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Comparative Evaluation on Several Reactor Type of Actinide Closed-Cycle Schemes

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Abstract. Naturally, nuclear fuel resources are coming from uranium and thorium fuels for nuclear energy utilization. As by product reactor operation, some spent nuclear nuclear are produce which can be optimized by optimum recycled fuel option, as well as new fuel resource to increases fuel sustainability aspect of nuclear fuel. Several nuclear reactor types and the utilization of some recycled fuel options from their spent nuclear fuel as well as fuel breeding capability of the reactor based on those uranium and thorium fuel cycles. Some important parameters have been analyzed such as reactor performance of criticality and fuel conversion as well as some actinide productions in the present evaluation based on several fuel cycle schemes. As a basic recycling scheme, an open and a closed-fuel cycle of some actinides was used based on water-cooled reactor system, including light water and heavy water coolant. Basic analysis of the system is based on an equilibrium burnup calculation for the present computational approach analysis. Once through case requires more fissile materials than MOX fuel scheme to maintain criticality condition and heavy water coolant requires more fissile material than light water coolant for UOX fuel case, however, it shows the opposite trend for in case of MOX fuel. Thorium cycle requires more fissile material of U-233 for heavy water coolant than light water coolant. In term of light water case, the required fissile material of U-233 is less for thorium case than fissile material of U-235 in MOX fuel case. Fuel conversion ratios are obtained less than unity except for heavy water coolant of MOX fuel case, which obtains slightly more than unity. Thorium fuel shows better fuel breeding capability as well as heavy water coolant, which gives more fuel conversion capability than light water coolant. Actinide compositions of plutonium gives more than 1% for light water coolant and more than 10% for heavy water coolant case. For different fuel scheme cases, it shows that plutonium recycled scheme as MOX fuel case gives higher production of actinide or trans-uranium actinides from neptunium up to Curium than UOX fuel case for H₂O coolant. Total even mass plutonium isotope produces higher than total odd mass plutonium isotope for both coolants and heavy water coolant produces more than its production for light water coolant. Better composition of even mass plutonium has shown better proliferation resistance level which is shown by plutonium recycled scheme and heavy water coolant case.

1. Introduction

Nuclear energy sustainability can be improved, which has a similar trend with the renewable energies as a sustainable energy source [1]. Nuclear fuel cycle option and fuel sustainability aspect can be used to improve nuclear fuel sustainability of the reactor, which can be maintained by improving reactor design capability for breeder reactor as well as optimization of fuel usage and new fuel exploration and fuel mixing program between uranium and thorium as well as by product actinide such as plutonium and minor actinides. Some sensitive issues for nuclear utilization especially in term of recycle program, that are an issue which has corresponding to the nuclear proliferation resistance issues. To reduce the proliferation resistance level, some barriers were used such as material barrier of nuclear fuel based on isotopic composition. Some reactor designs are also contributed to the fuel



sustainability as well as nuclear proliferation resistant issues especially when the reactor are using some recycling products such as plutonium from uranium cycle and U-233 production from thorium fuel cycle. For decades some thorium fuel technologies have been developed in conjunction with the uranium fuel technology for commercial purposes, for both conventional and advanced nuclear reactor. One of the excellent thorium fuel programs was a thorium breeder reactor program for breeding program as well as in uranium fuel technology. As an excellent fuel, thorium fuel cycle gives some good features such as higher fuel breeding potential, better fuel stability and better level of proliferation resistance [2-6] in comparison with others fuel cycles. In term of proliferation resistance feature, there are some feature, which can be used as material barrier such as a barrier of isotopic composition. It affects to critical mass, heat-generation rate, spontaneous neutron generation and radiation. In term of isotopic barrier feature such as in isotopic barrier of plutonium, it is mainly comes from some compositions of even mass number of plutonium isotope such as ^{238}Pu , ^{240}Pu and ^{242}Pu for uranium-plutonium cycle which is also in similar dependency for thorium-uranium cycle which is depending on some composition of isotope ^{232}U .

