

Fuel Sustainability And Actinide Production Of Doping Minor Actinide In Water-Cooled Thorium Reactor

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Abstract. Fuel sustainability of nuclear energy is coming from an optimum fuel utilization of the reactor and fuel breeding program. Fuel cycle option becomes more important for fuel cycle utilization as well as fuel sustainability capability of the reactor. One of the important issues for recycle fuel option is nuclear proliferation resistance issue due to production plutonium. To reduce the proliferation resistance level, some barriers were used such as material barrier of nuclear fuel based on isotopic composition of even mass number of plutonium isotope. Analysis on nuclear fuel sustainability and actinide production composition based on water-cooled thorium reactor system has been done and all actinide composition are recycled into the reactor as a basic fuel cycle scheme. Some important parameters are evaluated such as doping composition of minor actinide (MA) and volume ratio of moderator to fuel (MFR). Some feasible parameters of breeding gains have been obtained by additional MA doping and some less moderation to fuel ratios (MFR). The system shows that plutonium and MA are obtained low compositions and it obtains some higher productions of even mass plutonium, which is mainly Pu-238 composition, as a control material to protect plutonium to be used as explosive devices.

1. Introduction

Energy supply which can sustain its supply to secure world energy demand in order to maintain their prosperities and daily life activities are substantial to be pursued. In term of nuclear energy, its sustainability of nuclear energy comes from optimum fuel utilizations based on existing fuel resources, fuel management of the reactor including fuel cycle program as well as fuel breeding program. Fuel cycle option becomes more important for fuel cycle utilization as well as fuel sustainability capability of the reactor. Those fuel optimization programs can be improved which has a similar trend with the renewable energies has been shown as a sustainable energy source [1]. In addition, a similar way, is to “re-use” spent fuel such as some depleted uranium, plutonium and minor actinides as a new fuel to be used for conventional or advanced nuclear reactors. In term of recycle nuclear fuel program, one of the important issues is in conjunction with the nuclear proliferation resistance issues. The issue comes from the production of good quality of weaponable grade of spent nuclear fuel such as plutonium. To reduce the proliferation resistance level, some barriers were used such as material barrier of nuclear fuel based on isotopic composition. Some material barrier of isotopic composition can be estimated from critical mass, heat-generation rate, spontaneous neutron generation and radiation. Isotopic barrier of plutonium comes from the even mass number of plutonium isotope such as ²³⁸Pu, ²⁴⁰Pu and ²⁴²Pu and in case of thorium cycle will depend on ²³²U. For decades some thorium fuel technologies have been developed, for both conventional and advanced nuclear reactor as well as some thorium breeder reactor programs which was also developed for breeding program in uranium fuel technology. Thorium fuel cycle have some advantages including better fuel breeding



capability in thermal and epi-thermal neutron energy region, higher fuel stability and higher level proliferation resistance [2-6] in comparison with others fuel cycles.

Some analyses on nuclear fuel sustainability and actinide production composition have been done based on heavy water-cooled thorium reactor system and will be shown in the present study. Fuel cycle flow scheme will be based on the fuel recycled composition which all actinide compositions except fission products are recycled into the reactor as a basic fuel cycle scheme. Two key important parameters are evaluated such as doping composition of minor actinide (MA) and volume ratio of moderator to fuel (MFR) which have some significant impact to the reactor performances as well as fuel composition behaviors.

2. Parameter and Method

Some analyses on nuclear fuel sustainability and actinide production composition have been done based on heavy In the present study, well established reactor technology of water-cooled reactor based technology has been adopted as a basis for evaluation which is based on current LWR plant technology as general design parameter and using heavy water as coolant and moderator instead of light water. **Table 1** shows a basic design parameters which consist of some key parameters such as moderator to fuel ratio (MFR), burnup and doping rate of minor actinide (MA) based on large 3000 MWt power output and heavy water as coolant and moderator. Employed MFR of 1 and 1.5 are used to evaluate a moderator effect to the reactor performance in comparing to standard MFR of PWR (MFR =2) which show the neutron spectra are relatively harder than standard PWR. Minor actinide (MA) effects are used based on no MA doping and with 10 % MA doping for fix discharged fuel burnup of 36 GWd/t. A 1.452 cm was used as fuel pin diameter based on the regular blanket fuel diameter of the Shippingport [2,6-7]. Fuel cycle scheme of closed cycle fuel that all actinides are returned to the reactor and only FPs are sent to final disposal stream, are used for this analysis based on adopted thorium fuel based with additional MA are used for doping material. To evaluate fuel sustainability based on fuel conversion or fuel breeding capability and actinide production of the reactors, an equilibrium burn-up calculation code (Equilibrium Cell Iterative Calculation System: ECICS) was used which is coupled with SRAC code and JENDL3.2 nuclear data library [2,7-18]. Fuel sustainability based on fuel breeding and fuel conversion ratio are based on the reaction rate of fissile and fertile nuclides and some small contributions of intermediate nuclides. When the conversion ratio is higher than unity than the definition becomes fuel breeding ratio and some surplus fuel from fuel breeding production is defined as fuel breeding gain.

