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Effect of TRU fuel loading on core performance and plutonium production of FBR

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ABSTRACT

The effect of trans-uranium (TRU) fuel loading on the reactor core performances as well as the actinide and isotopic plutonium compositions in the core and blanket regions has been analyzed based on the large FBR type. Isotopic plutonium composition of TRU fuel is less than that of MOX fuel except for Pu-238 composition which obtains relatively higher composition. A significant increase of plutonium vector composition is shown by Pu-238 for TRU fuel in the core region as well as its increasing value in the blanket region for doping MA case. Excess reactivity can be reduced significantly (5% at beginning of cycle) and an additional breeding gain can be obtained by TRU fuel in comparison with MOX fuel. Doping MA in the blanket regions reduces the criticality for a small reduction value (0.1%) and it gives a reduction value of breeding ratio. Loading MA in the core regions as TRU fuel composition gives relatively bigger effect to increase the void reactivity coefficient mean while it gives less effect for loading MA in the blanket regions. Similar to the void reactivity coefficient profile, loading MA is more effective to the change of Doppler coefficient in the core regions in comparison with loading MA in the blanket regions which gives slightly less negative Doppler coefficient. Obtained Pu-240 vector compositions in the core region are categorized as practically unusable composition for nuclear device based on the Pellaud's criterion. Less than 7% Pu-240 vector compositions in the blanket region are categorized as weapon grade composition for no doping MA case. Obtaining 9% of Pu-238 composition by doping MA 2% in the blanket regions is enough to increase the level of proliferation resistance for denaturing plutonium based on the Kessler's criterion.

1. Introduction

Obtaining high fuel breeding capability and reducing spent fuel of LWR at the same time as a burner reactor are difficult to be achieved by thermal reactor technologies and it can be obtained easier by adopting fast reactor technologies. Although it has some feasibilities to achieve breeder reactor by thermal reactor or near epi-thermal spectrum reactor for a small breeding gain such as adopting thorium cycle at demonstrated LWBR shippingport (Freeman et al., 1989), light water coolants type for thorium case (Akie et al., 1991; Kim and Downar, 2002; Sidik et al., 2007) and for U–Pu fuel cycle case (Iwamura et al., 1999, 2006, 2007; Hibi and Sekimoto, 2005; Sidik et al., 2006) as well as closed fuel cycle option (Takaki, 2000). In addition, some designs used heavy water coolants for both thorium fuel and U–Pu fuel cycles (Hibi et al., 2001; Sidik et al., 2008; Jagannathan and Usha, 2006) as well as adopting molten salt reactor type (Nuttin et al., 2005). In case of actinide transmutation of TRU, some reference shows the feasibility for several reactor types to be used for burner reactors (Choi and Downar, 1999; Hoffman and Stacey, 2003; Taiwo et al., 2006). However, in achieving higher TRU burning values, it affects directly to the reduction value of breeding capability or even less conversion ratio. In the opposite way, in obtaining breeding condition; less transmutation factor are adopted because of less burnup value as well as low fissile content. Adopting fast reactor technology gives some advantages for achieving high breeding gain as sustainable energy source and in the same time it can be used to burn some TRU and transmutes some fission products for reducing environmental burder. In addition, by utilizing fast energy regions, not only high eta-value for high breeding gain will be achieved, but also some MAs which are loaded in to the reactors can be used for additional fission for maintaining the criticality as well as for increasing proliferation resistance level.

In comparison with the conventional fast reactor technology which utilizes MOX fuel type for core regions and puts depleted uranium into the blanket regions, recently, some recycled trans-uranium which contains not only plutonium but also some minor actinides (MA) can be utilized as a new mixed fuel as trans-uranium fuel which can be loaded into the core regions as driver fuel region or into the blanket regions as fissile converter regions or breeder

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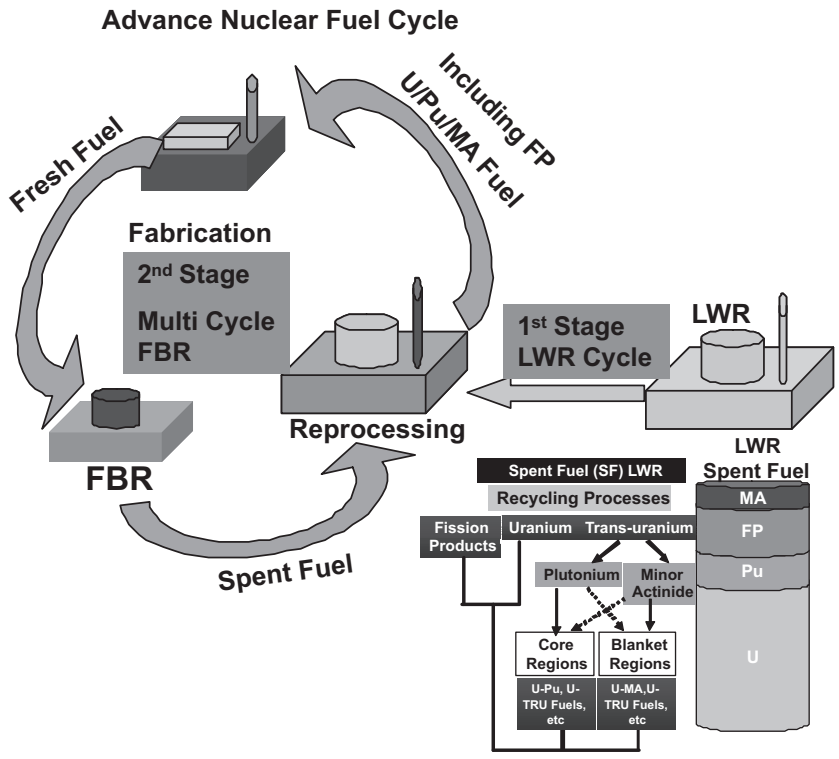

Fig. 1. Advance nuclear fuel cycle scheme.

regions for specific purposes such as extended reactor operation of long life core application (Sidik and Zaki, 2009; Sidik et al., 2009), burning MA purposes (Choi and Downar, 1999), transmutation TRU (Hoffman and Stacey, 2003) and for recycling MA in LWR (Taiwo et al., 2006). Some challenges should be overcome for this fuel cycle strategy which related to closed fuel cycle technology which includes some technologies for advanced reprocessing and fabrication. This technology will combine an established technology for recycling processes of uranium and plutonium fuel and also advanced technology for recycling MA as well as fission product (FP) which can be loaded as contaminated fuel or for transmuting FP.

These advance fuel cycle schemes of FBR fuel cycle technologies can be shown in Fig. 1 from fuel cycle of LWR technologies into FBR technologies. The first stage describes recycled LWR which means like a transition process from spent fuel LWR to be used as FBR fuel up to a certain period of time. This stage can be used individual fuel reprocessing facilities of LWR–FBR or combination of each process in one fuel cycle facility. The second stage explains the multi cycle of FBR fuel which means after finishing the transition period of LWR to FBR, assuming FBR fuel can be supply by them self from their own spent fuel. As new paradigm or point of view, MA is not longer popular as nuclear waste, but it popular as a new "fuel" resource which can be combined or loading with uranium or plutonium for maintaining the reactor operation as well as breeding capability. The important aspect of closed fuel cycle option is how to improve the fuel cycle technology, while nuclear proliferation aspect can be obtained by recycled MA for achieving more protected plutonium production (Saito et al., 2002; Meiliza et al., 2008). Some spent fuel actinides from LWR or FBR can be separated and grouped for fuel loading arrangement which can be used either for core fuel regions or blanket fuel regions as shown in Fig. 1 in regards to core performances, safety features, mass balances, and proliferation resistance and so on.

Sustainability of nuclear fuel has been shown by breeding capability of the reactor which shows a similar trend with the renewable energies as a sustainable energy source (Academies of Sciences, 2006). Fast reactor shows better capability for obtaining high breeding than thermal neutron reactor because of the superiority of (η) eta-value of fissile Pu-239 superior to other fissile materials (Michael and Otto, 1998). However, good fissile material means good quality for making a nuclear explosive device. Therefore, the challenge is, how to protect it not for nuclear explosive device which improving for maintaining better performance in criticality and fuel breeding. This paper intends to evaluate the effect of loading minor actinide (MA) in trans-uranium (TRU) fuel in the core regions and doping MA in blanket regions to the reactor core performances including criticality performance, fuel breeding capability, void reactivity and Doppler coefficients as well as actinide composition and isotopic plutonium vector composition for evaluating the proliferation resistance aspect of a large fast breeder reactor (FBR).

All of key parameters are evaluated during reactor operation in order to monitor the operation time dependency. Large FBR type of FaCT (Fast Reactor Cycle Technology) project is referred as core reference case (Ohki et al., 2008). FaCT project is based on the framework of nuclear energy policy of Japan, to promote research and development toward commercialization of FBR cycle technology from its potential long-term energy security and reduction in radioactive toxicity. Commercialization target of FBR was planned to be introduced at around 2050 by adopting the FBR cycle technology scheme based on the feasibility study on commercialization FR cycle system at around 2015. One of the targets of FaCT project is promoting proliferation resistance strategy of FBR technology which adopts no pure Plutonium in the cycle, however, by adopting mixed uranium–trans-uranium with low decontamination of fission products (FPs). This scheme is targeting some acceptable proliferation resistance levels to be used for protected plutonium production of FBR cycle. Adopting MA as doping material in the reactor can be utilized for increasing intrinsic properties of plutonium isotopes in regards of their high decay heat (DH) composition and high spontaneous fission neutron (SFN) rates as the material barrier from the even mass number (Pu-238, Pu-240 and

Pu-242). High potential barrier of isotopic plutonium barrier is Pu-238 which has the highest decay heat (DH) (560 W/kg) and SFN rate (2660 n/g/s) as the key role for material barrier parameter for intrinsic plutonium proliferation. Other even mass of plutonium also can be used as isotopic barrier of plutonium which similar to Pu-238 from high level of DH and SFN point of view. Regarding the isotopic plutonium barrier, some criteria have been proposed as proliferation resistance level as scientific approaches such as IAEA's, Pellaud's and Kessler's criteria (IAEA, 1972; Pellaud, 2002; Kessler, 2007).

2. Basic designs and calculation methods

2.1. Basic design parameters

Key parameters of investigated analyses have been adopted for evaluating the effect of trans-uranium fuel loading such as reactor core performance and fuel composition behavior during reactor operation. Reactor core is evaluated based on the criticality condition and fuel breeding capability as well as some safety aspect in regards to the void reactivity and Doppler coefficients. Fuel behaviors are analyzed from the view point of time dependency or burnup dependency behavior of fuel from the initial stage of fuel compositions up to the end of reactor operation. The fuel composition analyses are based on the heavy nuclides compositions such as uranium up to curium as well as their isotopic behavior during reactor operation in the core regions and blanket regions of the reactor. A cycle length of operation as reactor operation time is adjusted to 800 days operation for 4 fuel batches systems. A core–blanket system as a fuel arrangement of core design has been adjusted which consists of driver fuel regions (core regions) and breeding or converter regions (blanket regions). As driver core, core regions consist of high fissile content of plutonium which is divided into two core regions as inner and outer parts and blanket region as breeding regions in the axial and radial directions. As the comparative analysis, two different fuel types of MOX fuel and TRU fuel types have been examined for core region fuel and some loading MA content in the blanket region which is compared with no doping case. Table 1 shows some basic design parameters of the investigated FBR type as well as some typical fuel oxide composition in the core and blanket regions and some additional doping MA for blanket regions and fuel batches system. The actinide compositions at initial composition are based on the LWR spent fuel of 49 GWd/t irradiated fuel with 25 years ex-core for TRU (U–TRU oxide) fuel, MOX fuel and MA doping compositions which are tabulated in Table 1. Actinide compositions at initial composition for reference case and current evaluation case are tabulated in Table 2. Current employed actinide composition is relative lower composition of fissile plutonium and higher composition of trans-plutonium than reference case based on the FBR multi cycle composition.

Table 2
Initial actinide compositions.

Actinide	Present	Reference
PU-238	2	1.1
PU-239	46	54.1
PU-240	23	32.1
PU-241	4	4.3
PU-242	7	3.9
NP-237	6	0.5
AM-241	10	2
AM-242m	0	0
AM-243	1	1
CM-244	1	1
CM-245	0	0

LWR49: current employed actinide composition. Reference: actinide composition as reference case based on the multicycle composition of FBR.