Several nuclear reactor types and the utilization of some recycled fuel options from their spent nuclear fuel as well as fuel breeding capability of the reactor based on those uranium and thorium fuel cycles. Some important parameters have been analyzed such as reactor performance of criticality and fuel conversion as well as some actinide productions in the present evaluation based on several fuel cycle schemes. As a basic recycling scheme, an open and a closed-fuel cycle of some actinides was used based on water-cooled reactor system, including light water and heavy water coolant. Basic analysis of the system is based on an equilibrium burnup calculation for the present computational approach analysis.

Table 1. Reactor parameters

Parameters	Values/Type
Thermal Power Output [MWt]	3000
Coolant	H ₂ O and D ₂ O
Fuel Cycle Option	No and some Actinides closed
Supply Fuel Composition	U and Th-U233
Cladding	Zircaloy-4
Fuel pellet diameter [cm]	1.31
Fuel pin outer diameter [cm]	1.45
Moderator to Fuel Ratio (MFR) [-]	1
Burn-up [GWd/t]	36

2. Parameter and Method

As mentioned above, several key parameters has been analyzed on required fissile material for maintaining a criticality condition, nuclear fuel sustainability based on conversion ratio and fuel breeding ratio and actinide production composition for several fuel cycle schemes and water coolant types. Fuel cycle schemes are based on once through case or UOX case and plutonium (Pu) recycled case or MOX fuel case. Water coolants system are based on light water and heavy water coolants which basically adopted well established reactor technology of current LWR plant technology as general design parameter. As shown in **Table 1**, it shows some basic parameter of the reactor systems, which is based on a larger reactor of 3000 MWt power output. It was adopted a moderator to fuel ratio (MFR) of 1 which is a half value compare to a standard MFR of pressurize water reactor (PWR) (MFR =2) that gives the neutron spectra are relatively harder than standard PWR for a fix discharged fuel burnup of 36 GWd/t and a 1.452 cm for a larger fuel pin than standard PWR type [2,6-7]. Fuel cycle scheme of closed cycle fuel that no or some actinides are returned to the reactor and only FPs are sent to final disposal stream. To evaluate criticality condition, fuel sustainability and actinide composition

or fuel composition of the reactors, an approach has been used for equilibrium burn-up calculation code (Equilibrium Cell Iterative Calculation System: ECICS). The calculation is coupled with SRAC code and JENDL3.2 as nuclear data library [2,7-18].

3. Results and Discussions

3.1. Required Fissile Material of U-235 and U-233

Criticality condition of the reactors, which affects to reactor operation, can be maintained by loading some fissile materials to have enough fission reaction in the reactor core to have chain reaction for neutron balance to run the reactor in criticality condition. Those fissile materials are mainly from enrichment of U-235 or recycled material of fissile plutonium such as Pu-239 and fissile uranium of U-233 from thorium fuel cycle basis. Besides adopting those several fuel cycle schemes, a water coolant technology bases are used such as light water and heavy water coolants for comparative purposes. Obtained results of required fissile materials are shown in **Figures 1** and **2**, which is based on required fissile material of U-235 and U-233 for different water coolants. Figure 1 shows fuel cycle scheme of UOX, which means once through case, requires higher fissile materials in comparing with MOX fuel scheme, which means all plutonium materials are recycled. Less required fissile material of U-235 for MOX fuel is estimated from the contribution of fissile Pu-239 and Pu-241 after those materials are recycled into the reactor. Therefore, contribution of U-235 to maintain criticality condition becomes less because of the fission reaction can be maintained also by fissile material of Pu-239 and Pu-241. In term of UOX fuel case or once through fuel case, those plutonium materials are not recycled into the reactor, therefore for maintaining the reactor in critical condition, some fissile material of U-235 are required more. Different coolant type is estimated to give some effect to the reactor criticality as well as to the required fissile materials. It shows that UOX case require more fissile material for heavy water coolant case (D₂O) than light water coolant (H₂O). Heavy water coolant gives less thermal condition of neutron in the reactor, which causes the reactor becomes harder, therefore to maintain some criticality condition, it requires more fissile materials. In case of MOX fuel, it shows that the opposite trend for heavy water coolant than light water coolant have been obtained for requires fissile materials. Less fissile materials are required for heavy water coolant than light water coolant for MOX fuel case. This condition can be estimated from the recycled plutonium content into the reactor that recycled plutonium from heavy water is higher than light water, which contributes to help the reactor to maintain the reactor in critical condition. Therefore, required fissile material of U-235 becomes less because of the higher contribution of recycled plutonium.

