Comparative Analysis on Fuel Breeding for Less Moderation Ratio of Water Cooled Reactor

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Abstract. Nuclear fuel breeding aspect of water-cooled reactor become one of the important issues to extend the sustainability aspect of nuclear fuel in line with fast breeder reactor program with closed fuel cycle concept. In the present study, nuclear fuel sustainability aspect of conversion ratio, several fuel-recycling schemes, nuclear fuel composition and isotopic plutonium composition have been evaluated based on a water-cooled reactor of light water (H₂O) and heavy water (D₂O) as coolants for less ratio of moderator to fuel (MFR). Less fissile content is required for plutonium (Pu) recycling scheme than once through scheme for both coolant types and it requires more fissile content for heavy water coolant (D₂O) of U-235 than light water coolant for both fuel cycle schemes. Plutonium recycling scheme obtains higher fuel conversion ratio than once through for both coolant types and more fuel conversion ratio is shown by heavy water coolant than light water coolant. It shows near fuel breeding can be obtained by light water coolant and breeder reactor capability can be obtained by heavy water coolant. Higher composition of trans-uranium including plutonium and minor actinides (MA) are shown by plutonium recycling case and heavy water coolant, which is estimated that can contribute to have more fuel-breeding capability. Composition of plutonium and americium increases significantly for heavy water coolant, while neptunium and curium compositions are almost the same for both coolants. Plutonium recycling scheme and heavy water coolant produces more even mass plutonium isotopes such Pu-238, Pu-240 and Pu-242 as fertile material, which can be estimated to give better fuel breeding capability and higher level proliferation resistant.

1. Introduction
World sustainable development without any greenhouse effect to the environment especially for the world energy demand has been fulfilled by nuclear energy over than 50 years period especially for developed countries. Several decades, many developing countries are also planning or show their interest to run their nuclear power program in order to meet their need of national energy demand. A capability to increase sustainability of nuclear fuel resource is essential to perform the sustainable development of the world. A similar trend can be fulfilled nuclear energy utilization with the renewable energies as a sustainable energy source by breeder reactor program and fusion reactor [1]. Nuclear reactor utilization have been improved to increases the innovative reactor design to fulfill the requirement of advanced nuclear technologies such as developing a small power reactor and for extending reactor operation for long-live reactor operation, which can be used remote and less population area as well as for area, which has less transmission or grid. In term of nuclear fuel resources, utilization of uranium, as well as developing and utilizing thorium fuel resources as a “partner” fuel with uranium fuel can be optimized. Thorium breeder reactor programs had been promoted in the past and some research activities have been done to meet the global nuclear energy...
contribution as well as Uranium fuel technology. The better performance of thorium is estimated coming from the higher eta-value of fissile U-233 in thermal and epi-thermal energy regions, which gives some advantages such as better breeding capability and better fuel stability as well as better proliferation resistance level in comparison to uranium cycle [2-6]. The utilization of commercialized light water reactor (LWR) through enormous operation experiences indicates that such water plant technology is reliable and acceptable for both public concern and utilities of nuclear power plant. In the present study, fuel-breeding ratio as fuel sustainability aspect of nuclear fuel will be analysed based on a water-cooled reactor. Fuel cycle evaluation will be based on uranium and plutonium fuels as supply fuels with light water (H₂O) and heavy water (D₂O) as coolants. A ratio of moderator to fuel (MFR) is used to be less in comparing to current LWR MFR value, in order to increase fuel-breeding capability because of harder spectrum by reducing ratio of moderation to fuel.

2. Analysis Method

Some basic parameters for employed reactor design are shown in Table 1. Less moderation ratio is used, which is set into 1.0 as half of current MFR of LWR and employed discharged fuel burn-up is examined by adjusting fuel discharge rate in the equilibrium fuel composition calculation for about 36 GWd/t which is same level with LWR design. An equilibrium burn-up calculation code with some iterative analysis (Equilibrium Cell Iterative Calculation System: ECICS) is used for various fuel cell designs and burn-up conditions [2,7-15]. About 1238 fission products and 129 heavy nuclides have been used in this equilibrium burn-up calculation code. It codes is coupled with the PIJ cell calculation module of SRAC [16] and it used JENDL3.2 as nuclear data library [17]. Those equilibrium burnup methods has been used also for evaluating thorium fuel cycle performance in water cooled reactor system [18-20]

| Table 1 Parameters             | 3000  | H₂O and D₂O |
|-------------------------------|-------|-------------|
| Thermal Power Output [MWt]    |       |             |
| Coolant                       |       |             |
| Fuel cycle option             |       |             |
| Zirconoy-4                    |       |             |
| Cladding                      | 0.8   |             |
| Fuel pellet diameter [cm]     | 280   |             |
| Averaged pellet power density [W/cc] | 1.0  |             |
| Moderator to fuel ratio (MFR) [\text{-}] | 36   |             |
| Burn-up [GWd/t]               |       |             |

