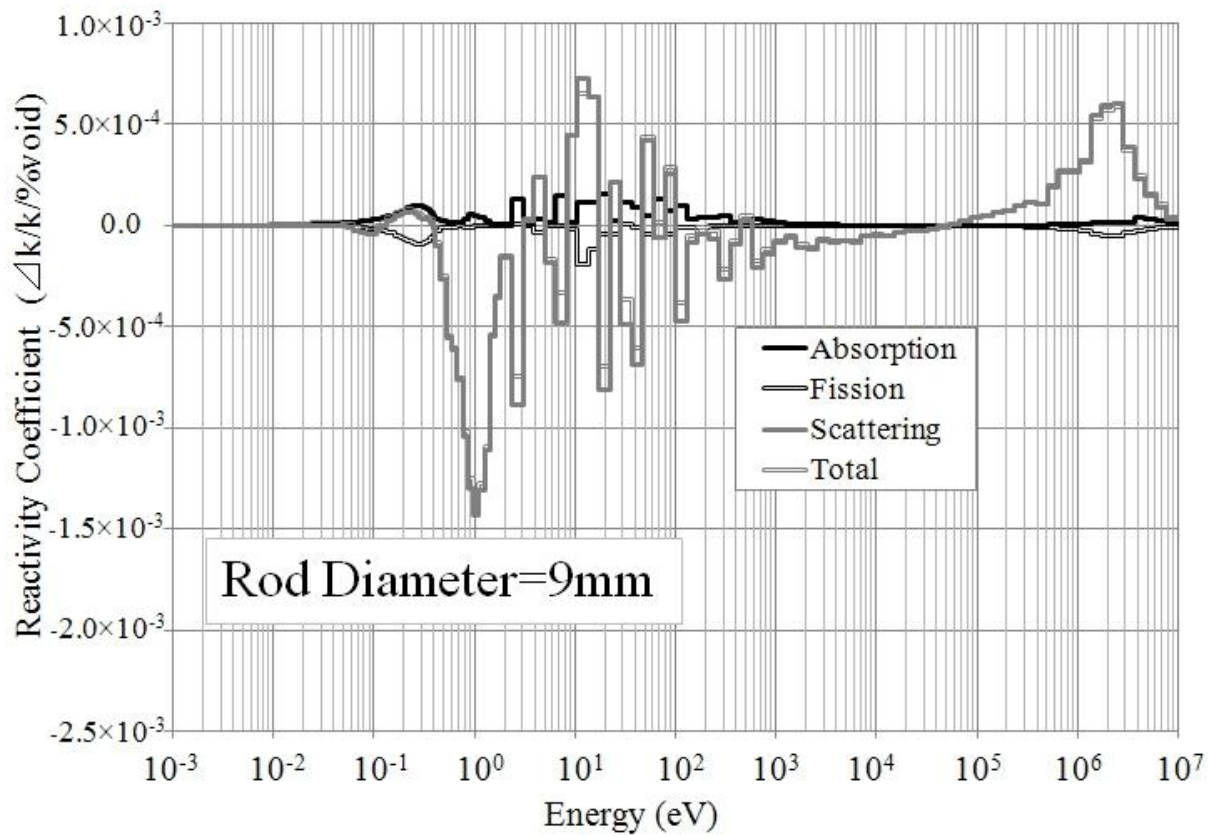


Fig. 5 Void reactivity coefficient without MA(2/3)

(at 9mm of fuel rod diameter)

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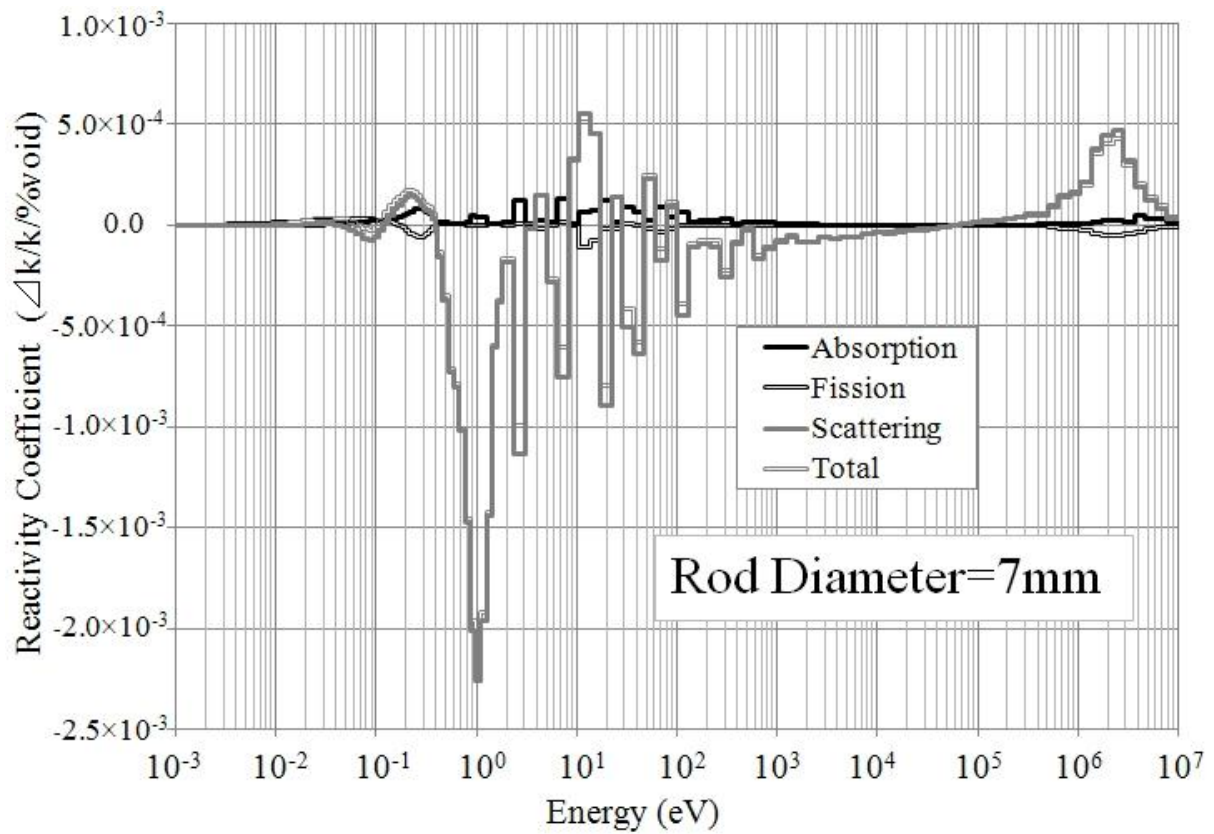