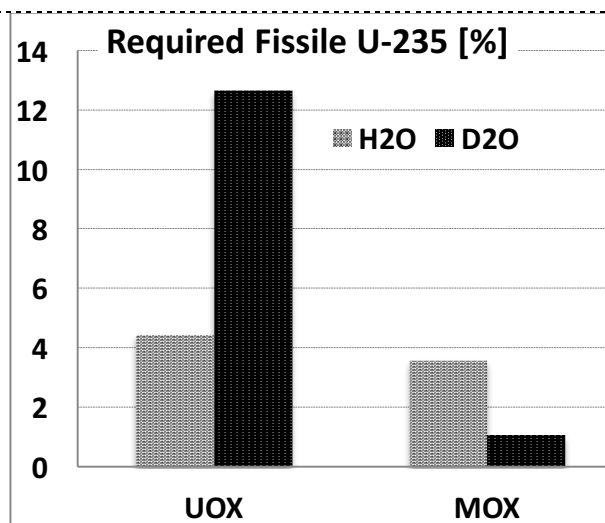


Figure 1 Required Fissile material of U-235 for Different Coolants and Uranium Fuel Cycles

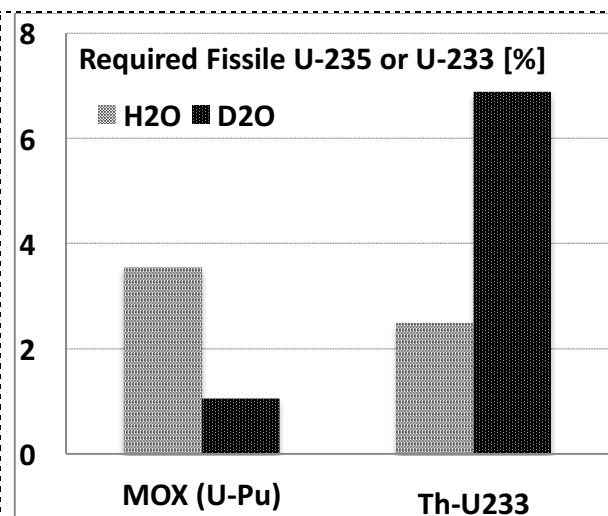


Figure 2 Required Fissile material of U-235 and U-233 for Different Coolants and Fuel Cycles

In addition, Obtained results of the required fissile material based on uranium and thorium fuel cycles are shown in Figure 2. It shows require fissile material of U-233 of thorium fuel cycle for heavy water coolant is higher than light water coolant, which is similar to UOX fuel case. In term of light water case, the required fissile material of U-233 is less for thorium case in comparing with the required fissile material of U-235 in MOX fuel case. However, It requires more fissile material of heavy water coolant in thorium fuel case than MOX fuel case. Light water coolant in both cases of fuel cycle gives some effect to make the neutron in thermal condition or softened the neutron spectrum. In thermal condition as well as in epithermal condition, more fission reaction is obtained by U-233 than U-235 as well as with other fissile materials. Therefore, fissile U-233 is easier to make the reactor critical, which requires less fissile material for criticality condition. In case of heavy water coolant, in this condition of MOX, it uses plutonium to support the U-235 fissile to make critical, therefore supply U-235 becomes less. In thorium case, recycled plutonium does not used, therefore more U-233 materials are needed to maintain the reactor in critical condition.