Table 1. Reactor parameters

Parameters	Values/Type
Thermal Power Output [MWt]	3000
Coolant	D ₂ O
Fuel Cycle Option	All Actinides closed
Supply Fuel Composition	Th + MA
Cladding	Zircaloy-4
Fuel pellet diameter [cm]	1.31
Fuel pin outer diameter [cm]	1.45
Moderator to Fuel Ratio (MFR) [-]	1 and 1.5
Burn-up [GWd/t]	36
MA Content [%]	0 - 10

3. Results and Discussions

3.1. Fuel sustainability of breeding capability

Obtained results based on fuel conversion capability to evaluate the effect of doping MA in the reactor are shown in **figure 1**. Obtained fuel conversion capabilities are higher than unity, which means the results have fuel-breeding capability. As shown in Figure 1, doping material of MA is effective to increase the fuel breeding level because of some additional fissile materials are produced from converted MA material during reactor operation. To estimate some surplus from fuel breeding condition, a fuel breeding gain is adopted which is shown in **figure 2** for fuel sustainability from the effect of MA doping. Initial condition for thorium reactor without additional MA material as doping obtained higher than unity, which means fuel-breeding gain can be achieved. Additional fissile material based on breeding gain is estimated of about 1,2% additional fissile materials were produced during reactor operation. In addition, when some MA material are loaded into the reactor, the fuel breeding gain is increasing significantly from 1.2% up to about 2,2% for MA doping of 10%. Those materials of MA are estimated to produce more fissile material from fuel conversion process of MA into some plutonium fissile and fertile materials through neutron capture during reactor operation.