Fig. 5 Void reactivity coefficient without MA(3/3)

(at 7mm of fuel rod diameter)

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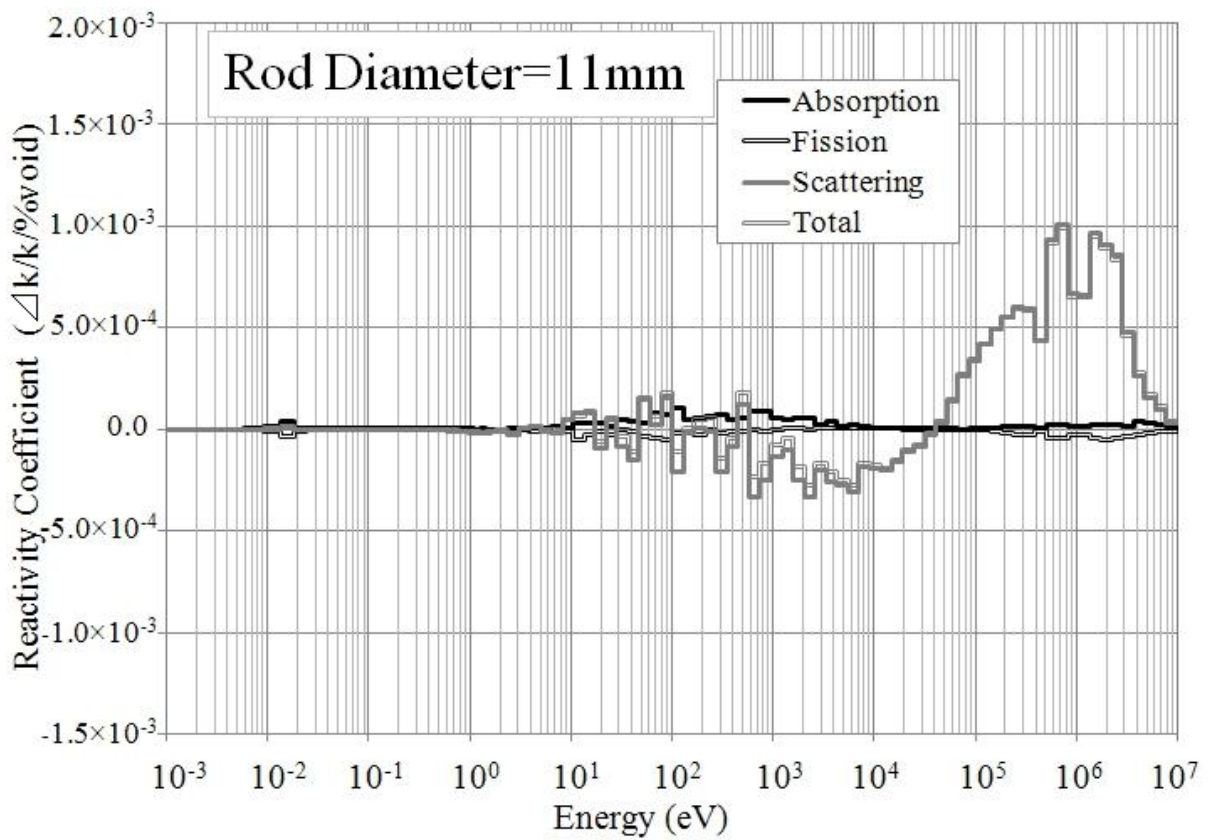


Fig. 6 100% void reactivity coefficient without MA(1/3)

(at 11mm of fuel rod diameter)

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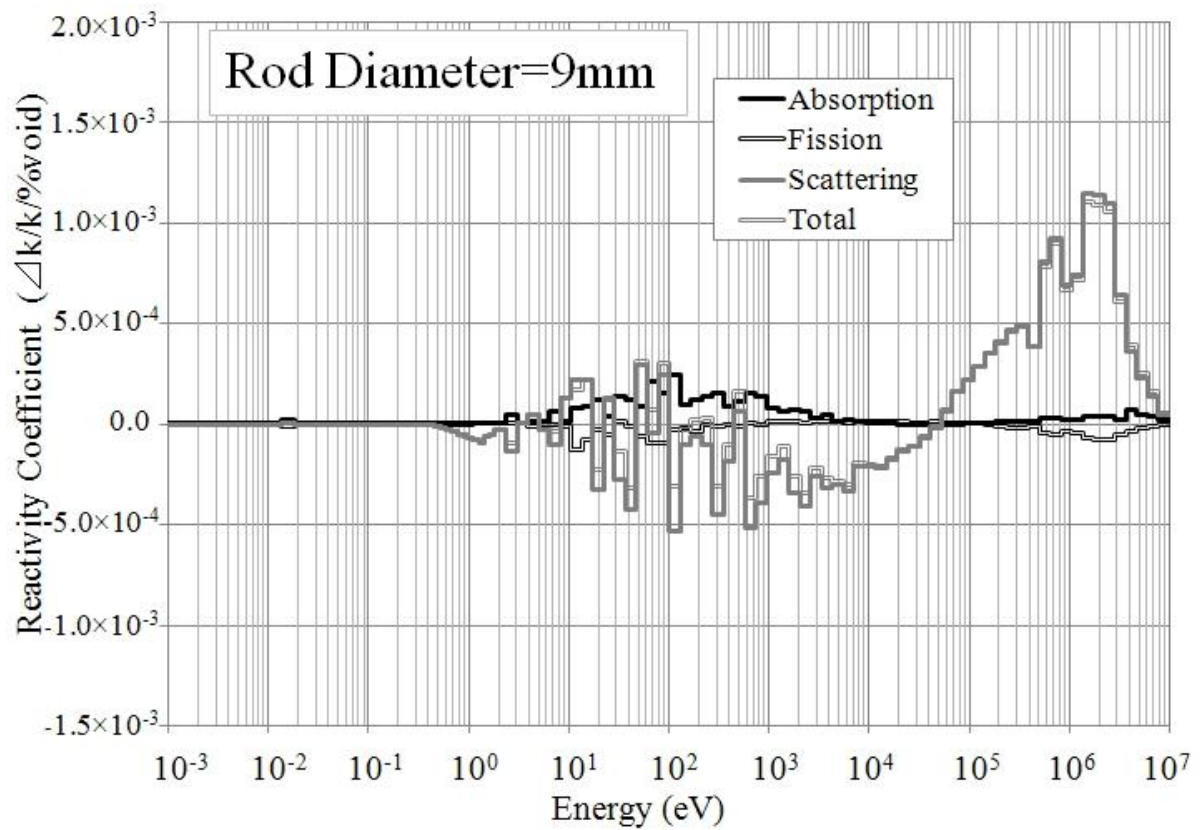