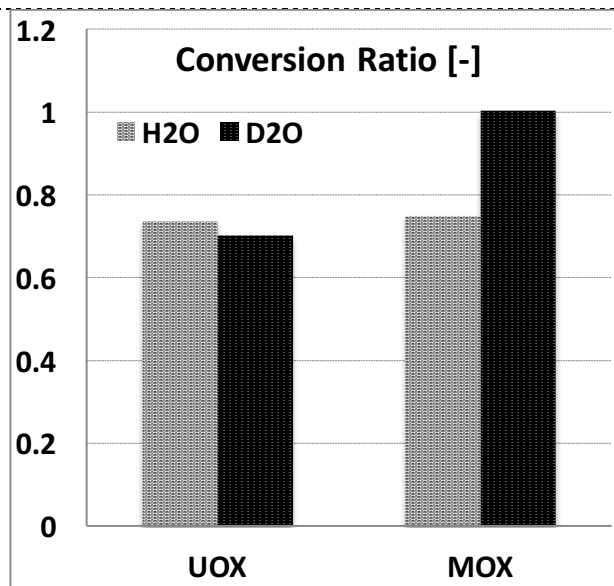


Figure 3 Fuel Conversion Ratio for Different Coolants and Uranium Fuel Cycles

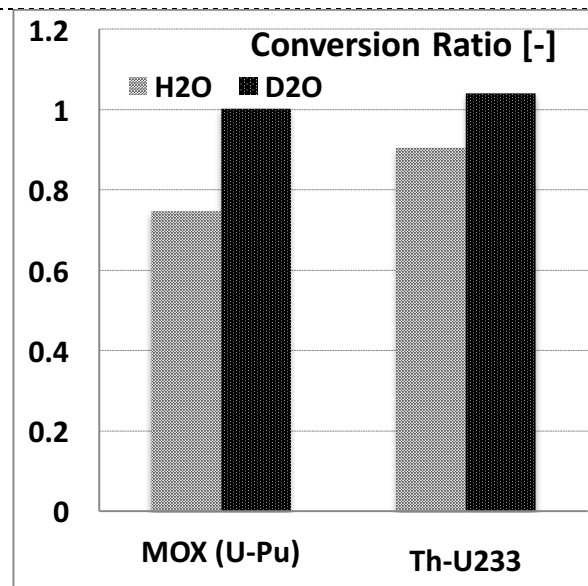


Figure 4 Fuel Conversion Ratio for Different Coolants and Uranium and Thorium Cycles

3.2. Fuel Conversion Ratio For Different Coolant and Fuel Cycles

Fuel breeding ratio can be obtained from fuel conversion ratio when it is higher than unity. In some cases, the fuel conversion is near to unity, which can be estimated as near breeder condition or high fuel conversion ratio. Fuel conversion ratio is also can be shown as the fuel capability to convert fuel fertile material into fuel fissile material, which can be used as fissionable material for maintaining reactor criticality. Some obtained results of fuel conversion ratios are shown in **Figures 3** and **4** for different coolants and fuel cycle Schemes. It shows that fuel conversion ratio of light water coolant for UOX and MOX fuels are less than unity as well as fuel conversion ratio for heavy water coolant of UOX fuel case. However for heavy water coolant of MOX fuel case, it obtains slightly more than unity than light water case. In this condition only heavy water coolant can obtain a fuel breeding condition. Thorium fuel case, it shows better fuel breeding capability than MOX and UOX fuel cases. Both heavy water and light water coolants for thorium fuel, which give a fuel conversion ratio level to near breeding and higher than unity to have breeder condition. Heavy water coolant gives more fuel conversion capability and it obtains breeding condition than light water coolant. Higher fuel conversion capability and obtained fuel breeder condition can be estimated from more contribution of recycled plutonium in case of comparison of UOX and MOX fuel cases. These plutonium condition

affects to have a better fuel conversion or have a breeder condition in addition to fissile U-235. In addition, thorium fuel, which is mainly the contribution from U-233, obtains better fuel conversion capability than fuel conversion capability of U-235 and Plutonium. These conditions can be estimated from the eta-value condition that U-233 is superior than others in thermal and epi-thermal energy regions, which is also effective to make easier for criticality condition as mentioned in the previous section of criticality aspect.