2.2. Calculation methods

Reactor design specifications are one the important part for obtaining reactor criticality condition and fuel breeding capability as well as some composition of material as initial fuel loading. Several investigated designs for some specific design purposes are adopted for obtaining higher inner fuel conversion capability in the blanket regions as fissile production regions for maintaining longer reactor operation (Sidik and Zaki, 2009; Sidik et al., 2009; Sekimoto and Zaki, 1991; Zaki and Sekimoto, 1995a,b; Sidik, 2009). Additional fissile materials of plutonium are produced through capturing process of neutron by fertile material in the blanket region as well as in the core regions while in this region much of fissile materials are consumed as well as some higher actinides as TRU nuclides and fission products from fission reactions. Some converted fissile materials of plutonium can be used to compensate the loss of fissile in the core regions for keeping the reactor critical during reactor operation. Similar to a conventional fast breeder reactor' design, core–blanket fuel arrangement system are adopted which puts some core fuel regions as driver fuel in the central part and in the surrounded areas are covered by blanket regions.

Two different enrichments of fuel core for MOX and TRU fuels are loaded which relatively higher enrichment value for the outer part are estimated to make the reactor power distribution in radial direction more flatten and it can reaches longer operation time. Blanket fuel regions are set in the radial and axial directions (lower and upper part) which cover inner core and outer core regions.

Table 1
Basic parameters.

Total thermal power	3530	MW
Enrichment (fuel content) (inner/outer core) of MOX and TRU fuel types	20.1/22.1 and 23.3/25.3	%
Volume fraction (fuel/structure/cool)	43.9/25.8/30.3	% %
Core, axial blanket	54.8/18.5/26.7	
Radial blanket		
Core	U–Pu oxide and U–TRU oxide	–
Pu composition (238/239/240/241/242)	2.4/56.1/28.1/4.9/8.5	%
TRU composition Pu (238/239/240/241/242)	2/46/23/4/7	%
Np237/Am241/Am242m/Am243/Cm244/Cm245	6/10/0/1/1/0	%
Blanket	Nat-uranium + minor actinide (MA)	–
MA composition		–
Np237/Am241/Am242m/Am243/Cm244/Cm245	33.3/55.6/0/5.6/5.6/0	%
Doping material in the blanket	MA [%]	0 & 2
Core height	100	cm
Axial/radial blanket thickness	20/20	cm
Operation cycle length	800	Day
Fuel batch (core/radial blanket)	4./4.	–

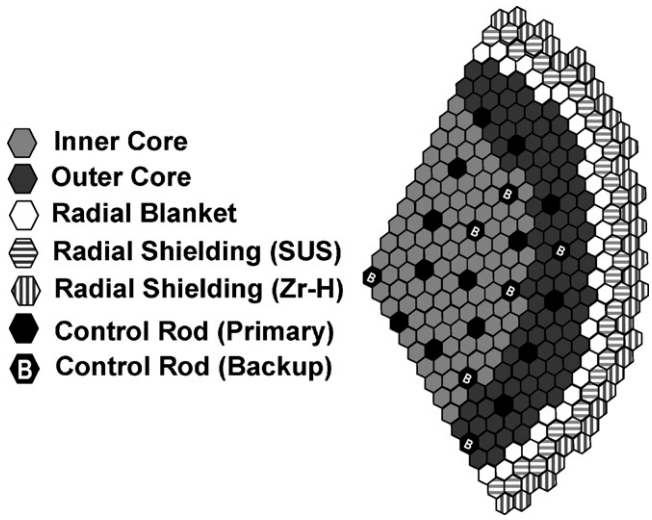

Fig. 2. Configuration of reactor core (1/3 scale).

Some control absorbers including control backup are used in the central ring of reactor core as well as it is located in between of each core regions. Outer part of the reactor core is surrounded by two different shielding materials; those are stainless steel and Zr–H which are adopted to enhance the capability of shielding material. To evaluate the burnup as time dependency in the core level for whole core configuration, core burnup calculation has been performed by using some coupled computer codes such as SLAROM (Nakagawa and Tsuchihashi, 1984), JOINT and CITATION (Fowler et al., 1971), and for nuclear data library is JFS-3-J-3.2R (Chiba et al., 2002) which is based on the JENDL 3.2 (Nakagawa et al., 1995). Two dimensional core calculation methods are used for optimization as R-Z model analysis. This model is for approaching the core arrangement of JSFR model as shown in Fig. 2.

The analytical study of neutronics design for minor actinide (MA) transmutation system of the critical experiment using MA was employed by JAEA in their JAEA research report. This study was performed to understand the current situation and discuss quantitatively the critical experiment using MA for fast reactor (FR) as well as accelerator driven system (ADS). As the result of the error analysis, fast reactor obtains 1.1% for criticality, 2.6% void reactivity, 4.0% Doppler reactivity and 30% for burnup reactivity (Sugawara et al., 2009). One of the targets of this study is related to the JSFR or FaCT project that can fulfill the nuclear proliferation point of view. Homogenous core is more relevant for more denaturing plutonium that mixed MA MOX fuel or MA depleted uranium can increase the proliferation resistance level since the fresh fuel up to the end of cycle. In current interest of study, FaCT project are targeting to analyze the MA doping up to 5%. Some experiments have also been conducted to evaluate the fuel pin capability, especially by loading mixed MA and MOX or depleted uranium.

2.3. Relative production rate analysis

Reactor criticality is basically based on the neutron multiplication factor of all material including fuel, cladding, coolant and other structure. Main criticality is shown by infinite multiplication factor which only consider neutron balance from all material excluding the leakage effect from geometry. Infinite multiplication factor can be expresses in Eq. (1):

$$k_{eff} \approx k_{\inf} = \frac{\left(\sum_{i=1}^{i=n} \upsilon \sum_{fi}\right)}{\left(\sum_{i=i}^{m} \sum_{ai}\right)} \quad (1)$$

$\upsilon \sum_{fi}$: macroscopic production of i isotopes (fuel materials). $\sum_{ai}$: macroscopic absorption of i isotopes (all materials including coolant and structure).

$$\text{Rel production rate}_i = \frac{\upsilon \sum_i}{\sum_{a\_total}} \quad (2)$$

$$\sum_{a\_total} = \sum_{i=i}^{m} \sum_{ai} \quad (3)$$

$$\text{delta-rel production rate}_i = \frac{\upsilon \sum_i}{\sum_{a\_total}}|_{TRU} - \frac{\upsilon \sum_i}{\sum_{a\_total}}|_{MOX} \quad (4)$$

An approach to understand the individual isotopes contribution based their own to criticality condition can be used the neutron production rate analysis as shown in Eqs. (2) through (4). The neutron production rate analysis is basically comes from the multiplication factor concept as shown in Eq. (1). Contribution of each nuclide can be express as a fraction of production rate which can be express as relative production rate (Eq. (2)). To analyze the difference of neutron production rate of individual isotopes to criticality condition for difference cases, it can be used Eq. (4) for comparing purposes such as TRU fuel case which is compared with MOX fuel case.

2.4. Relative capture rate analysis

Basic parameter of fuel sustainability comes from the concept of breeding ratio which is basically as conversion capability from fertile materials to fissile materials. Conversion ratio or breeding ratio can be express as shown in Eq. (5) based on reaction rate of capture fertile materials and absorption materials:

$$CR = BR = \frac{\left(\sum_{i=1}^{i=n} \sum_{c,fertile,i}\right)}{\left(\sum_{i=i}^{m} \sum_{a,fissile,i}\right)} \quad (5)$$

$\sum_{ci}$: macroscopic capture of i isotopes. $\sum_{ai}$: macroscopic absorption of i isotopes

In this evaluation, basic materials of fertile and fissile are based on U-238 and Pu-240 as fertile materials and for fissile materials are Pu-239 and Pu-241.

$$CapFer_i = \frac{\sum_{c,i,fertile}}{\sum_{a,total,fissile}} \quad (6)$$

$$\sum_{a,total,fissile} = \sum_{a,Pu-239} + \sum_{a,Pu-241} \quad (7)$$

$$delCapFer_i = \frac{\sum_{c,i,fertile}}{\sum_{a,total,fissile}}|_{TRU} - \frac{\sum_{c,i,fertile}}{\sum_{a,total,fissile}}|_{MOX} \quad (8)$$

Breeding ratio analysis which based on the individual isotopes contribution can be analyzed by Eqs. (6) through (8). Eq. (5) is based on the assumption of simultaneous production of fissile material form fertile and loss of fissile material to another material or makes a fission reaction. Eq. (6) shows the contribution of each nuclide as relative capture fertile rate as a fraction of each capture rate to total absorption of fissile material. The difference of neutron capture rate from individual isotopes can be used for difference cases. It can be used Eq. (8) for comparing purposes such as TRU fuel case which is compared with MOX fuel case.

3. Results and discussions

Core regions contribute as main contribution for reactor criticality as well as power contribution because of high enough of fissile materials for obtaining enough fission reaction. High criticality make the reactor has high excess reactivity which is one of

the issues for evaluating the criticality safety. This safety aspect in regard to the condition that how to maintain the reactor criticality condition for a certain period of operation and also for longer time operation which have a low excess reactivity especially at the beginning of operation. Doping MA is one of the options for reducing the excess reactivity because of high capture cross-section which can control the population of produced neutron in the core. This MA works as burnable poison for poisoning criticality level becomes smaller. However, in term of capturing neutron by those MA material which can be used for converting process from MA to plutonium, this process can be recognized as converter process which means, MA can be distinguish as fertile materials. As can be estimated that fuel conversion process not only occur in the blanket regions but also in the core regions, however, the main contribution for breeding capability of the reactor comes from blanket regions.

Blanket regions which are adjusted in the outer part of reactor can be estimated as fuel production regions or fuel conversion regions from fertile material into fissile material through neutron capture process. It causes the breeding ration becomes higher meanwhile in the same time, reactor criticality condition becomes lower and makes the reactor operation shorter because of large of neutron are consumed in this blanket regions. Adding some TRU materials in the core as well as in the blanket regions will affects to the reactor criticality condition. That criticality condition analysis which based on the TRU fuel utilization will be shown and discussed in this section. In addition, reactor core behavior will be shown as a function of reactor operation time and several fuel cycle steps. Some comparative analyses are evaluated such as different fuel loading in the core regions and doping MA in the blanket regions as a function of reactor operation time. The evaluations of actinide compositions as well as the plutonium production compositions in the core and blanket regions have also been studied especially for confirming the adopted TRU fuel effects and MA doping. Those evaluations of plutonium production are mainly based on the even mass of plutonium isotopes (Pu-238, Pu-240 and Pu-242) for investigating the plutonium proliferation resistance aspect (Saito et al., 2002; Meiliza et al., 2008).

3.1. Heavy metal compositions

3.1.1. Element composition of heavy metal

Heavy metals compositions are evaluated based on the nuclide chain of uranium fuel chain which focuses on uranium through curium actinides. Some investigated results of actinide element compositions for comparative analysis which based on different fuel loading in the core regions (TRU and MOX fuel types) and loading doping MA in the blanket region are shown in Fig. 3. The compositions of all actinides are based on the percent weight of HM during reactor operation. Inner core region is selected as representative for actinide composition analysis in the core region as well as radial blanket region for actinide composition analysis in the blanket regions. As the main actinide, Uranium compositions are obtained the highest compositions for all fuel loading cases in the core and blanket regions which is followed by plutonium composition and so on. Actinide elements of plutonium and uranium for TRU fuel type have slightly less composition than MOX fuel type except for trans-plutonium actinide compositions in the core regions. Higher compositions of americium (Am), neptunium (Np) and curium (Cm) for TRU fuel because of MAs have already exist from the initial fuel loading in TRU composition which reduces the uranium and plutonium compositions as also shown in Table 3.