Fig. 6 100% void reactivity coefficient without MA(2/3)

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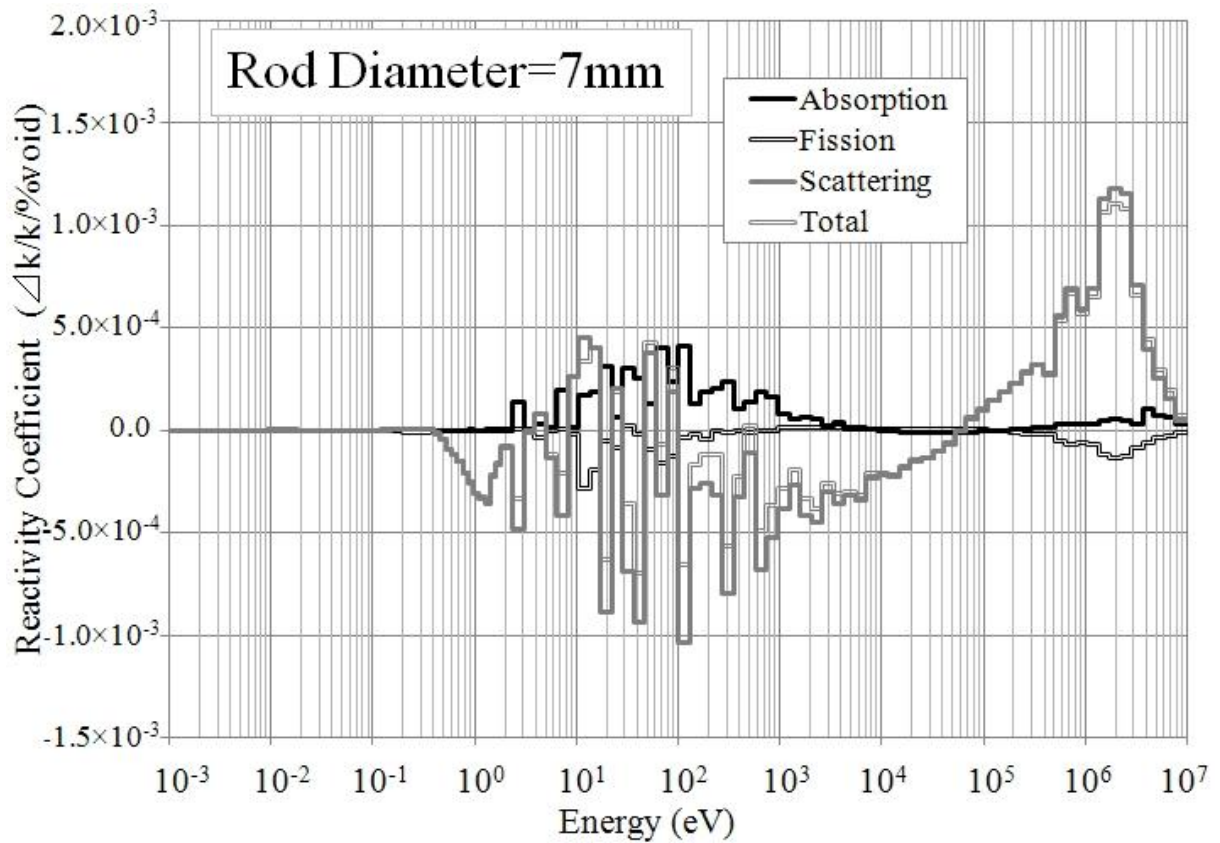


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(at 7mm of fuel rod diameter)

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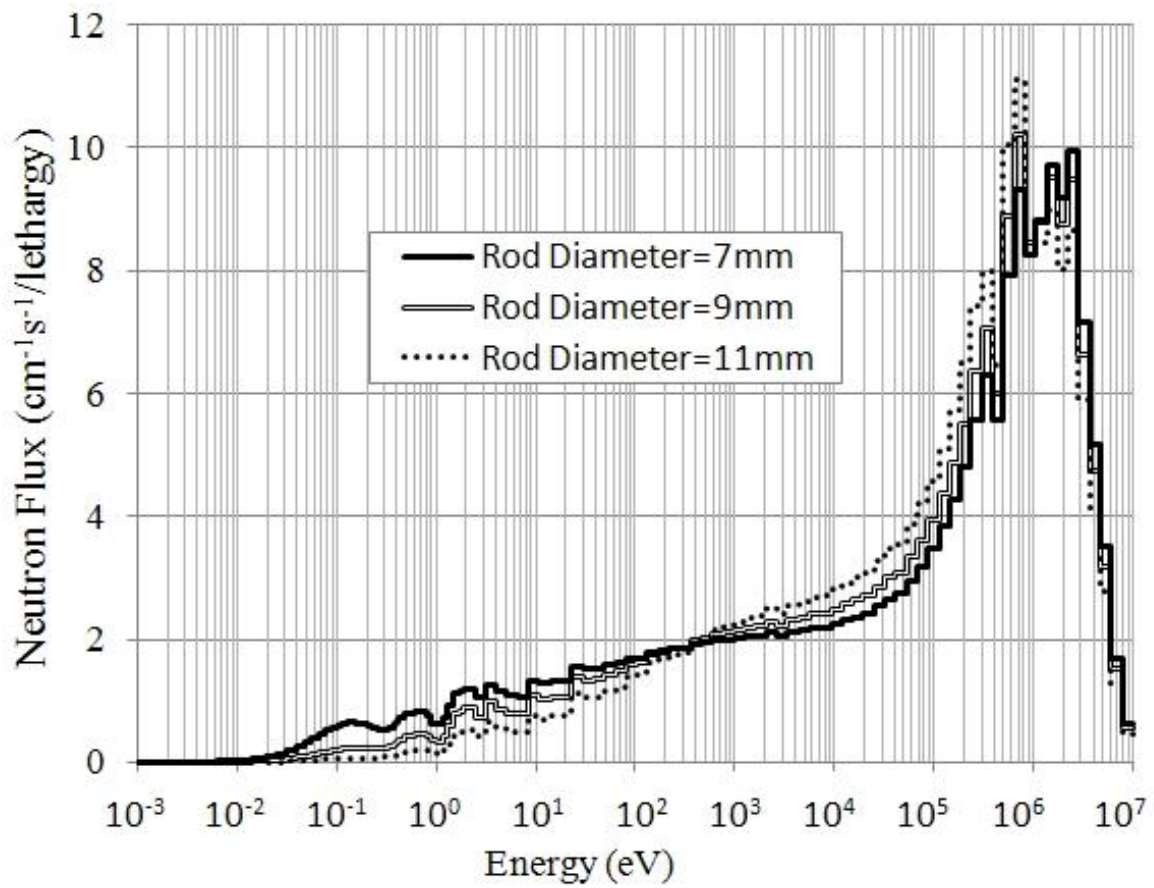