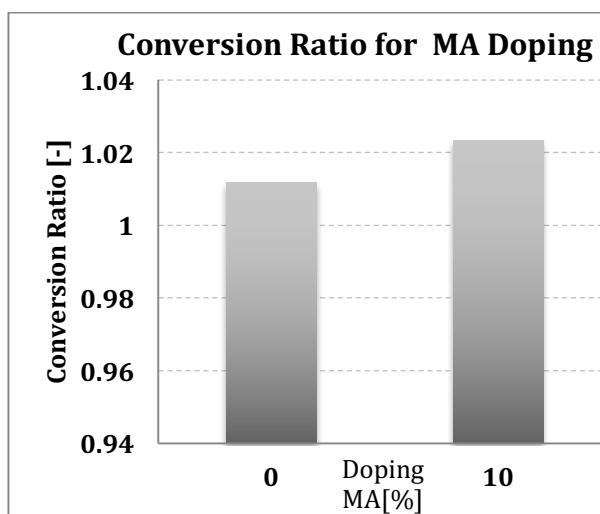


Figure 1 Fuel conversion ratio for MA content of 0 and 10 % as doping

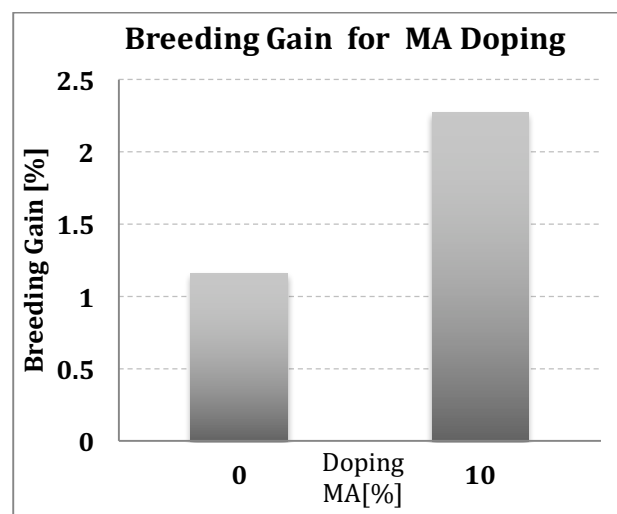


Figure 2 Fuel breeding gain for MA content of 0 and 10 % as doping

As mentioned in the previous section that less moderation ratio to fuel or MFR is expected to make the reactor has a harder neutron spectrum, which is estimated to have more fuel conversion ratio or fuel-breeding ratio based on higher production of fissile material, which is converted from fertile material by absorption neutrons. The effect of less moderator to the reactor performance capability in relation to fuel sustainability are shown in **figure 3** which shows MFR of 1 and 1.5 as representative of different MFR for less moderation ratios. MFR of 1.5 is difficult to have fuel conversion higher than unity in comparing to smaller MFR value of 1, which obtains fuel conversion ratio of higher than unity. MFR of 1 is good enough to produce more fissile materials and it obtained more than supply fuel. Meanwhile MFR of 1.5 is not sufficient to achieve more fissile material, which is higher than unity. It is estimated that MFR of 1 has good enough neutron spectrum to make the reactor having some fuel-breeding ratio because of harder neutron spectrum, which is used to convert some fertile material of thorium as well as additional MA as doping to fissile material. Neutron spectrum of MFR of 1.5 is no sufficient to convert more breeding fuel through neutron capture during reactor operation. As expected that, fuel-breeding gain only can be obtained by MFR of 1 while MFR of 1.5 is difficult to have fuel-breeding gain as mentioned in **figure 4**. Figure shows that two MFR values give a positive and a negative values for fuel breeding gain which shows a positive value of almost 2 % of additional fuel breeding is achieved by MFR of 1. A negative fuel breeding gain is obtained by MFR of 1.5 which means the fuel breeding gain of the reactor is not sufficient to achieved higher than unity, it request more than 5% additional breeding gain. Even though fuel conversion ratio of 0.95 is higher enough to be called as higher converter reactor. Based on the MFR effect to achieve fuel breeding

gain, is estimated that between MFR 1 and MFR 1.5 has an optimum value to produce a breeding gain condition and its breeding gain is expected become higher for less MFR values. The results show that some feasible parameters can be used for obtaining breeding gain and it can be fulfilled by some additional MA doping as well as arranging some less moderation to fuel ratios (MFR), although higher MFR is expected to become a high conversion reactor.

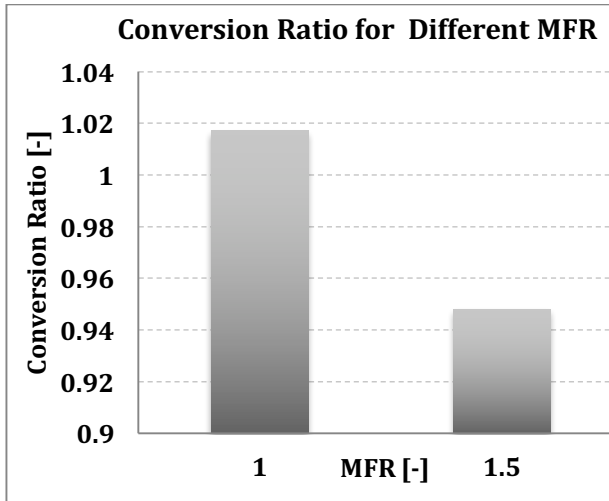


Figure 3 Fuel conversion ratio for different less MFR values.