One of the important aspects of nuclear sustainability of the reactor is capability of fuel conversion process from fertile materials into fissile materials. Conversion ratio definition is based on the reaction rate of fissile and fertile nuclides and some contribution of intermediate nuclides. For parametric survey analysis, the obtained value of the conversion ratios is evaluated by using the equilibrium atom composition. This equation is employed based on the fertile and fissile nuclides with the contribution from intermediate nuclides. This fuel conversion process shows the reactor has a capability to produce fissile material during reactor operation, which can be used for the next reactor operation through fuel recycling process. Fuel conversion process can be defined also as a fuel conversion ratio, which can be shown as a gain of conversion process during reactor operation. A ratio of fuel conversion process obtains higher than unity can be defined as fuel breeding process.

In addition, to evaluate the fuel behavior in the reactor in equilibrium condition, heavy nuclide compositions are evaluated. This fuel behavior will affect to the reactor performances and to estimate the fuel management of nuclear waste composition and recycled fuel utilization. Those heavy metal is used as main fuel composition such as uranium (U), neptunium (Np), plutonium (Pu), americium (Am) and Curium (Cm). As main heavy metal it is used U and Pu as major actinide as well as minor actinide (MA) such as Np, Am and Cm. Moreover, some compositions of isotopic plutonium are evaluated to estimate its contribution to the total plutonium elements. Changing composition in isotopic plutonium level is also evaluated as fuel conversion and transmutation processes as well as isotopic plutonium barrier analysis for proliferation resistance aspect.
3. Results and Discussions
In this section, it will be presented and discussed some results and analysis, which is based on required fissile content, fuel breeding aspect, heavy metal fuel composition as well as isotopic plutonium compositions. In the present study, required fuel content which is based fissile content to maintain reactor criticality, fuel-breeding ratio as fuel sustainability aspect of nuclear fuel will be analysed based on a water-cooled reactor of light water (H₂O) and heavy water (D₂O) as coolants. Fuel cycle evaluation will be based on uranium and plutonium fuels as supply fuels by adopting less ratio of moderator to fuel (MFR) to increase fuel-breeding capability because of harder spectrum by reducing ratio of moderation to fuel.

![Figure 1 Required Fissile Content U-235 for different coolant types](image1.png)

![Figure 2 Fuel Conversion Ratio for different coolant types](image2.png)

3.1 Required Fissile Content
Evaluation of reactor criticality as a factor of reactor operation from fission reaction should be maintained carefully to achieve the reactor critical condition are more than unity in order to keep the reactor operation. To maintain the reactor critical from fission reaction, the reactor requires some of fissile contents that make the fission reactions occur and maintain the chain reaction for criticality condition. Some composition of fissile for criticality condition is defined as required fissile content. Obtained results of required fissile contents of U-235 are shown in Figure 1 for different coolants of light water (H₂O) and heavy water coolant (D₂O). The results show that plutonium (Pu) recycling scheme gives less required fissile content in comparing with once through fuel process or both coolant types. Less required fissile content is estimated from the contribution of addition fissile material of plutonium when those plutonium are recycled into the reactor. Additional fissile plutonium as fissile material content will support the required fissile material of U-235 as supply fuel. While once through schemes, there is no additional fissile content from recycled material, therefore, it requires only from U-235. Heavy water coolant (D₂O) shows higher required fissile content of U-235 than light water coolant for both fuel cycle schemes. This condition can be estimated that to achieve a criticality condition of the reactor by using heavy water coolant (D₂O), the reactor need more fissile content due to harder spectrum of the reactor which is requires more fissile content to achieve criticality condition through fission reaction process of fissile materials. In can be estimated that more plutonium are recycled will requires less supply fissile content of U-235 and when the reactor uses a heavy water as coolant, it will requires more fissile content to run the reactor in operation.
3.2 Nuclear Fuel Conversion Ratio

One of the important aspects of nuclear sustainability of the reactor is capability of fuel conversion process from fertile materials into fissile materials. This fuel conversion process shows the reactor has a capability to produce fissile material during reactor operation, which can be used for the next reactor operation through fuel recycling process. Fuel conversion process can be defined also as a fuel conversion ratio, which can be shown as a gain of conversion process during reactor operation. A ratio of fuel conversion process obtains higher than unity can be defined as fuel breeding process, which has fuel-breeding gain. When the reactor achieves a fuel breeding condition, it can be estimated that the reactor has a capability becomes a breeder reactor. Obtained fuel conversion ratio in the system is shown in Figure 2 for different coolants and fuel cycle schemes. It shows that fuel conversion process of plutonium recycle schemes obtains higher conversion ratio for both coolant types. Through recycling process of plutonium, it affects to increase a significant value of fuel conversion ratio in comparing to once through fuel process. Heavy water coolant gives better conversion ratio of plutonium recycle scheme in comparing with light water coolant, however for once through case its conversion ratio becomes less. Fissile plutonium content in recycling process gives more contribution to increase fuel conversion capability of heavy water in plutonium recycling process, however for once through case; there is no contribution from plutonium as fissile content. In term of plutonium recycle schemes, it shows high conversion ratio for light water coolant which reaches about 0.9 conversion ratio, and it reaches better conversion ratio for heavy water coolant case. It show heavy water coolant obtain breeding process that show conversion ratio higher than unity. It is estimated that heavy water coolant has capability to obtain breeder reactor when the plutonium recycle scheme is used for maintained the reactor in operation.