Fig. 7 Forward spectra in state of voided without MA

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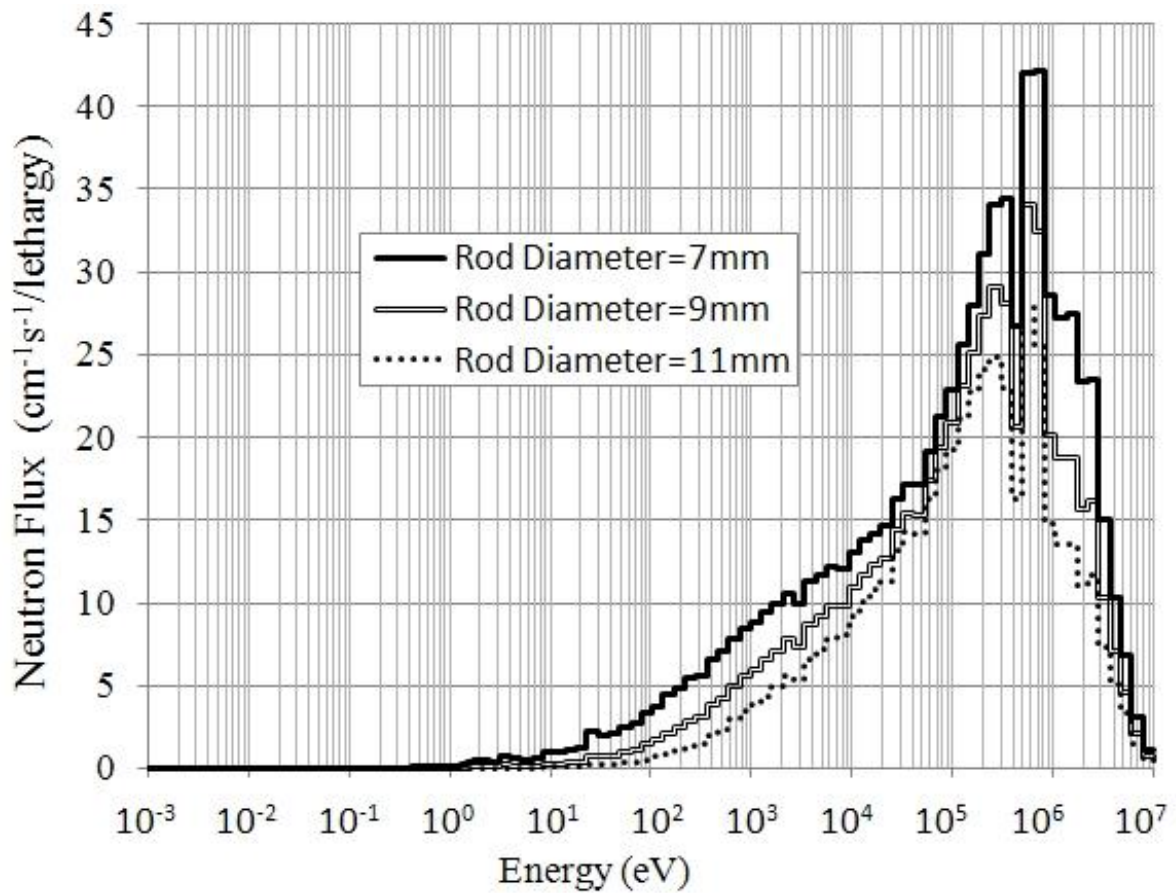