Compositions of MA increase with increasing reactor operation time for MOX fuel loading while MA compositions of TRU fuel decrease with increasing the time except for curium composition. As tabulated in Table 3, some MA of TRU fuel can be reduced by irradiation process in the reactor core; however, at the same time its irradiation process builds up actinide composition of curium which can be produces from plutonium and trans-plutonium actinides although its compositions are very small. Some additional plutonium compositions are obtained from converted minor actinide

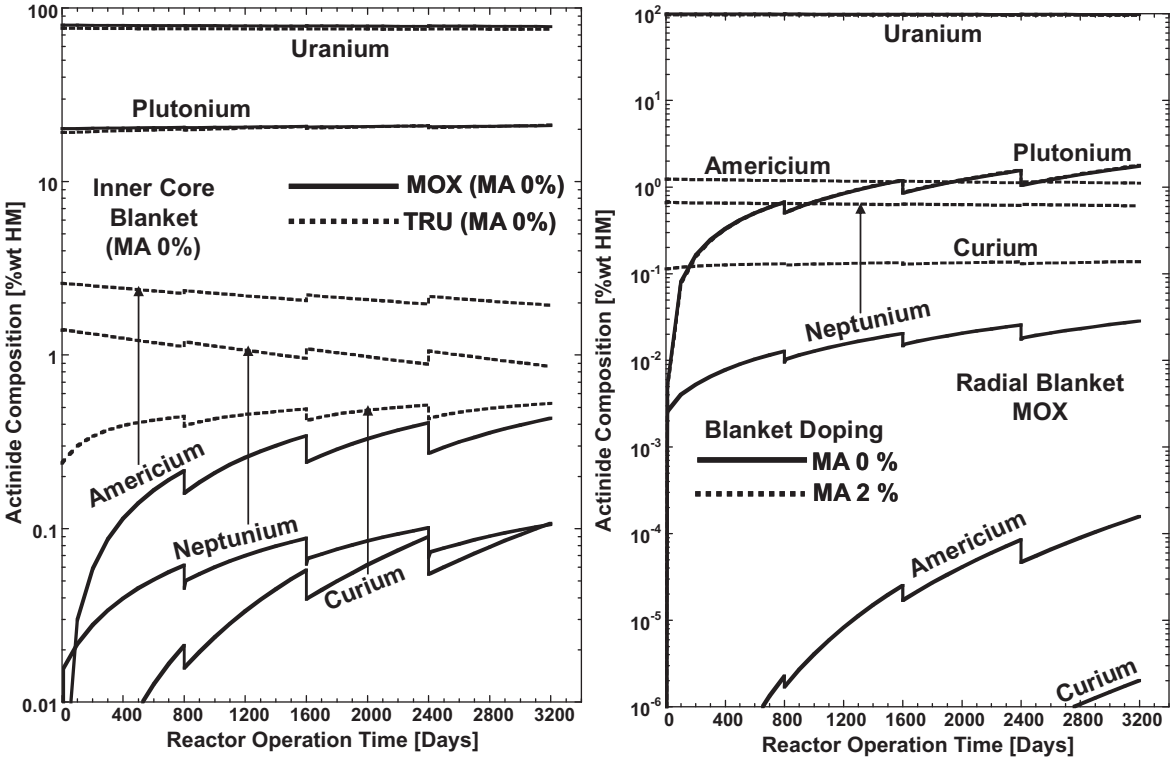

Fig. 3. Actinide composition of MOX and TRU fuel.

Table 3
Actinide composition of MOX and TRU fuel types for no doping case in core regions.

Actinide composition		MOX MA 0%				TRU MA 0%			
Element	Unit (%wt)	Inner core		Outer core		Inner core		Outer core	
		BOC	EOC	BOC	EOC	BOC	EOC	BOC	EOC
Uranium	U/HM	79.79	78.32	77.78	77.22	76.57	75.52	74.56	74.22
Neptunium	Np/HM	0.00	0.11	0.00	0.08	1.39	0.861	1.51	1.116
Plutonium	Pu/HM	20.21	21.04	22.22	22.22	19.21	21.16	20.85	21.77
Americium	Am/HM	0.00	0.43	0.00	0.42	2.59	1.94	2.82	2.44
Curium	Cu/HM	0.00	0.11	0.00	0.06	0.24	0.53	0.26	0.45

(MA) of americium and neptunium through neutron capture which affects to the decrease of those MA during reactor operation. MA contents in TRU fuel composition at the initial fuel composition are about 4.2% (inner core) and 4.6% (outer core) and it reduces with increasing reactor operation up to 3% and 4% at EOC, respectively. Similar to core regions, higher MA compositions of MA doping case in the blanket regions have been obtained caused by the existing MA composition since the initial of fresh fuel loading as well as plutonium compositions in comparison with MOX fuel as shown also in Table 4. Plutonium compositions increase with the time for both no doping and doping MA cases and it reach higher composition than trans-plutonium composition of doping MA case. Both blanket regions are effective to produce plutonium of about 4% wt HM and 2% wt HM for axial and radial blanket regions, respectively. Blanket regions are also effective to reduce the MA compositions although the decreasing values are relatively small except for curium compositions.

3.1.2. Isotopic composition of each nuclide

Obtained actinide compositions of each isotopic actinide from neptunium to curium are shown in Figs. 4–6 during reactor operation. Isotopic plutonium composition of TRU fuel obtains less composition than its isotopic composition of MOX fuel except for Pu-238 composition which obtains relatively higher composition. Increasing plutonium element composition as mentioned in the previous section and it shown in Fig. 5 can be estimated from the increase of all isotopic plutonium composition except Pu-242 composition which obtains less composition for longer operation time. The significant increasing composition is shown by Pu-238 for TRU fuel in the core regions as well as its increasing value in the blanket regions for doping MA case. This phenomenon comes from the higher conversion composition of MA into Pu-238 which is mainly form Np-237 through neutron capture. Higher composition of all isotopic MA are obtained by TRU fuel type in the core regions as well as doping MA in the blanket regions during reactor operation in comparison with MOX fuel and no doping MA case, respectively, except for Np-239 which shows slightly less composition. Isotopic compositions of main MA (Am-241 and Np-237) decrease with increasing operation time for TRU fuel and doping MA and its decreasing composition levels are more significant for core region in comparison with blanket regions.

3.2. TRU fuel and MA doping effects on criticality conditions

3.2.1. Criticality profile

Two different fuel types are compared in this evaluation which is based on the MOX fuel and TRU fuel types. In addition, to evaluate the effect of MA doping to the criticality condition, 2% of MA doping is adopted which is compared with no doping MA case. Obtained criticality conditions of all cases are shown in Fig. 7 as a function of reactor operation time. Criticality condition decreases with increasing operation time and it reaches almost the same criticality condition for both fuel types at the end of operation. TRU fuel achieves smaller criticality condition than MOX fuel from the beginning of operation. On the other hand, it can be considered as some reduction value of excess reactivity can be obtained fuel from the beginning of cycle when MOX fuel is replaced by TRU fuel. Doping MA in the blanket zone gives a reduction value for criticality condition for both MOX and TRU Fuels from the beginning of operation up to the end of operation.

The criticality difference of TRU fuel which is compared with MOX fuel and its difference of doping case for both fuel cases are shown in Fig. 8. This criticality difference of TRU–MOX (MA0) comes from the difference value of TRU criticality in comparison with MOX fuel criticality. It can be also considered as excess reactivity reduction value. In case of doping MA, its value comes from the comparison result of criticality condition for no doping MA case in comparison with doping MA case for both MOX and TRU fuel types. Adopting TRU fuel type in the core region gives the effective value for reducing the excess reactivity especially at the beginning of operation and it reduction value becomes smaller for longer operation time. At the beginning of cycle (BOC), it reduction value of excess reactivity can be obtained more then 5% and its value becomes smaller up to the end of cycle (EOC) which shows almost zero difference. As shown in Table 5, replacing fuel composition in the core regions from MOX fuel to TRU fuel compositions gives relatively higher reduction value of criticality especially at beginning of cycle (BOC) form 1.09 to 1.04 and it reaches almost unity at the end of cycle (EOC) for both fuel types. It can be estimated that by loading some actinide into the core regions, such as some minor actinides, it makes the criticality condition becomes smaller. This phenomenon comes from the high capture cross-section of minor actinide which plays as burnable poison or as fertile material. This estimation of MA as fertile material can be shown in next section

Table 4
Actinide composition of MOX fuel type for no doping and doping MA cases in blanket regions.

Actinide composition		MOX MA 0%				MOX MA 2%			
Element	Unit (%wt HM)	Axial blanket		Radial blanket		Axial blanket		Radial blanket	
		BOC	EOC	BOC	EOC	BOC	EOC	BOC	EOC
Uranium	U/HM	100.00	96.03	100.00	98.22	97.98	94.30	97.98	96.36
Neptunium	Np/HM	0.00	0.06	0.00	0.03	0.66	0.55	0.66	0.61
Plutonium	Pu/HM	0.00	3.90	0.00	1.75	0.00	4.04	0.00	1.79
Americium	Am/HM	0.00	0.00	0.00	0.00	1.24	0.95	1.24	1.11
Curium	Cu/HM	0.00	0.00	0.00	0.00	0.11	0.17	0.11	0.14

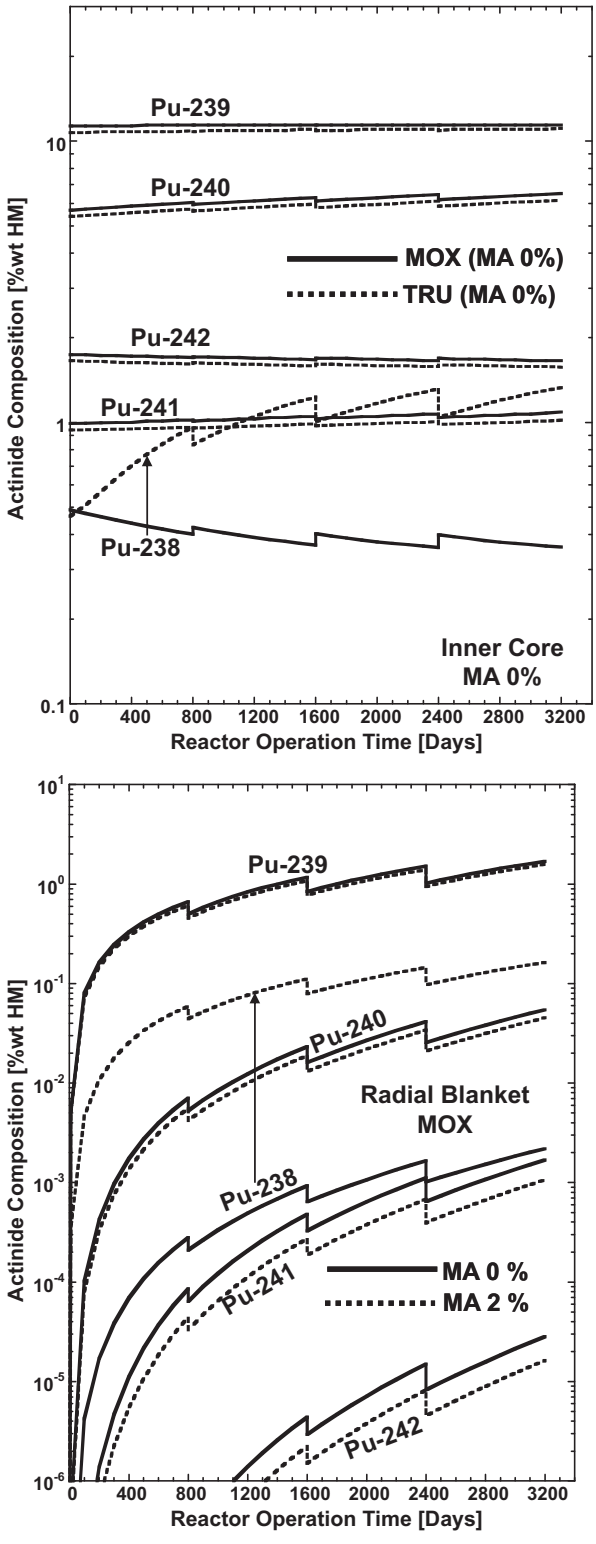

Fig. 4. Actinide composition of isotopic plutonium.