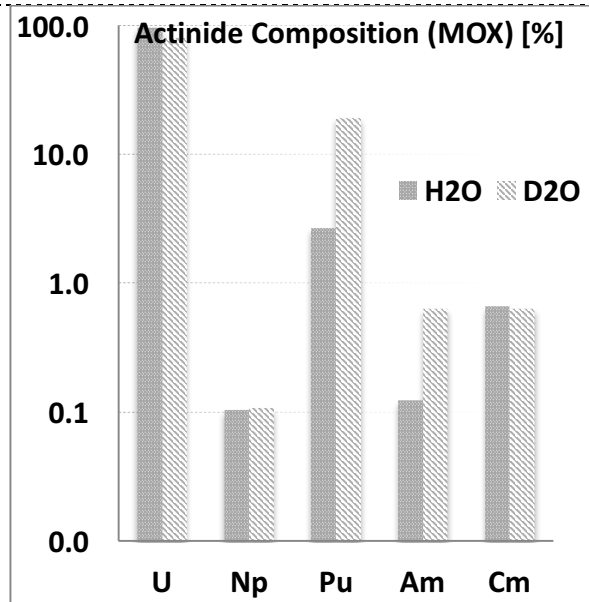


Figure 5 Actinide Composition of Fuel Element for Different Coolants of MOX Fuel

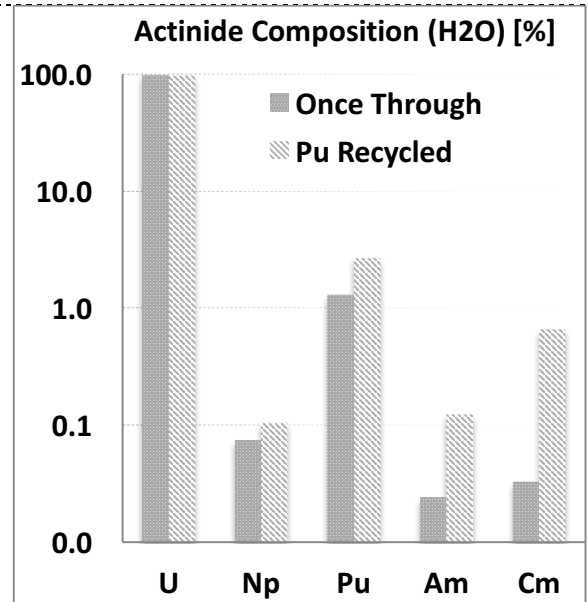


Figure 6 Actinide Composition of Fuel Element for Different Fuel Cycles of H2O Coolant

3.3. Actinide element compositions For Different Coolant and Fuel Cycles

Fuel behaviour of the reactor are effective also to make the reactor condition become critical condition or becomes breeding condition or high conversion condition. Contribution of different fresh fuel as supply fuel as well as different recycled fuels are effective to change the fuel composition trend in the reactor especially for trans-uranium and trans-thorium fuel compositions. Heavy metal nuclide as main nuclide can be represented by these nuclide such as uranium (U), Neptunium (Np), Plutonium (Pu), Americium (Am) and Curium (Cm). These fuel compositions as obtained results are shown in **Figures 5 and 6** for different coolants and fuel cycled schemes. As main fuel composition Uranium is obtained as highest fuel composition and it is followed by plutonium and others actinide compositions. Actinide compositions other than uranium are obtained less, which gives less than 1 % of fuel composition, except for plutonium which gives more than 1% for light water coolant and more than 10% for heavy water coolant case. Different coolants are effective to produce more actinides such as plutonium and Americium, however its very limited change for Neptunium and Curium as shown in Figure 5 for MOX fuel case. For different fuel scheme cases, it shows that plutonium recycled scheme as MOX fuel case gives higher production of actinide or trans-uranium actinides from neptunium up to Curium than UOX fuel case, as shown in Figure 6 for H2O coolant. These increasing actinide materials can be estimated from the contribution of recycled Pu material, which leads to increase plutonium production as well as trans-plutonium productions.