Fig. 8 Forward spectra in state of 100% voided without MA

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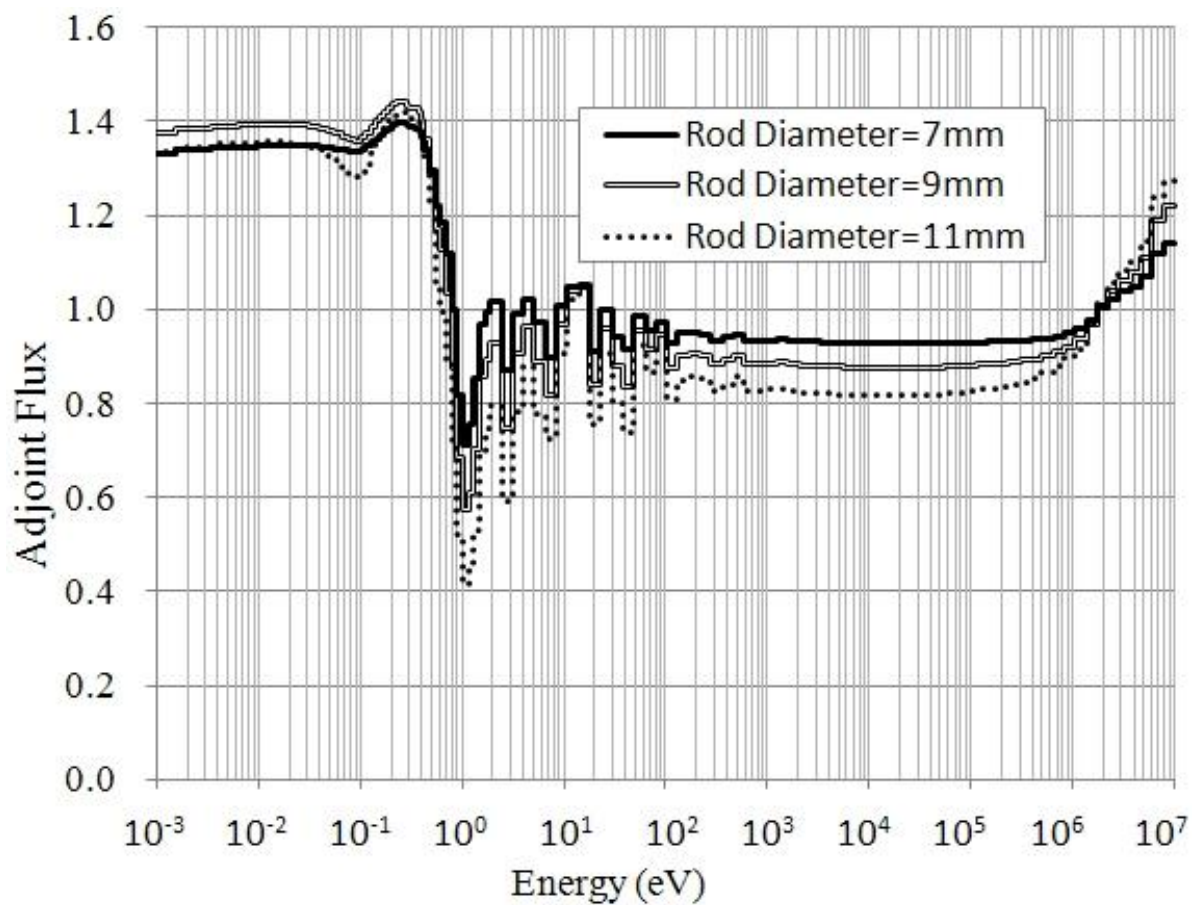


Fig. 9 Adjoint spectra in reference state without MA

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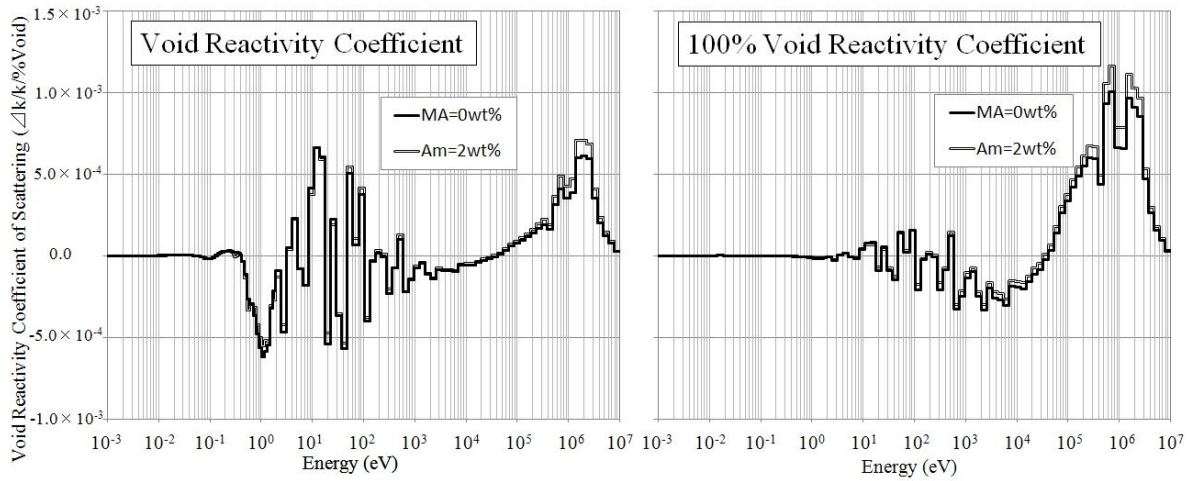


Fig. 10 Effect on loaded MA to scattering term at fuel rod diameter of 11 mm (1/2)

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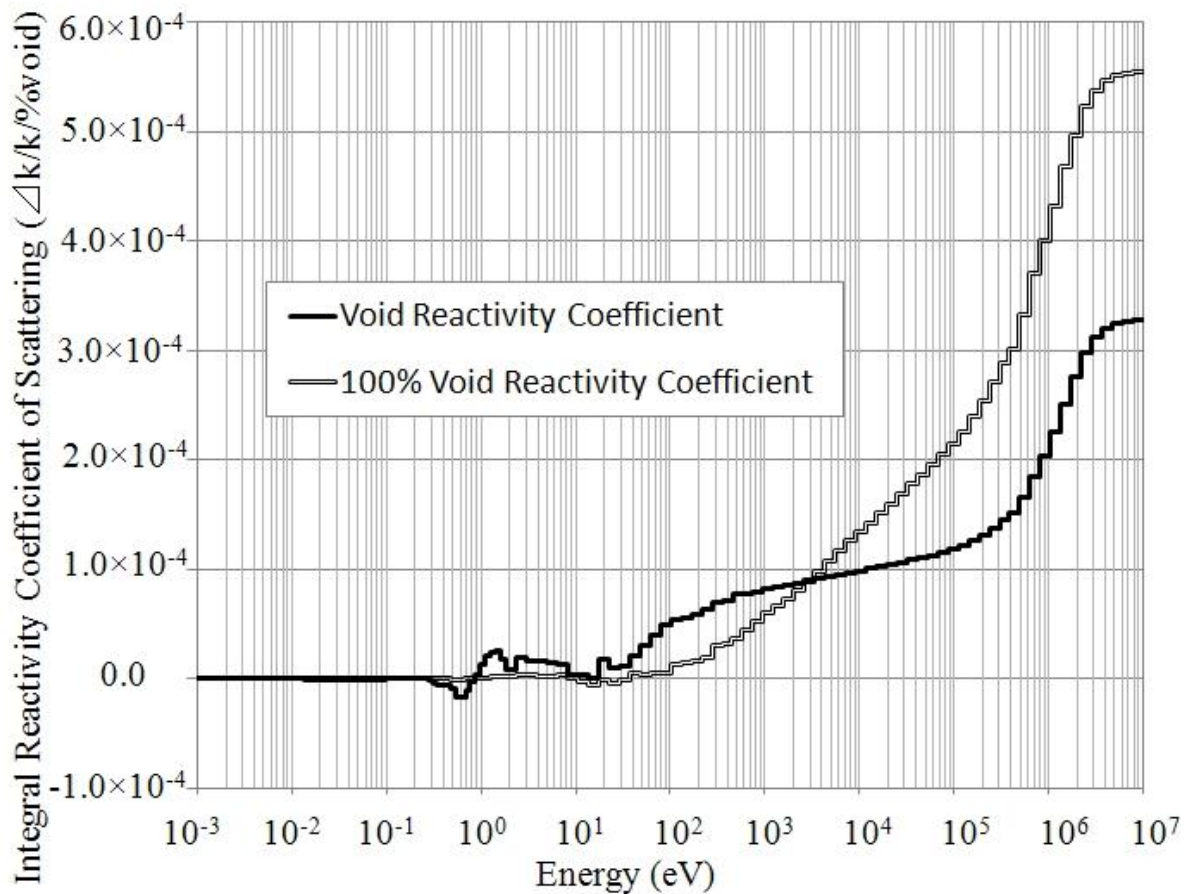