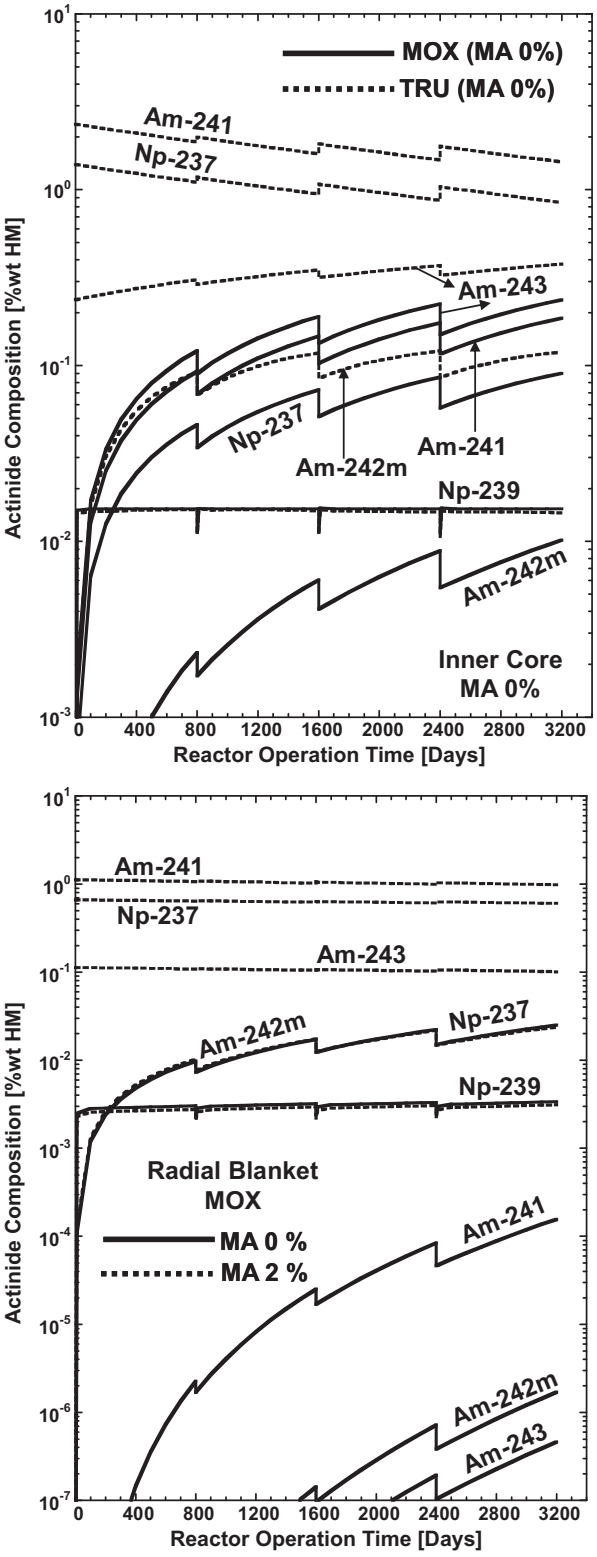

Fig. 5. Actinide compositions of isotopic neptunium and americium.

of breeding profile which shows the breeding change when MOX fuel is changed by TRU fuel type. Doping MA in the blanket region gives the reduction value which can be estimated from the criticality difference. The obtained reduction value by adding MA material in the blanket region to the criticality performance shows a small value which is about 0.1% reduction or less as shown in Fig. 8 as well as shown in Table 5.

3.2.2. Actinides contribution to the criticality

To understand the mechanism of criticality difference from the contribution of each actinide can be estimated from the relative production rate analysis concept as mentioned in the previous section. The obtained results of relative production rate of each actinide are shown in Fig. 9 for MOX and TRU fuel case comparison. It can be seen from the figure, the highest contribution of critical-

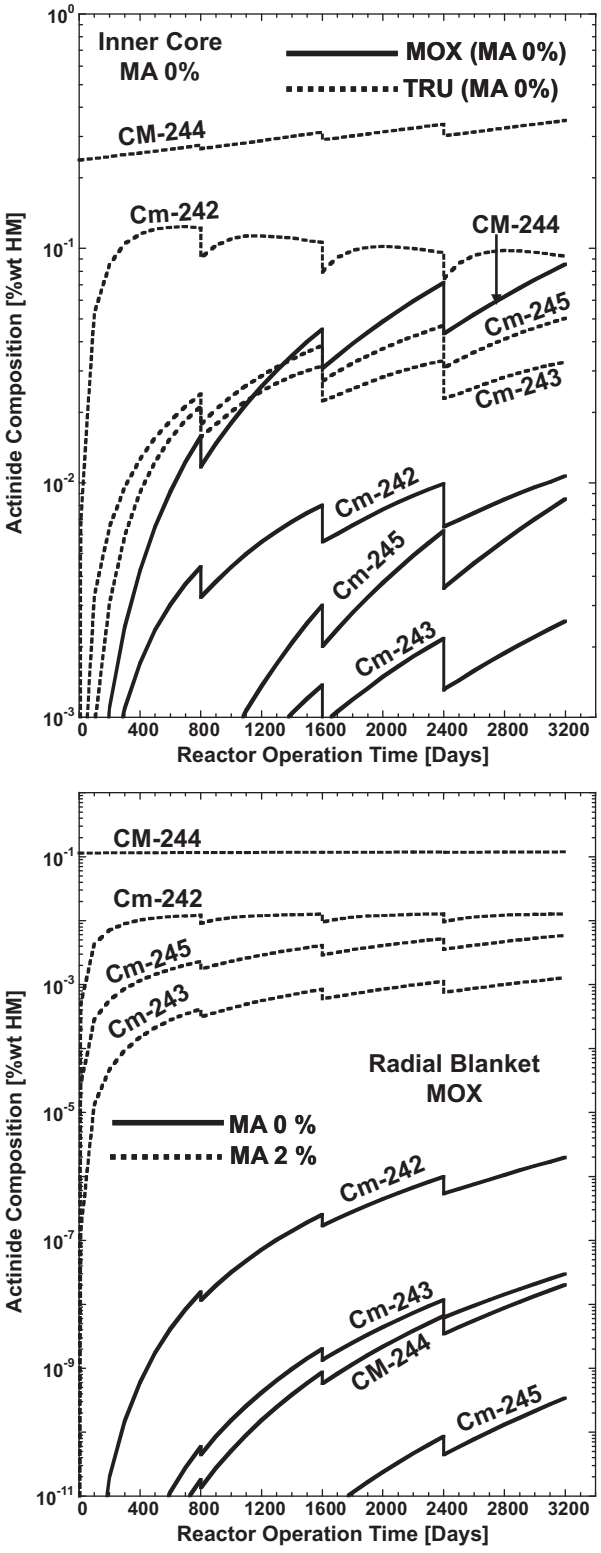

Fig. 6. Actinide composition of isotopic curium.

ity condition comes from Pu-239 and it is followed by Pu-241 and so on. In case of uranium and plutonium actinides composition, all actinides of MOX fuel case give higher criticality contribution than TRU fuel case except for Pu-238; it has higher criticality contribution of TRU fuel than MOX fuel. In case of MA contribution to the criticality condition, its shows the opposite condition comparing with uranium and plutonium contribution, those MA nuclides of

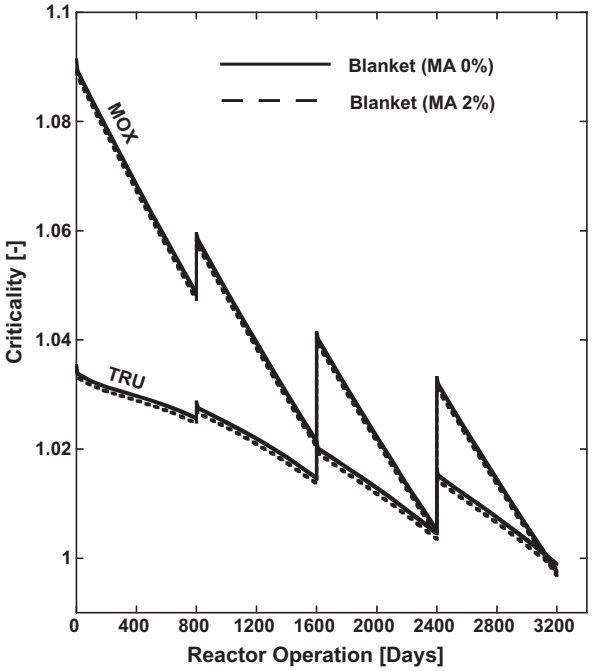

Fig. 7. Reactor criticality of MOX and TRU fuels for no doping and with doping MA cases.

TRU fuel gives higher contribution than MOX fuel. This condition can be easily estimated because of higher MA composition in the core region to the criticality condition for TRU fuel case as well as Pu-238. The total contribution to the criticality condition from all actinide is shown in Fig. 10 for TRU fuel case which is compared with MOX fuel case. Fissile materials show negative contribution which means less criticality contribution and the highest negative value is obtained by Pu-239.

All MA nuclides contribute to the positive value as well as Pu-238. As the total value from summation of all contribution, a negative value is obtained and its negative value decreases and it

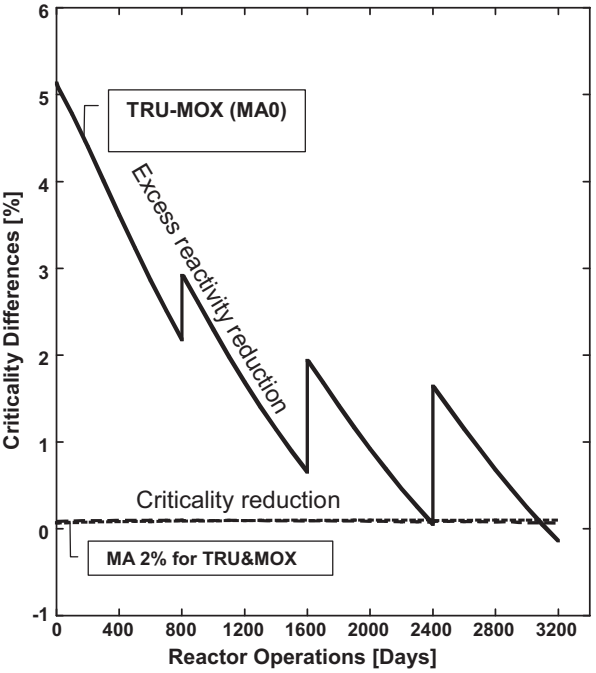

Fig. 8. Criticality differences of MOX and TRU fuels.

Table 5
Some key parameters of core performances.

Parameter	Unit	MOX MA0		MOX MA2		TRU MA0		TRU MA2	
		BOC	EOC	BOC	EOC	BOC	EOC	BOC	EOC
K-eff	–	1.09	1.00	1.09	1.00	1.04	1.00	1.03	1.00
BR	–	1.13	1.09	1.11	1.08	1.15	1.10	1.13	1.09
VRC	1E−3 dk/k/vol.%	38.60	37.60	39.90	38.40	48.20	37.90	47.80	38.70
DC	1E−6 dk/k/K	−6.12	−0.20	−6.04	−0.13	−4.47	−0.35	−4.37	−0.28

reaches to a zero value at EOC. It can be estimated from the total contribution of all nuclides that negative contribution which means less criticality is obtained which can be considered as a reduction value of criticality. The same approach can be adopted for MA doping effects to the criticality condition for both TRU and MOX fuel cases. Fig. 11 shows the delta relative production rate of both obtained results of MOX and TRU fuels for doping MA effect. As mentioned before, the strong contribution for reduction value of criticality comes from Pu-239 and the positive contribution comes some MA and Pu-238.

3.3. Fuel breeding capability of TRU fuel

Fuel conversion capability of the reactor will be shown and discussed in this section based on the TRU fuel composition which is loaded into core regions only or also loaded into blanket regions. Those obtained TRU's result will be compared with MOX fuel behavior as well as mentioned in the previous sections. This section will describes the breeding ratio as conversion ratio value higher than 1 as breeding index for evaluation. The conversion ratio analysis is based on the fissile material of Pu-239 and Pu-241, and fertile material of Pu-240 and U-238. The obtained results will be shown and evaluated during reactor operation to analyze the effect of operation time to the breeding capability of the reactors. Fuel breeding capability shows a tight relation to the fuel conversion capability of the blanket regions for FBR core type. However, as a whole system, fuel conversion processes occurs not only at the blanket regions but also it occurs at the core regions during reactor operation, even though the main contribution comes from blanket region and very small contribution from core regions. Arranging some blanket regions make the reactor has higher fuel breeding capability through fuel conversion processes of fertile materials to fissile materials. Meanwhile, arranging some core regions is designed for maintaining criticality condition of the reactor. In addition, changing the loading material as driver fuel can be estimated having some effects to the conversion capability of the core and furthermore it affects to conversion ratio capability as a whole core active region (including core and blanket regions).