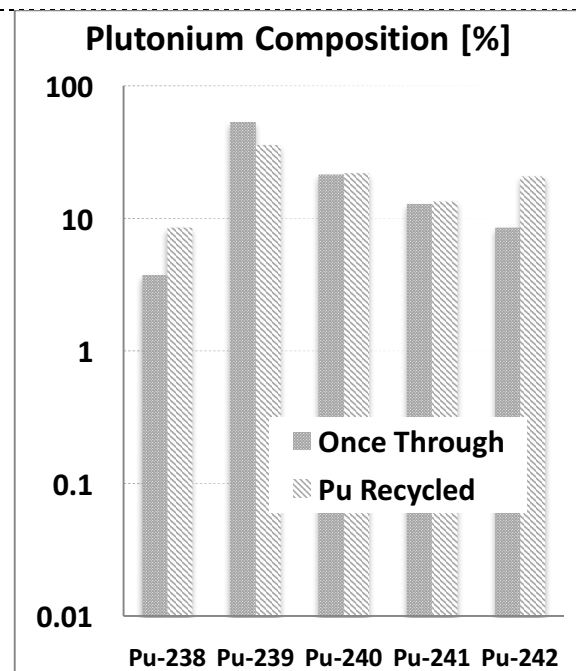


Figure 7 Plutonium Composition for Different Uranium Fuel Cycles of H₂O Coolant

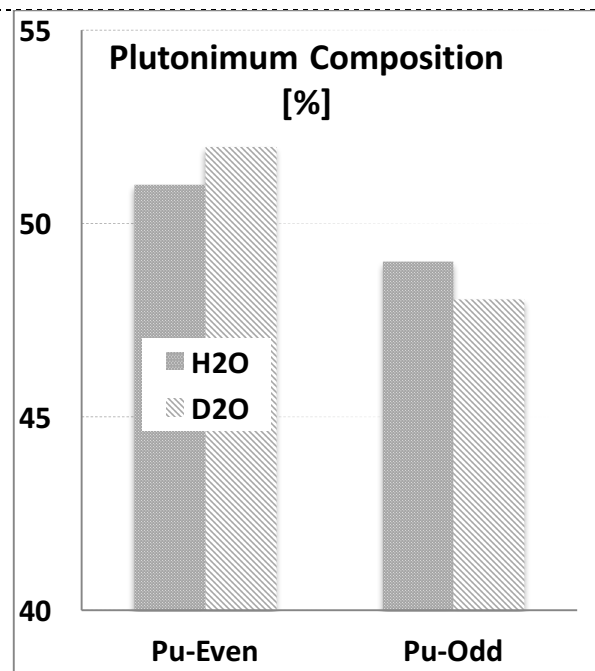


Figure 8 Plutonium Composition for Different Coolants of Plutonium recycled scheme