Fig. 10 Effect on loaded MA to scattering term at fuel rod diameter of 11mm (Cumulative value of the difference of reactivity between with 2wt% of Am and without MA from lower energy region)(2/2)

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Recycling

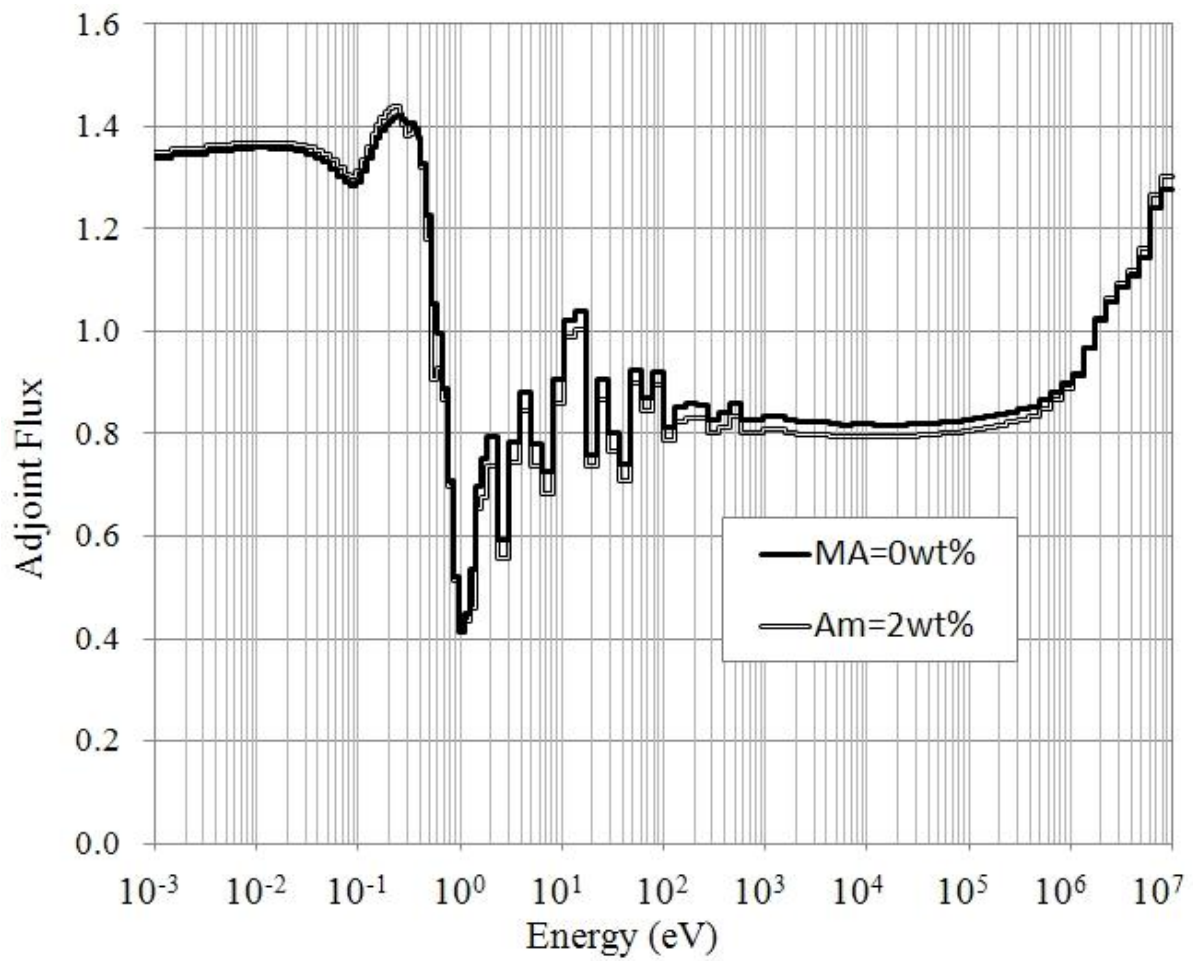