3.3.1. Breeding ratio profile

Obtained results of breeding ratio profile during reactor operation of TRU fuel and MOX fuel types are shown in Fig. 12 for no doping and with doping MA materials in the blanket regions. Breeding ratio decreases with increasing operation time for both fuel types. TRU fuel shows higher breeding ratio than MOX fuel from BOC up to EOC. Breeding ratio is reduced by doping MA in the blanket zone for both MOX and TRU fuels. Additional fuel breeding of TRU fuel comparing with MOX fuel and the reduction value breeding caused by doping MA in the blanket region can be estimated by the breeding ratio difference as shown in Fig. 13. This breeding ratio difference profile is given by the comparison results for both fuel types which mean the difference value of achievable fuel

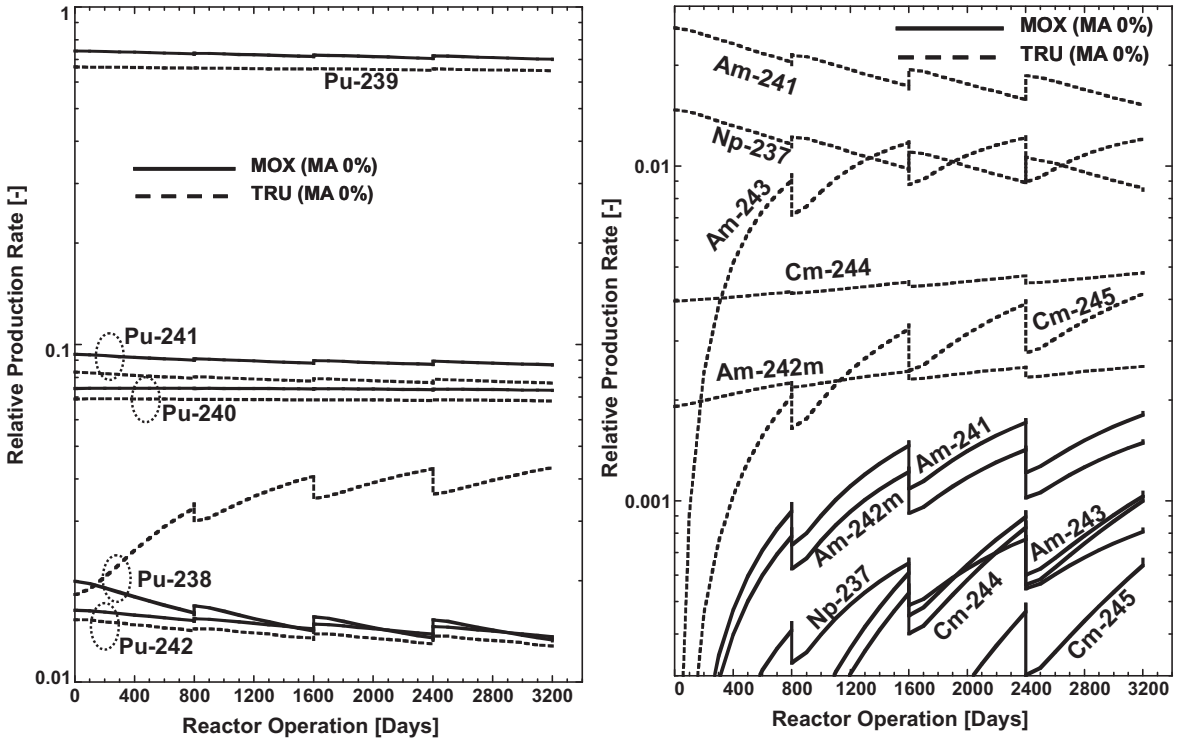

Fig. 9. Relative production rate of MOX and TRU fuels for no doping case.

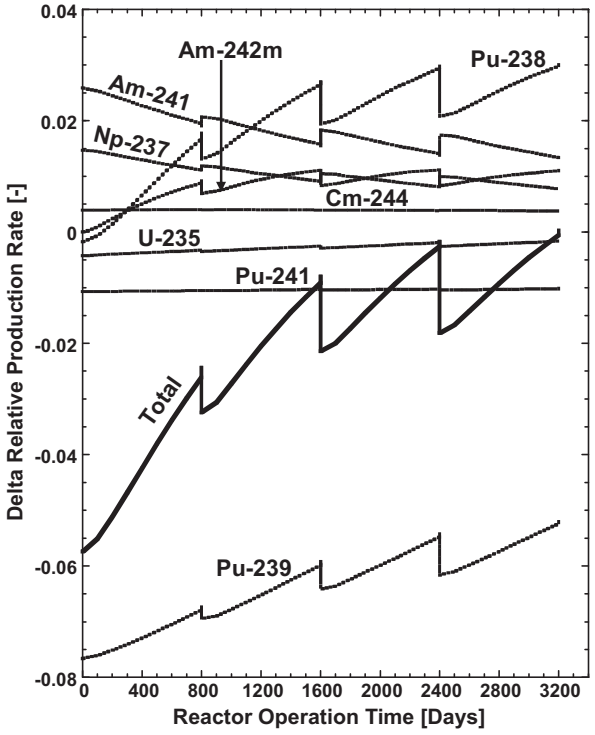

Fig. 10. Delta relative production rate of compared MOX with TRU fuels for no doping.

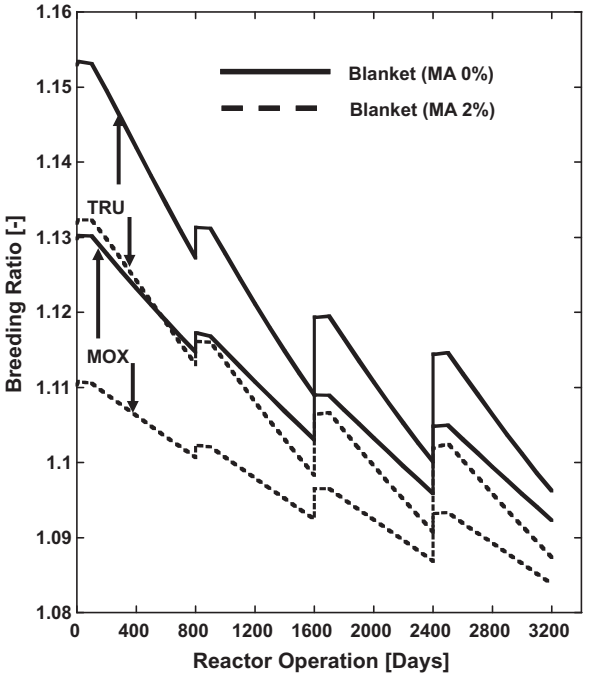

Fig. 12. Breeding capability of MOX and TRU fuels for no doping and with doping MA.

conversion capability when MOX fuel as driver material in the core is replaced by TRU fuel. Additional breeding can be obtained by TRU fuel type which is compared with MOX fuel type as driver fuel in the core regions. It difference value of breeding ratio can be express also as breeding gain in percentage unit for replacing MOX fuel by TRU fuel. TRU fuel gives more than 2% of additional breeding gain compared with MOX fuel at the BOC from 1.13 to 1.15 and it reduces with increasing time which shows from 1.09 of MOX fuel to 1.1 of TRU fuel as shown in Table 5. The breeding difference of TRU fuel with 2% MA in the blanket regions and MOX fuel with no doping material in the blanket regions has less than 2% and it obtains smaller value for higher operation time. TRU actinides have some advantages for increasing breeding capability, however, if the amounts of some high capture actinide increase

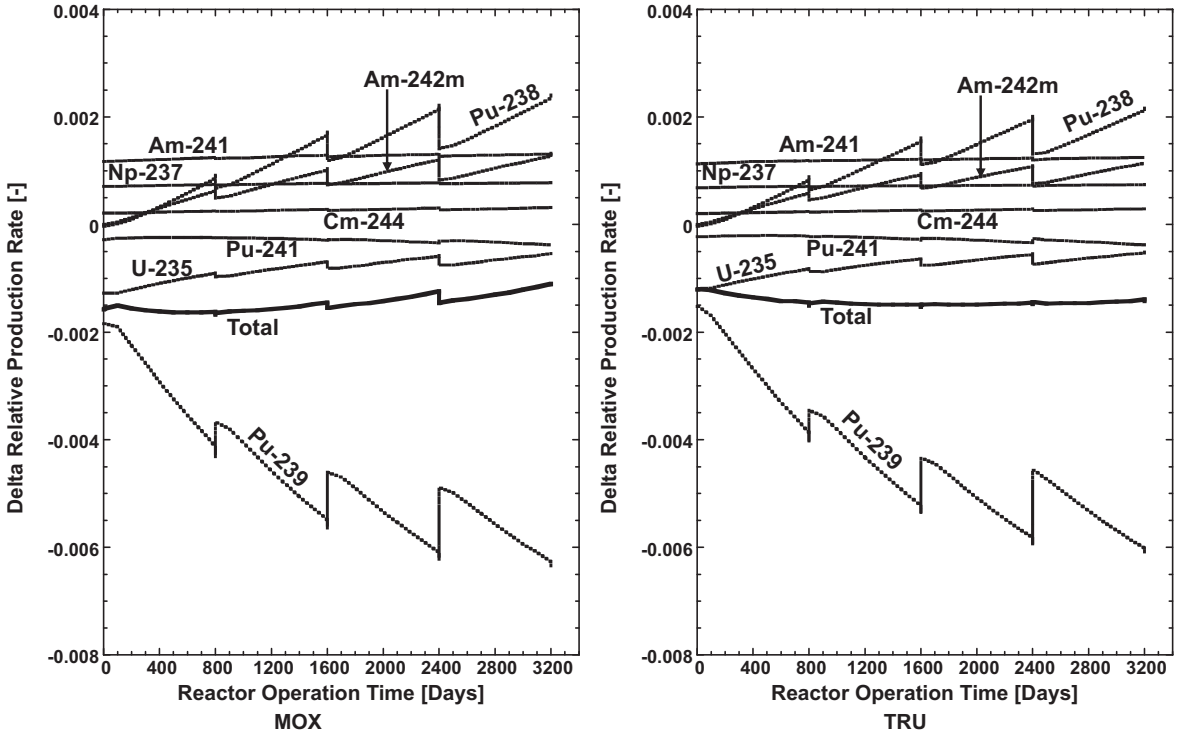

Fig. 11. Delta relative production rate of compared MOX and TRU for no MA doping case with MA doping case.

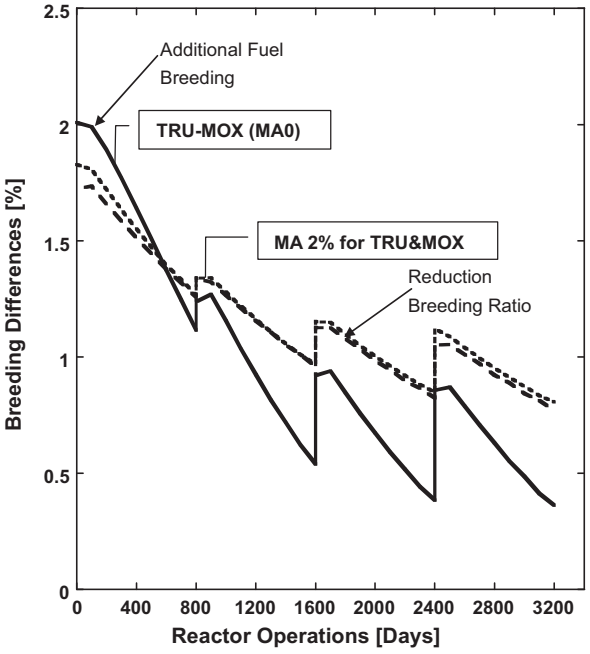

Fig. 13. Breeding ratio differences of MOX and TRU fuels.

and those actinide less capability to convert to fissile material, it will reduce the breeding capability with increasing the operation time as well as by reducing fissile material because of maintaining the reactor criticality.

3.3.2. Fissile and fertile contribution to breeding ratio

Fuel breeding mechanism can be estimated from the basic investigated concept in this paper. The basic concept is come from the contribution of fertile and fissile materials as mentioned in the previous section. Relative capture rate of fertile material can be adopted to estimate the fertile contribution to the breeding condition. Obtained results of relative capture rate of fertile material are shown in Fig. 14 for MOX and TRU fuel case comparison. Higher contribution of breeding ratio comes from U-238 than Pu-240 for both MOX and TRU fuel cases. Higher U-238 contribution can be obtained by TRU fuel than MOX fuel, however it slightly less contribution of Pu-240 for TRU fuel than MOX fuel. Positive contribution which means higher contribution of breeding comes from U-238 and negative contribution or less contribution comes from Pu-240. As the total contribution, its shows positive value which means higher breeding or additional fuel breeding can be obtained by TRU fuel because of higher contribution of U-238 as the main contribution and its total contribution value decreases with increasing operation time. Breeding capability can be estimated from the profile of relative capture rate of U-238 which shows relatively same trend with total contribution of breeding. In case of MA doping effect to the breeding condition can be estimated by the same approach for both TRU and MOX fuel cases. The results are obtained for both MOX fuel and TRU fuel type for doping MA effect which are shown in Fig. 15. Figure shows the total breeding contribution of doping MA (2%) gives negative contribution which means less breeding is achieved.