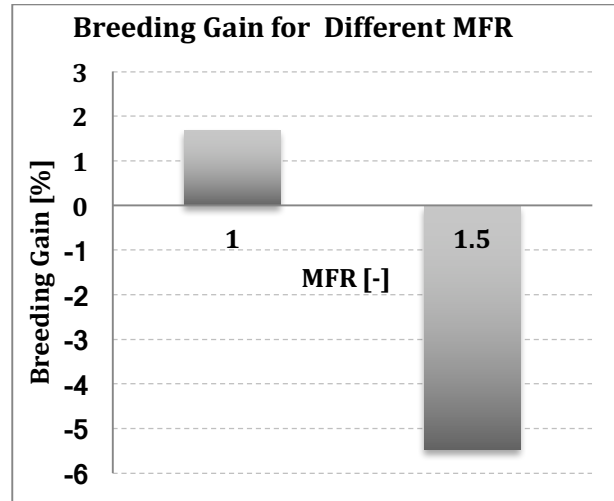


Figure 4 Fuel breeding gain for different less MFR values

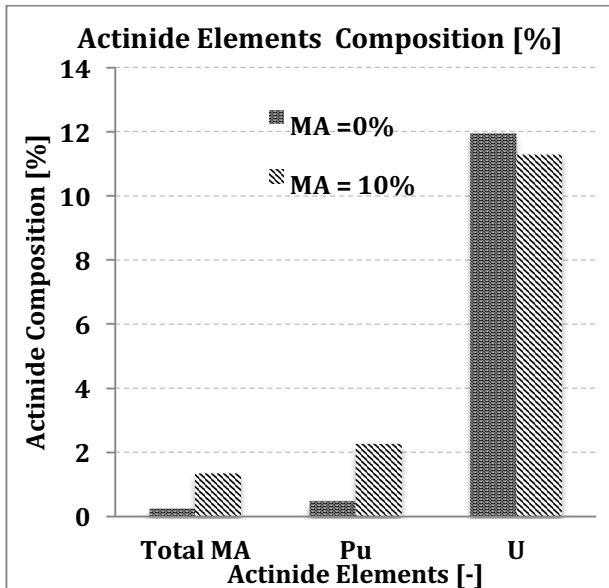


Figure 5 Actinide element composition for different MA doping rates

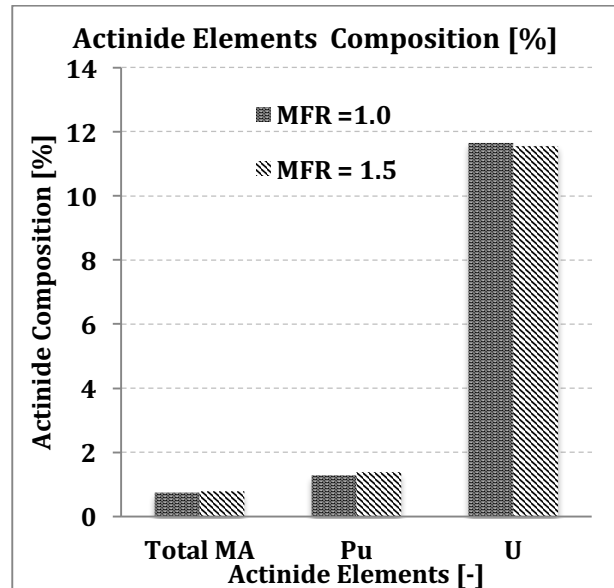


Figure 6 Actinide element composition for different less MFR values

3.2. Actinide element compositions

Some obtained results of actinide compositions are shown in **figures 5** through **8** for different MA doping and MFR values, which is based on equilibrium nuclide density composition. Some actinide composition based on actinide element of MA, plutonium and uranium are shown in figures 5 and 6 for different effects of MA doping and less MFR values. Doping MA is effective to increase

plutonium production as well as MA, while uranium element is decreasing when MA is loaded. Plutonium element composition is produced from converted MA as well as some MA is still exist as or production from produced MA. Uranium production is coming mainly from thorium cycle, which is mainly from U-233. This decreasing uranium is estimated from less fraction of thorium as fresh fuel because some portions are replaced by MA material as doping materials at fresh fuel. The effect of MFR to produce actinide element is shown in Figure 6 from MFR 1 and 1.5. It shows that higher MFR (MFR of 1.5) produces slightly more MA and plutonium productions, while uranium is slightly decreasing. Changing the neutron spectra from both employed MFR are not so significant to the change in actinide element compositions. Both data show that plutonium compositions are obtained 2% or less from total actinides, while uranium compositions are obtained more than 10%.