Fig. 11 Adjoint spectra in reference state at fuel rod diameter of 11mm

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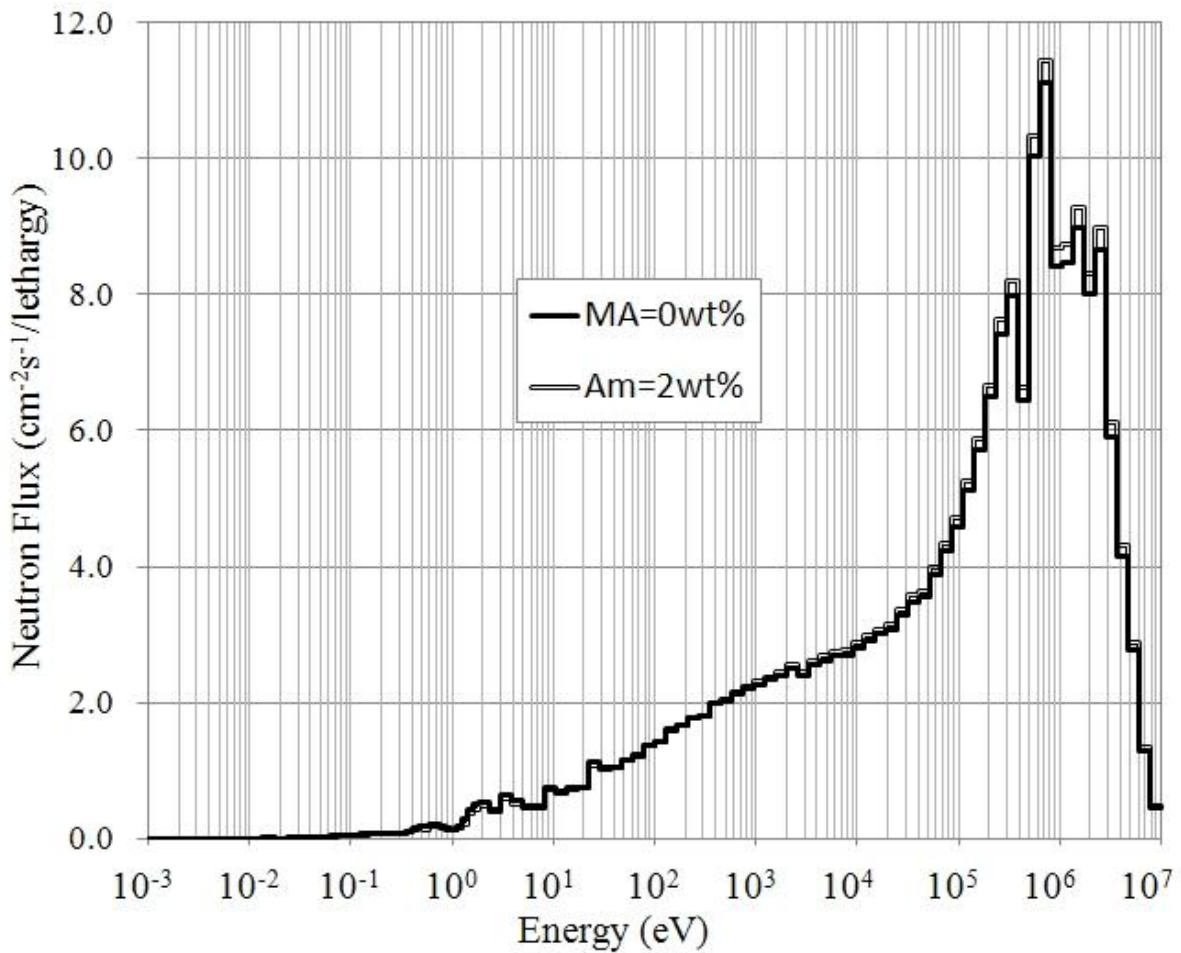


Fig. 12 Spectra in the state of voided at fuel rod diameter of 11mm

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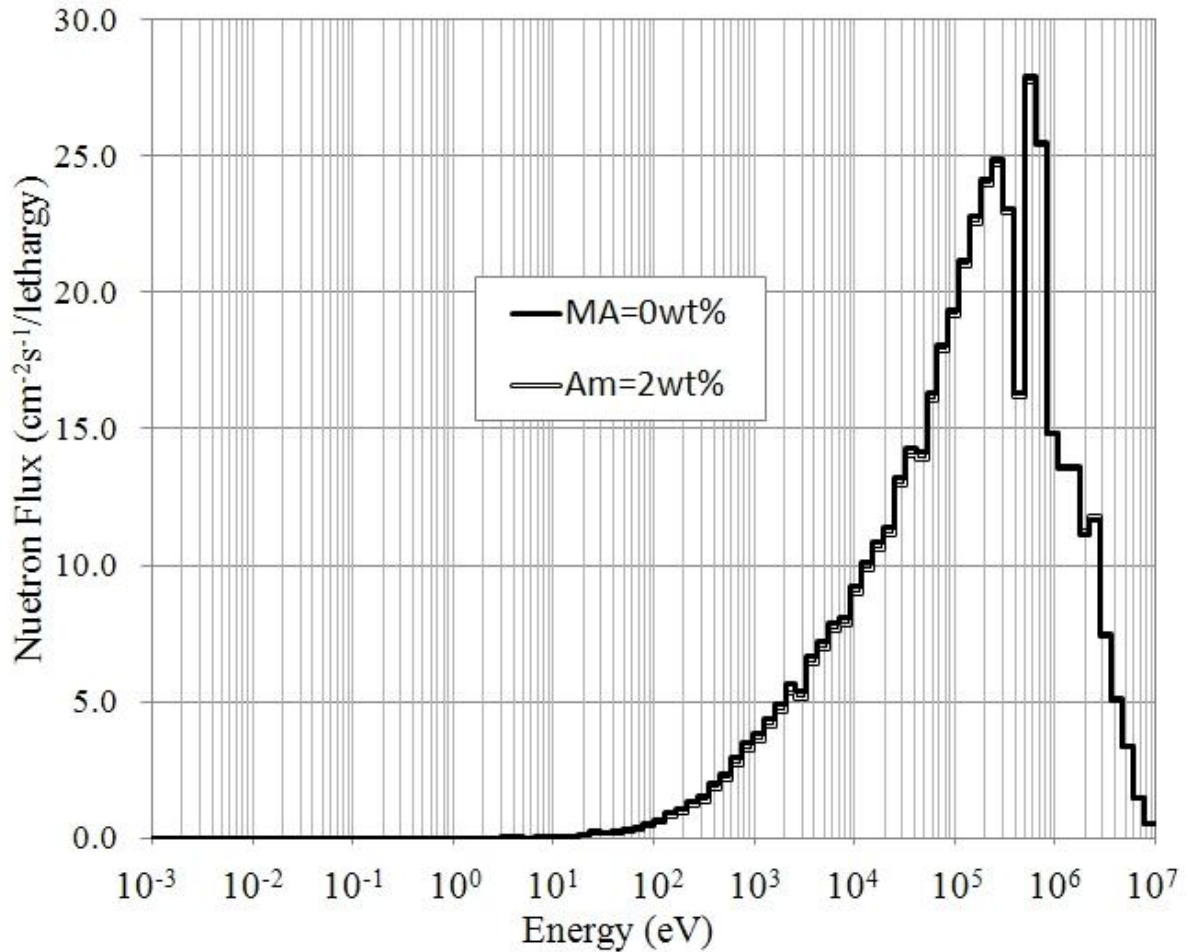