Negative contribution comes from the main contribution of U-238 which gives negative contribution value during reactor operation. Based on this breeding contribution from each actinide which is based on the fertile material, U-238 gives the main contribution, whether it becomes positive which means higher contribution of breeding or becomes less breeding contribution. Adopting MA nuclide as additional fuel for increasing breeding capability of the reactor is effective for TRU fuel in the core region which is shown in Fig. 15 (right figure) that shows some additional breeding can be achieved during reactor operation. However, loading MA in the blanket region gives reduction value of breeding caused by less relative capture rate of U-238 during reactor operation. It shows a relatively same reduction value of breeding capability (doping MA) in the blanket region for both MOX and TRU fuels which is shown by a reduction value of U-238 (less contribution of U-238) in the blanket region because of same doping rate of MA. However the actual values of breeding are different for both fuel cases which show TRU fuel with doping MA obtains higher breeding than MOX fuel with doping MA.

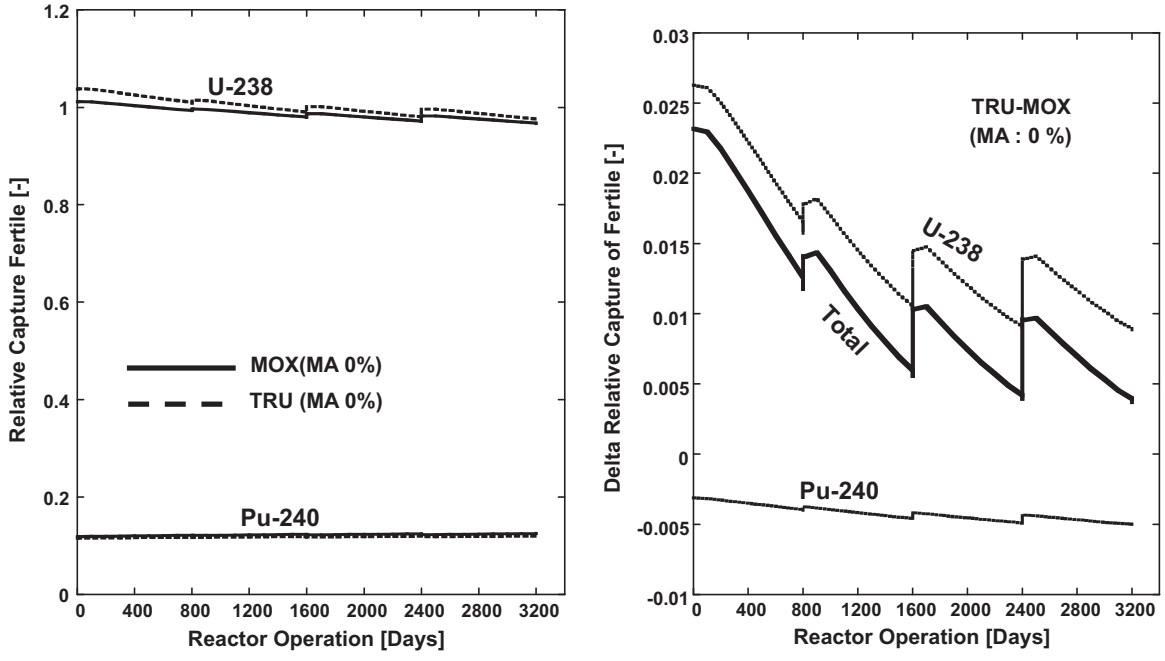

Fig. 14. Relative capture fertile rate of compared MOX with TRU fuels for no doping case.

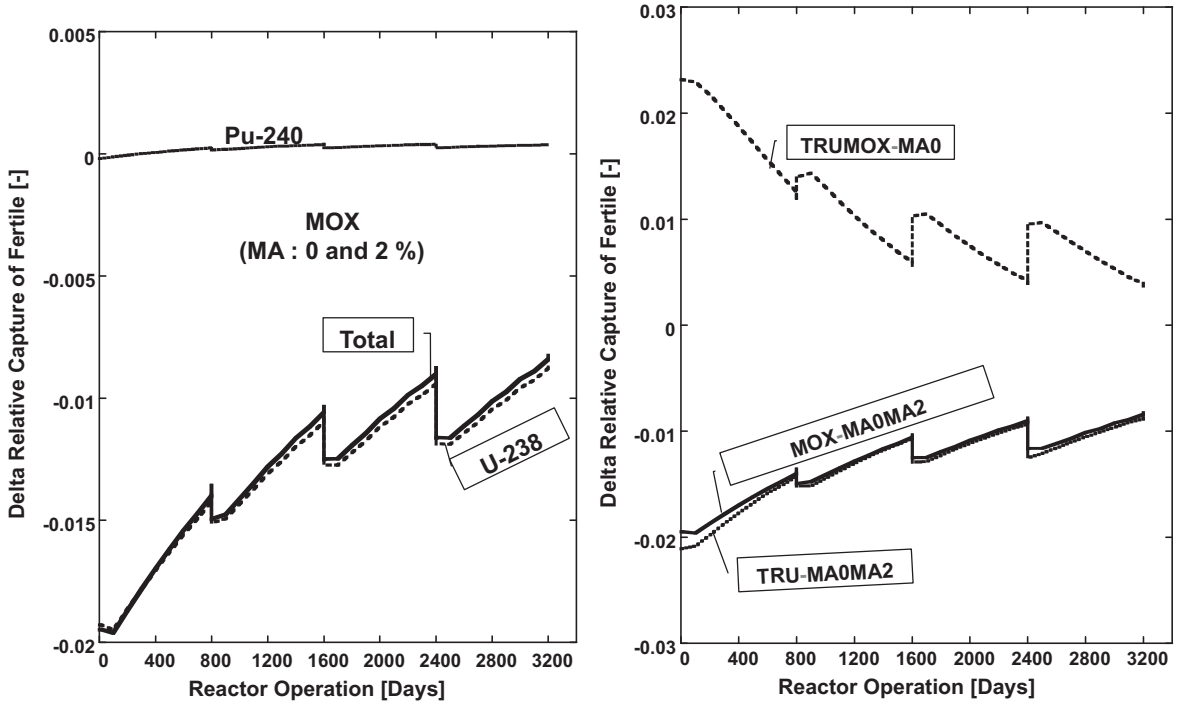

Fig. 15. Delta relative capture fertile rate of MOX and TRU fuels for no MA doping and with MA doping cases.

3.4. Void reactivity and Doppler coefficients

Reactivity coefficient in regards to the voided condition of the reactors is evaluated as a function of reactor operation time for different fuel and doping MA rates. The voided condition is assumed that the reactor has a 100% voided in the core and blanket regions. TRU fuel gives higher void reactivity coefficient comparing with MOX fuel and its profile decreases with increasing reactor operation time for both fuel cases. Loading MA content as TRU fuel type which consists of U–Pu–MA oxide fuel in the core make the reactors have higher reactivity coefficient function when coolants are voided as shown in Fig. 16. Less void reactivity difference of both fuel cases at longer operation time, it is caused by higher TRU composition of both fuel cases as recycled fuel from the second recycled batches up to 4th batches. In case of loading MA in the blanket regions, it shows almost no effect to the void reactivity coefficient condition, however, it gives a different profile of both doping MA and no doping MA cases longer reactor operation time which shows doping MA effect has slightly higher void reactivity coefficient than no doping MA case. It can be estimated that loading MA in the core regions have relatively bigger effect to the void reactivity conditions and it less effective for loading MA in the blanket regions. Table 5 shows that replacing MOX fuel by TRU fuel compositions in the core regions gives the increasing value of void reactivity coefficient (VRC) from 38.6×10^{-3} [dk/k/%vol] (MOX) to 48.2×10^{-3} [dk/k/vol.%] (TRU) at BOC and from 37.6×10^{-3} [dk/k/vol.%] to 37.9×10^{-3} [dk/k/vol.%], respectively. As mentioned in the previous section, some MA nuclides and Pu-238 give positive contributions to the criticality condition as shown in Fig. 10 for comparative cases of TRU and MOX fuel types as well as in Fig. 11 for doping MA cases. This approach can be used to estimate the reason why VRC values can be obtained by TRU fuel compared with MOX fuel.

Doppler coefficient (DC) in regards to the voided condition of the reactors is evaluated as a function of reactor operation time for different fuel and doping MA rates for increasing temperature of fuel from 1370 K to 1870 K which about 500 K as a temperature difference. The temperature change has been set for the analysis of Doppler coefficient for 500 K temperature increase which affect to the reactivity change during reactor operation. TRU fuel obtains less negative Doppler coefficient than MOX fuel during reactor operation except for 4th recycled batches of EOC which shows slightly more negative DC as shown in Fig. 17. Smaller differences value of DC for both fuel cases comes from the contribution of increasing TRU production which is produced for longer operation and those are recycled into the reactors for the second cycle up to the 4 recycled batches. Loading MA in the blanket regions shows slightly less negative DC than no doping MA case along the reactor operation and shows its value relatively same value during reactor operation. Loading MA is more effective to the change of DC in the core regions in comparison with loading MA in the blanket regions as also mentioned in the case of void reactivity coefficient.

3.5. Plutonium vector analysis

Plutonium composition analysis is evaluated for estimating the plutonium isotopes vector composition based on the plutonium production which mainly comes from converted depleted uranium as loaded fuel. Those plutonium vector compositions are recognized at certain level for some plutonium categorization which is mainly based on isotopic Pu-238, Pu-239 and Pu-240. High level of plutonium quality is recognized to have more fissile content of plutonium (Pu-239 and Pu-241) and it shows as less proliferation resistance. Reduction value of plutonium quality can be obtained by increasing even mass of plutonium isotopes which can be called as isotopic barrier of plutonium which gives higher proliferation resistance level. Higher plutonium production can be obtained by increasing converted depleted uranium into Pu-239, and as mentioned in the previous section, it can be increased by increasing converted MA into Pu-238. Increasing composition of other plutonium isotopes can be obtained from the derivative product of Pu-239 such as Pu-240 and so on. In regards to the proliferation resistance concern, the important issue is how to increase the isotopic barrier of plutonium for protecting the plutonium production especially from blanket region of fast breeder reactor. It is estimated

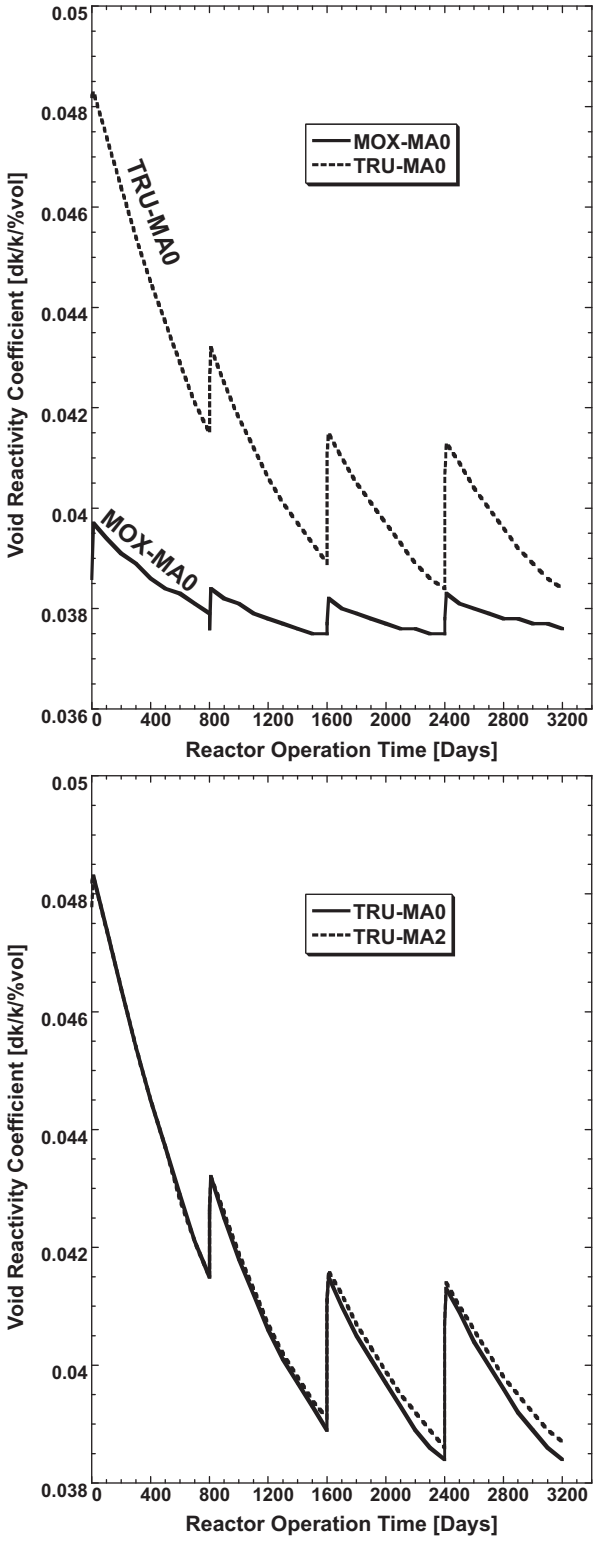

Fig. 16. Void reactivity coefficients of MOX and TRU fuels.