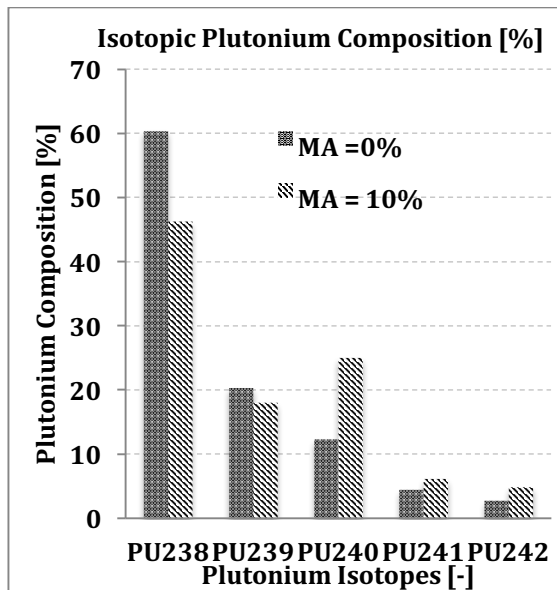


Figure 7 Isotopic Plutonium composition for different MA doping rate

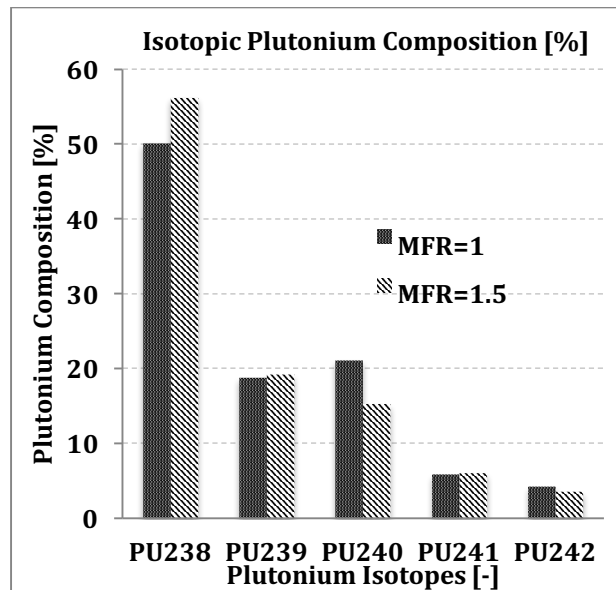


Figure 8 Isotopic Plutonium composition for different MFR Values

3.3. Plutonium isotopes compositions

Obtained produced plutonium composition based on isotopic plutonium compositions are shown in figure 7 and 8 for different MA doping rates and different MFR values. Data shows that both effect of MA doping and MFR values have a significant change in plutonium isotopes composition. The main contributions of total plutonium composition are coming from Pu-238, followed by Pu-239 or Pu-240 and Pu-241, Pu-242. MA doping is effective to increase the composition Pu-240 up to Pu-242 while it affects to decrease compositions of Pu-238 and Pu-239. While the opposite trend is shown by the effect of higher MFR that shows an increasing trend are obtained by Pu-238 and Pu-239 for higher MFR, while less composition for Pu-240 up to Pu-242. MA doping affects to reduce Pu-238 from 60% composition without doping up to about less than 50% when 10% doping is employed. While its Pu-238 composition for different MFR values are shown more than 50%. These Pu-238 values are higher enough based on protected plutonium composition in term of proliferation resistance point of view issue. The composition of Pu-238 is suitable to protect the plutonium to be used for explosive devices based on some even number mass of plutonium isotope which can be used to some criteria of plutonium characterization such as IAEA, Pellaud and Kessler criteria (IAEA, 1972; Pellaud, 2002; and Kessler, 2004) [19-21]. Trans uranium composition including plutonium and MA is expected to be less composition for thorium based reactor which is shown that very low MA compositions are obtained, while plutonium are achieved less than 2% in total composition for MA doping cases. In term of isotopic plutonium composition, it shows higher production of even mass plutonium mainly

Pu-238 which can be used as a control material to protect plutonium to be used as explosive devices which is higher enough based on Kessler criterion.

4. Conclusions

Nuclear fuel sustainability and actinide production composition analyses have been done based on heavy water-cooled thorium reactor system which adopted all actinide compositions except fission products are recycled into the reactor as a basic fuel cycle scheme. Some important parameters are evaluated such as doping composition of minor actinide (MA) and volume ratio of moderator to fuel (MFR) which have some significant impact to the reactor performances as well as fuel composition behaviors. Some feasible parameters have been obtained to obtain some breeding gains such as some additional MA doping as well as arranging some less moderation to fuel ratios (MFR). Trans uranium composition including plutonium and MA for thorium based reactor obtained very low compositions although for MA doping cases. The system obtains some higher productions of even mass plutonium, which is mainly Pu-238 composition which can be used as a control material to protect plutonium to be used as explosive devices based on Kessler criterion.

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