3.4. Plutonium isotopes compositions For Different Coolant and Fuel Cycles

As mentioned, contribution of elemental composition of actinide will be based on some isotopic composition. Isotopic composition will be composed by even mass and odd mass actinides. In term of plutonium element is based on isotopic plutonium composition of even and odd mass isotopes such as Pu-238, Pu-239, Pu-240, Pu-241 and Pu-242. Obtained results of plutonium isotopes are shown in **Figure 7** and **8** for different fuel cycle schemes and coolants. Each plutonium isotope has its own trend composition for different fuel cycles and coolants. It shows Pu-239 is produced as a main production, and its followed by Pu-240 and others. Production of Pu-239 is estimated from the conversion process of U-238 after capturing some neutrons and it converts into Pu-239. Pu-240 production is also from capturing neutrons of Pu-239 and Pu-240 converts to Pu-241 after capturing neutron as well as Pu-242. In case of Pu-238 production is estimated from (n,2n) reaction of Pu-239 and it converts to Pu-238. In cane of plutonium recycled or MOX fuel case, it shows better production than once through case for all plutonium isotopes except for Pu-239, which obtains less production. More plutonium productions are coming from the contribution of recycled plutonium loading into the reactor. Some decreasing Pu-239 is estimated from the fission process of Pu-239 is more to maintain the reactor in critical condition. This fission reaction of Pu-239 gives some decreasing composition of Pu-239 for plutonium-recycled scheme in comparing with once through case. Total even mass plutonium isotope, which is a total combination of Pu-238, Pu-240 and Pu-242, produces more composition of more 50% than total odd mass plutonium isotope of less than 50%, which is combination of Pu-239 and Pu-241. Total even mass plutonium production is obtained more for heavy water coolant than its production for light water coolant as shown in Figure 8. While it's total odd mass production becomes less. Higher composition of even mass plutonium gives an indication of the composition of plutonium has better proliferation resistant level for the system, which is shown by plutonium recycled scheme and heavy water coolant case. In case a specific composition of Pu-238, it shows better production for recycled Pu, which is more than 8% as well as less production of Pu-239 of less than 40%. This composition of Pu-238 can be adopted to protect the plutonium to be used for explosive devices based on some even number mass of plutonium isotope because of some internal material barrier of plutonium such as decay heat and spontaneous neutron fission. These plutonium

barriers, which is based on even mass plutonium composition was used for some plutonium criteria such as IAEA, Pellaud and Kessler criteria (IAEA, 1972; Pellaud, 2002; and Kessler, 2004) [19-21].

4. Conclusions

Some important key performances have been evaluated such as reactor performance of criticality and fuel conversion as well as some actinide productions based on several fuel cycle schemes open close or once through cycle and a closed-fuel cycle of some actinide was used based on water-cooled reactor system, including light water and heavy water coolant. Once through case or UOX case requires higher fissile materials than MOX fuel scheme to maintain criticality condition. In UOX fuel case, heavy water coolant case requires more fissile material than light water coolant (H₂O), however, in case of MOX fuel, it shows the opposite trend for heavy water coolant than light water coolant. In case of thorium cycle, it requires more fissile material of U-233 for heavy water coolant than light water coolant, which is similar to UOX fuel case. In term of light water case, the required fissile material of U-233 is less for thorium case in comparing with the required fissile material of U-235 in MOX fuel case. Fuel conversion ratio of light water and heavy water coolants for UOX and MOX fuel cycles are less than unity except for heavy water coolant of MOX fuel case, which obtains slightly more than unity or becomes a fuel breeding condition. Thorium fuel shows better fuel breeding capability than MOX and UOX fuel cases. Heavy water coolant gives more fuel conversion capability and it obtains breeding condition than light water coolant. Actinide compositions other than uranium are obtained less, which gives less than 1 % of fuel composition, except for plutonium which gives more than 1% for light water coolant and more than 10% for heavy water coolant case. Different coolants are effective to produce more actinides such as plutonium and Americium, however its very limited change for Neptunium and Curium for MOX fuel case. For different fuel scheme cases, it shows that plutonium recycled scheme as MOX fuel case gives higher production of actinide or trans-uranium actinides from neptunium up to Curium than UOX fuel case for H₂O coolant. Total even mass plutonium isotope produces more composition than total odd mass plutonium isotope for both coolants and it is obtained more for heavy water coolant than its production for light water coolant. Higher composition of even mass plutonium gives an indication of the composition of plutonium has better proliferation resistant level for the system, which is shown by plutonium recycled scheme and heavy water coolant case.

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