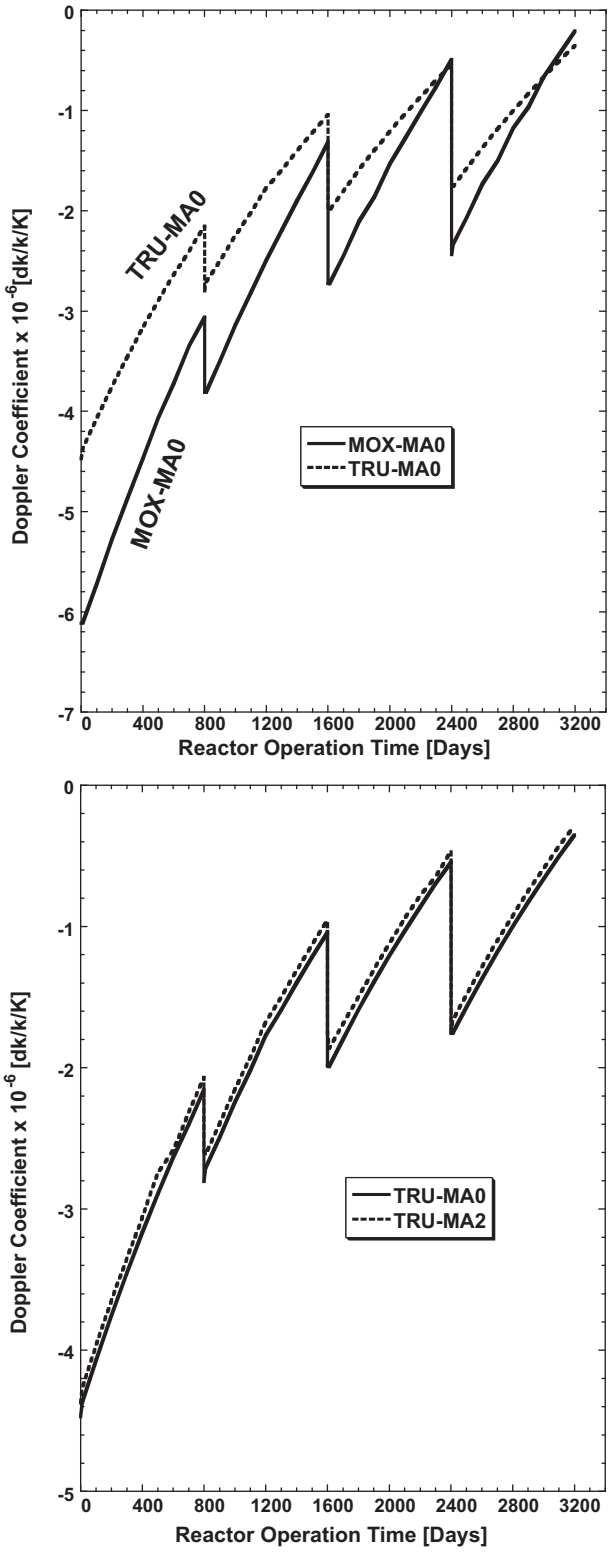

Fig. 17. Doppler coefficients of MOX and TRU fuels.

that obtained plutonium composition at the blanket region reaches a certain level of weapon grade plutonium composition (Pellaud, 2002; DeVolpi, 1982; Mark, 1993).

Isotopic plutonium vector compositions are shown in Figs. 18–21 for different fuel type, doping MA rate and fuel zones. Isotopic vector compositions of Pu-238, Pu-239 and Pu-242 decrease while its vector compositions of Pu-240 and Pu-241 increase with increasing the time in the core regions. In case of plutonium vector composition in the blanket regions, it increases with the time except for Pu-239. Almost pure Pu-239 vector composition is obtained at early irradiation time (10 days) and it reduces by increasing the time. Radial blanket region obtains higher isotopic plutonium vector composition of Pu-238 and Pu-239 than axial blanket and less vector composition for other

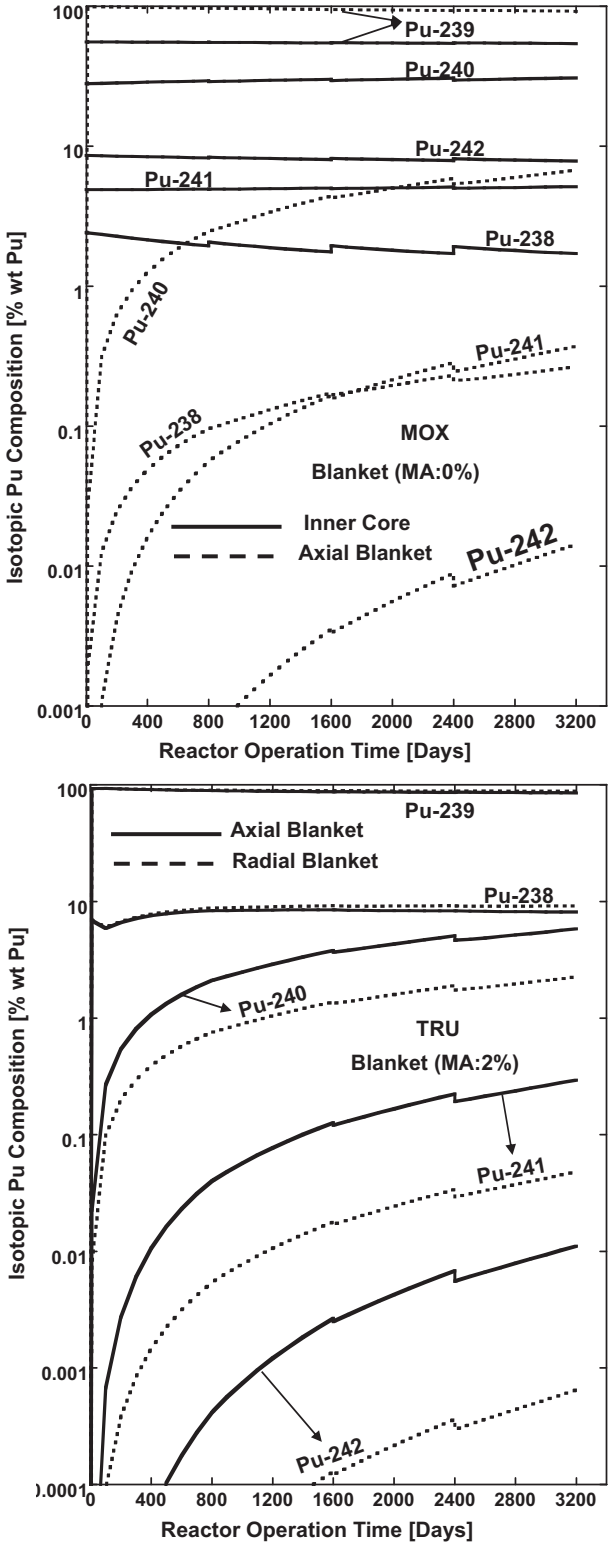

Fig. 18. Isotopic plutonium vector composition of MOX and TRU fuels.

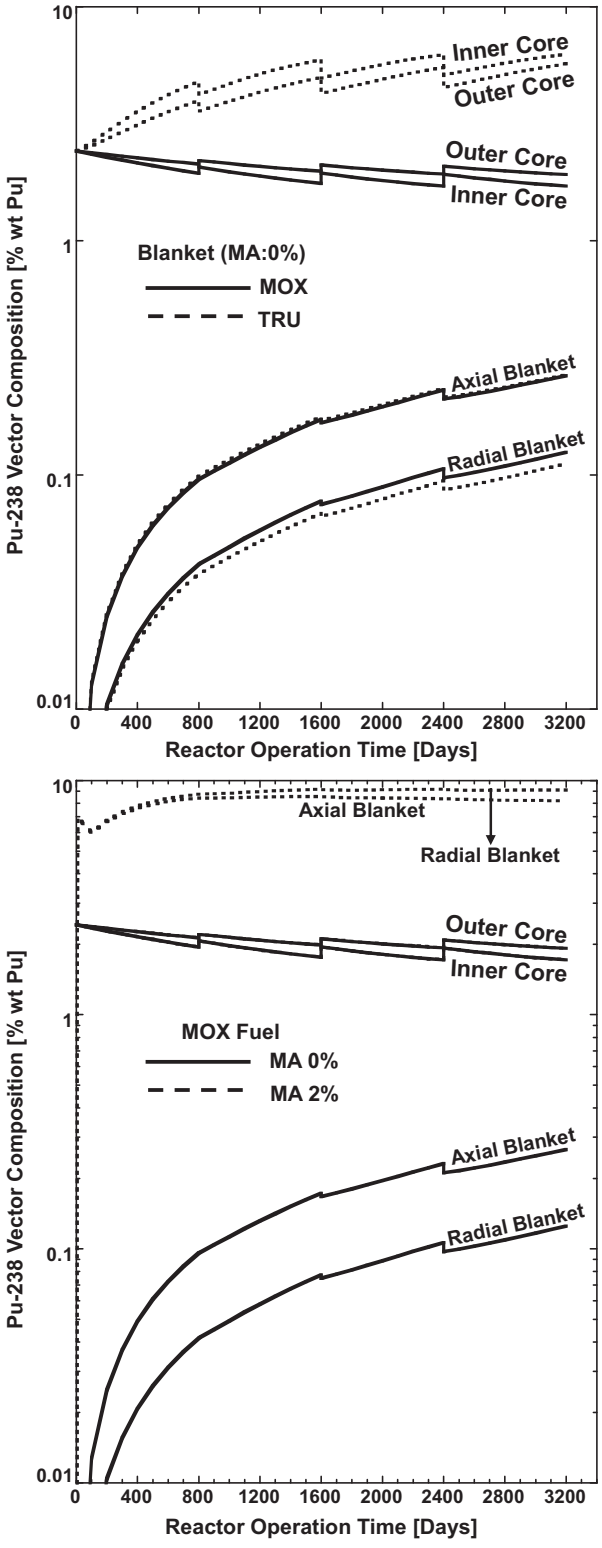

Fig. 19. Isotopic plutonium vector composition of Pu-238.

plutonium isotopes. Higher isotope Pu-238 compositions are obtained by TRU fuel in all reactor fuel zones except in radial blanket region which shows less composition. Its Pu-238 composition are also increasing with increasing the reactor operation time except for core regions of MOX fuel which shows less composition for longer operation time. In the core regions, increasing Pu-238 composition of TRU fuel comes from the increase of converted MA into Pu-238 during reactor operation as well as in the blanket regions. Reducing Pu-238 compositions of MOX fuel in the core regions are caused by less converted MA as the main producer of Pu-238 during reactor operation. Table 6 shows that core regions of TRU fuel type obtains about 6% Pu-238 compositions at the end of cycle while Pu-238 compositions of MOX fuel obtains less than 2%. Therefore, the increase of Pu-238 composition can be achieved by