Fig. 13 Spectra in the state of 100% voided at fuel rod diameter of 11mm

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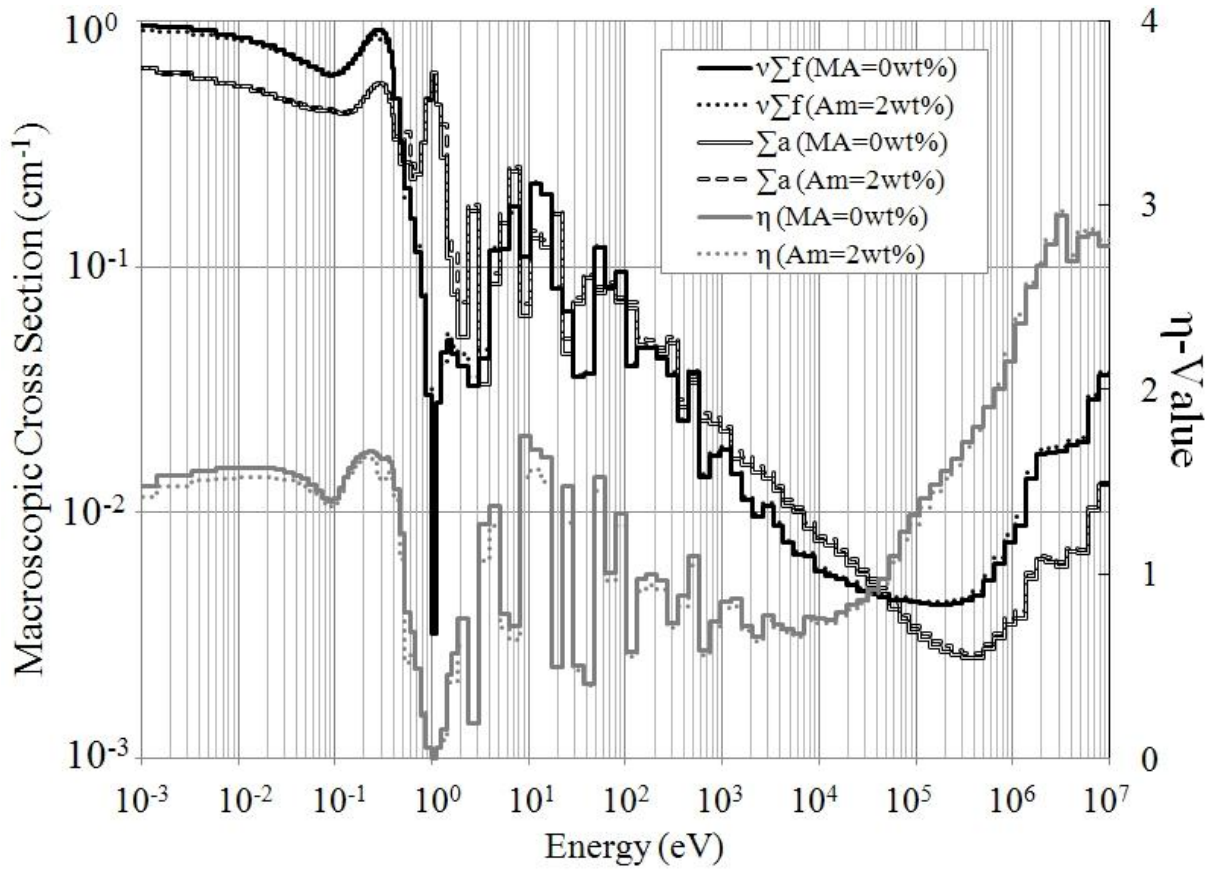


Fig. 14 Macroscopic cross sections and η -value

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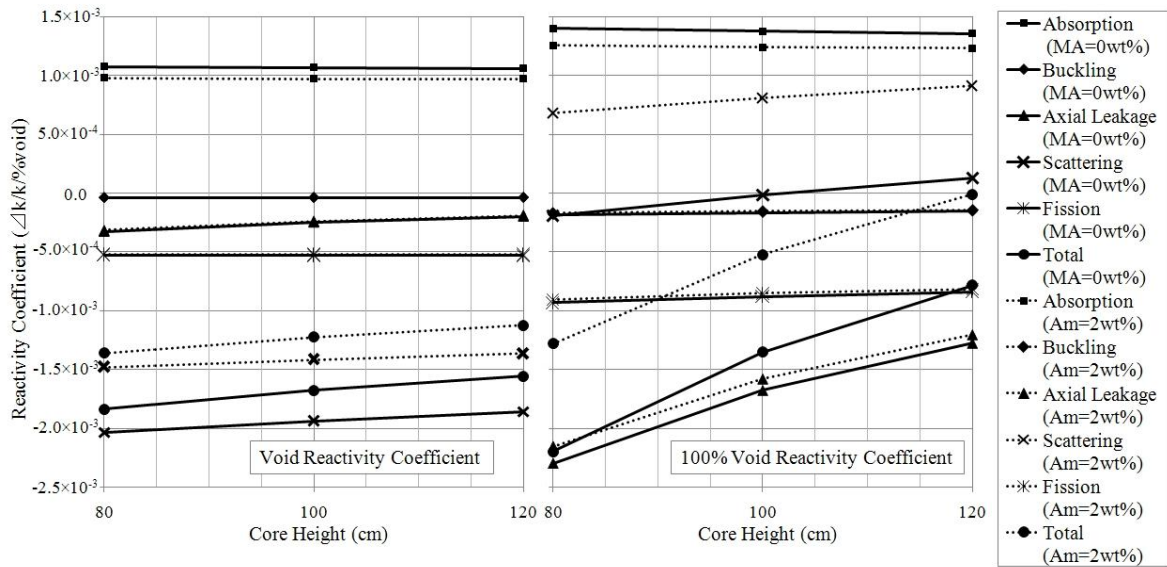


Fig. 15 Void reactivity coefficient and 100% void reactivity coefficient at fuel rod diameter of 9mm

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Recycling