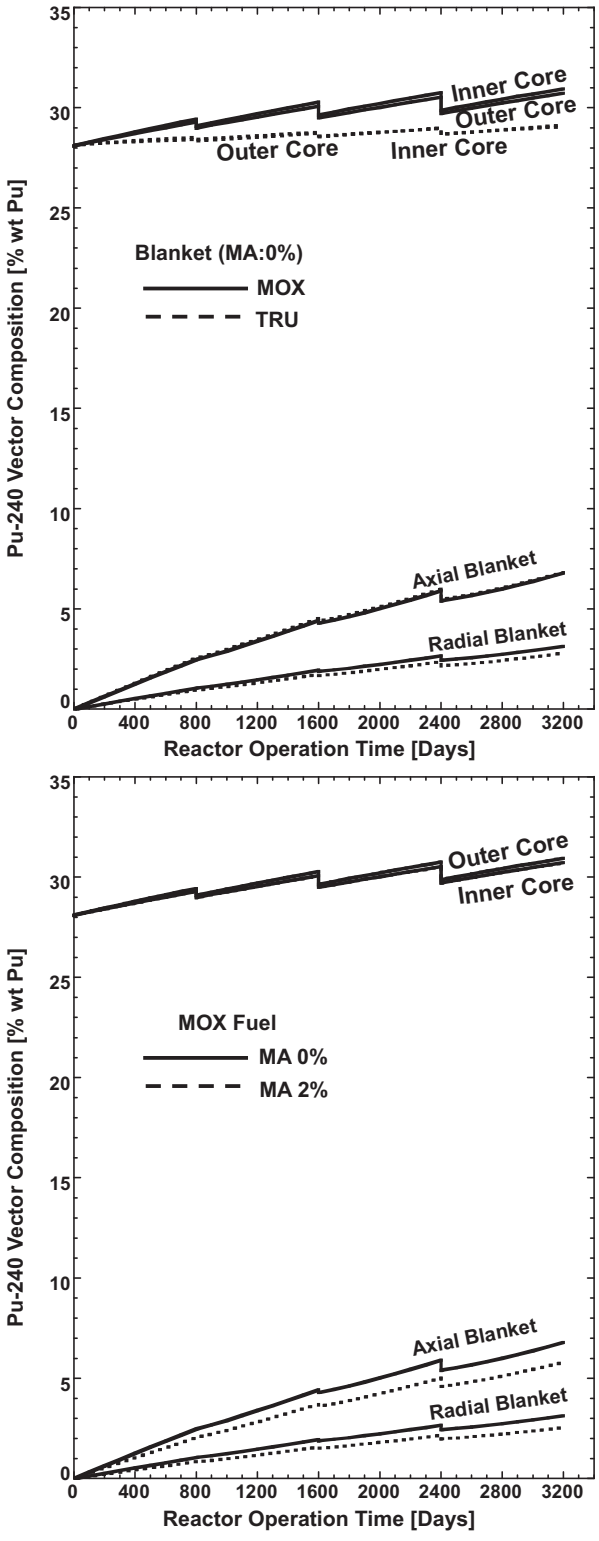

Fig. 20. Isotopic plutonium vector composition of Pu-240.

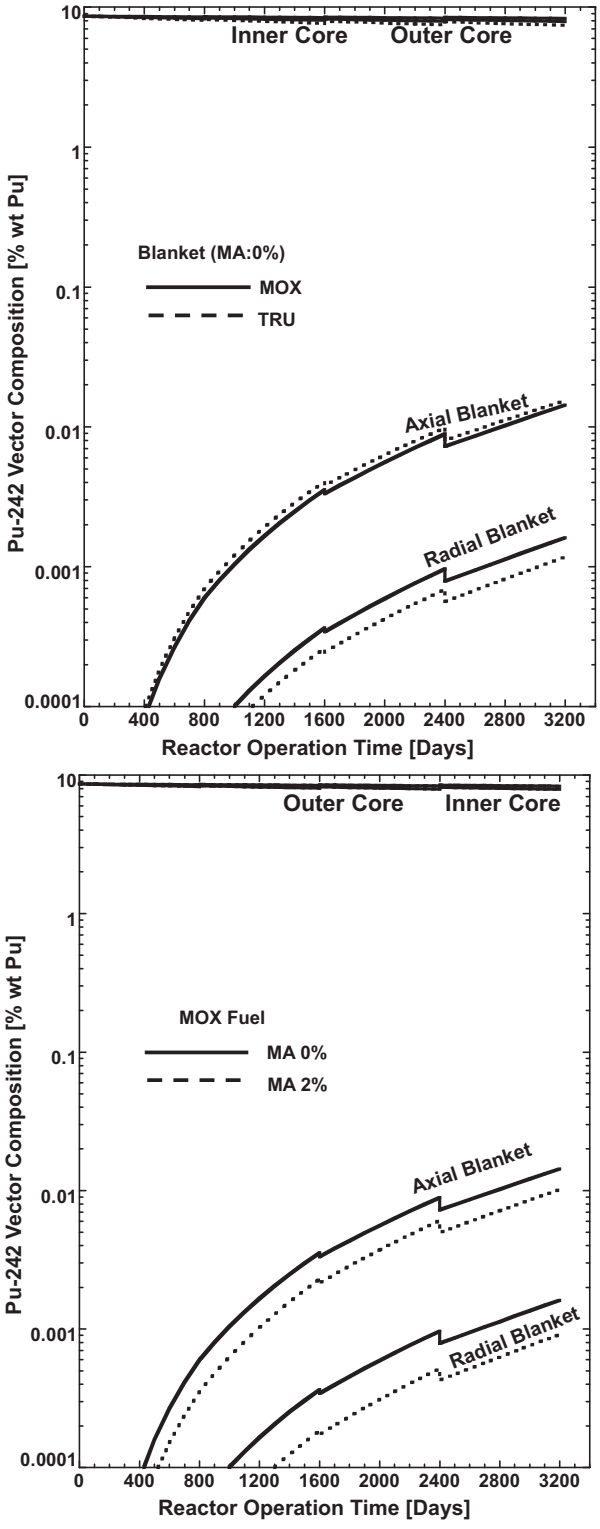

Fig. 21. Isotopic plutonium vector composition of Pu-242.

loading TRU fuel which consists of some MA compositions about 3 times higher in the core regions than MOX fuel. Axial blanket region gives higher Pu-238 vector composition than blanket region for no doping MA case, while by loading MA 2% is effective to increase Pu-238 vector composition in the blanket regions which shows higher composition of Pu-238 can be obtained by radial blanket region. It can be estimated that TRU fuel obtains relatively high level of proliferation resistance caused by higher isotopic barrier composition of Pu-238 as well as doping MA in the blanket regions as shown in Fig. 18.

Other even mass plutonium isotopes of Pu-240 and Pu-242 give an increasing vector composition with increasing operation time for both TRU and MOX fuel type in the core region as well as doping MA and no doping cases in the blanket regions. Pu-240 vector composition of MOX fuel obtains more than 30% composition at longer operation time for both inner and outer core regions while its Pu-

Table 6
Plutonium vector composition of MOX and TRU fuel types for no doping case in core regions.

Actinide [%wt Pu]	MOX MA 0%				TRU MA 0%			
	Inner core		Outer core		Inner core		Outer core	
	BOC	EOC	BOC	EOC	BOC	EOC	BOC	EOC
Pu-238	2.42	1.72	2.42	1.92	2.42	6.27	2.42	5.72
Pu-239	55.95	54.31	55.95	54.17	55.95	52.30	55.95	52.70
Pu-240	28.09	30.94	28.09	30.72	28.09	29.17	28.09	29.08
Pu-241	4.91	5.16	4.91	4.87	4.91	4.82	4.91	4.52
Pu-242	8.62	7.87	8.62	8.31	8.62	7.44	8.62	7.98

240 compositions are less than 30% during reactor operation for TRU fuel type. Axial blanket gives higher Pu-240 composition than blanket region for no doping and with doping MA cases. It obtains small difference values of Pu-240 composition of MOX fuel and TRU fuel type during reactor operation for all fuel regions. In case of doping MA in the blanket regions, Pu-240 compositions are reduced by doping MA which is shown in Fig. 20 as well as Pu-242 vector composition in Fig. 21. Pu-242 compositions in the blanket regions are very small which obtain less than 0.01% for both doping MA and no doping cases while in the core regions their compositions are about 8–9% composition. Based on the quantitative composition, only Pu-238 and Pu-240 compositions are effective for increasing proliferation resistance level in the blanket regions, however, all even mass plutonium composition are effective for isotopic barrier level in the core regions. In order to categorize the plutonium composition level based on the isotopic plutonium composition of even mass plutonium, it should be distinguished those composition based on the fuel regions, reactor operation time and different fuel loading as well as doping material such as doping MA.

Plutonium vector compositions in the core regions represents the MOX fuel composition which obtains Pu-240 composition nearly to 30% or even higher. Those Pu-240 compositions are categorized as practically unusable composition for nuclear device based on the Pellaud's criterion (Pellaud, 2002). In case of plutonium composition in the blanket regions, it shows low composition of Pu-240 for no doping as well as doping MA cases which obtains less than 7% composition of Pu-240 during reactor operation. Less than 7% Pu-240 vector composition make the blanket regions are categorized as weapon grade composition or even super grade composition at certain cases for no doping MA case. In case of doping MA, although Pu-240 composition are less than 7%, by obtaining relatively high composition of Pu-238 during reactor operation which reach higher than 9%, it can be categorized as high level of proliferation resistance level for denaturing plutonium even for high technology nuclear explosive based on the Kessler's criterion (Kessler et al., 2008). Pu-238 composition of radial blanket region with doping 2% MA is able to obtain 9% Pu-238; however, for axial blanket regions it obtains less than 9% as shown in Table 7. Therefore, it requires more doping MA for axial blanket region to reach Kessler's criterion for denaturing plutonium.

Table 7
Plutonium vector composition of MOX fuel type for no doping and doping MA cases in blanket regions.

Actinide [%wt Pu]	MOX MA 0%				MOX MA 2%			
	Axial blanket		Radial blanket		Axial blanket		Radial blanket	
	BOC	EOC	BOC	EOC	BOC	EOC	BOC	EOC
Pu-238	0.00	0.27	0.00	0.13	0.00	8.19	0.00	9.13
Pu-239	0.00	92.56	0.00	96.65	0.00	85.71	0.00	88.26
Pu-240	0.00	6.79	0.00	3.13	0.00	5.81	0.00	2.55
Pu-241	0.00	0.37	0.00	0.10	0.00	0.29	0.00	0.06
Pu-242	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00

4. Conclusion

Fuel behavior analysis on the effect of trans-uranium (TRU) fuel loading to the reactor core performances as well as the actinide composition and isotopic plutonium composition in the core and blanket regions has been analyzed based on the large FBR type. Actinide elements of plutonium and uranium for TRU fuel type have slightly less composition than MOX fuel type except for trans-plutonium actinide compositions in the core regions. Plutonium element compositions increase with increasing reactor operation time in which some additional plutonium compositions are obtained from converted minor actinide (MA). MA contents in TRU fuel composition in the core regions decreases with increasing reactor operation time which is similar trend with blanket regions. Isotopic plutonium composition of TRU fuel obtains less composition than its isotopic composition of MOX fuel except for Pu-238 composition which obtains relatively higher composition. The significant increasing composition is shown by Pu-238 for TRU fuel in the core regions as well as its increasing value in the blanket regions for doping MA case.

Excess reactivity can be reduced significantly by TRU fuel type which about 5% (BOC) and it reduces with increasing operation time in comparison with MOX fuel type. Doping MA in the blanket regions of both fuel types reduces the criticality for a small value of about 0.1% reduction or less. Less criticality comes from the less relative production rate of fissile materials which is mainly from Pu-239 and higher criticality contribution comes from MA nuclides and Pu-238. As the total value from summation of all nuclide contribution, a negative value is obtained and its negative value decreases and it reaches to a zero value at EOC for TRU and MOX fuel comparison. TRU fuel obtains higher breeding ratio during the reactor operation which gives more than 2% of additional breeding gain than MOX fuel at the beginning of operation and it reduces with increasing operation time. Doping MA into the blanket regions gives less breeding ratio (<2%) and it reduces with increasing operation time. U-238 as main nuclide plays as main contributor for breeding ratio, therefore, higher or less breeding ratio can be estimated from the relative capture rate of U-238. Higher relative capture rate of U-238 in TRU fuel is obtained than MOX fuel and less relative capture rate of U-238 is achieved by doping MA case than no doping case.

Loading MA in the core regions as TRU fuel composition gives relatively bigger effect to increases the void reactivity coefficient mean while it gives less effect for loading MA in the blanket regions. Similar to the void reactivity coefficient profile, loading MA is more effective to the change of Doppler coefficient in the core regions in comparison with loading MA in the blanket regions which gives slightly less negative Doppler coefficient.

Obtained Pu-240 vector compositions in the core region are categorized as practically unusable composition for nuclear device based on the Pellaud's criterion. Less than 7% Pu-240 vector compositions in the blanket region are categorized as weapon grade composition no doping MA case. Pu-240 compositions are less than 7% for doping MA case; however, it can be categorized as high level of proliferation resistance level for denaturing plutonium based on the Kessler's criterion caused by obtaining Pu-238 vector composition of 9%.

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