3.3 Composition of Heavy Nuclide

Heavy nuclide compositions are important to be evaluated to estimate fuel behaviour condition, which affect to the reactor performances as well as to estimate the nuclear waste composition and potential heavy nuclide which can be used as recycled fuel. Obtained compositions of heavy nuclides are shown in Figures 3 and 4 for different recycle fuel schemes and coolant types. Uranium gives the higher composition as main composition, and it is followed by plutonium and some other minor actinides (MA). Plutonium obtains higher than 1% composition in all recycling schemes and water coolant cases. In general, trans-uranium composition is higher for plutonium recycling case than once through case. Similar condition is shown by heavy water coolant that higher trans-uranium composition is obtained in comparing with light water coolant. Other minor actinide compositions are less than 1% composition, while plutonium composition can reach more than 10% for heavy water coolant. It is shown that more MA will be produced when plutonium is recycled and in the same time, more plutonium will be produced to increase fuel-breeding capability as shown in the previous section of

![Figure 3](image1.png)  
**Figure 3** Nuclide composition for different recycle schemes

![Figure 4](image2.png)  
**Figure 4** Nuclide composition for different coolant types
fuel conversion ratio. In term of individual MA of neptunium and curium, both compositions are almost same for heavy water and light water coolants, while plutonium and americium have a significant increase of composition for heavy water coolant.

![Figure 5 Plutonium isotopic compositions for different fuel cycle schemes](image1)

![Figure 6 Plutonium isotopic compositions for different coolant types](image2)

3.4 Isotopic Plutonium Composition
Composition of plutonium in isotopic composition level is evaluated to estimate the isotopic plutonium composition contribution to the total plutonium element composition as well as to analyse the changing composition in isotopic plutonium level for fuel conversion process or transmutation process and isotopic plutonium barrier analysis for proliferation resistance aspect. Obtained results of isotopic plutonium compositions are shown in Figure 5 and 6 for different fuel cycle schemes and different coolant types. It is shown that each plutonium isotope has its own composition, which is depending on fuel cycle schemes and coolants. Main plutonium is obtained by isotopic plutonium of Pu-239, followed by Pu-240 and other isotopes. Higher Pu-239 is estimated from fuel conversion process from U-238 by capturing neutron process through U-239, Np-239 and decay to Pu-239. Some other plutonium isotopes are produced by this Pu-239 production through capturing neutron as main producer. Plutonium recycling scheme is effective to increase the plutonium isotopes composition except for Pu-239, which is less production in comparing to once through scheme. A significant increase of isotopic composition is shown by Pu-238 and Pu-242. In these plutonium isotopes, it can be defined as two group compositions such as even mass plutonium and odd mass plutonium compositions. Odd mass plutonium is mainly can be identify as fissile material composition of plutonium or it can be defined as plutonium quality. This plutonium quality is the quality that shows a material has good enough for criticality of fissile material for reactor purposes or explosive devices. Those odd mass plutonium isotopes are Pu-239 and Pu-241. Even mass plutonium is used to control the composition of odd mass plutonium, which as mainly less criticality performance that fissile material as well as barrier isotopic level for nuclear non-proliferation analysis. Those even mass plutonium isotopes are Pu-238, Pu-240 and Pu-242, which can be also as fertile material which produces Pu-239 from Pu-238 after neutron capture process and Pu-241 from capturing neutron of Pu-240. Higher even mass plutonium compositions are obtained; higher level proliferation resistant can be achieved. The figure shows that even mass plutonium as summation of all even mass plutonium are obtained higher than odd mass plutonium for both light water and heavy water coolants. Heavy water coolant gives higher even mass plutonium and less odd mass plutonium than light water coolant.
4. Conclusion

Fuel sustainability aspect of nuclear fuel, fuel-recycling schemes, fuel behaviour composition and isotopic plutonium composition have been analysed based on a water-cooled reactor of light water (H$_2$O) and heavy water (D$_2$O) as coolants for less ratio of moderator to fuel (MFR). Plutonium (Pu) recycling scheme requires less fissile material content than once through fuel scheme for both coolant types as well as heavy water coolant (D2O) requires more fissile content of U-235 than light water coolant for both fuel cycle schemes. Higher fuel conversion ratio can be obtained by plutonium recycle schemes than once through for both coolant types and it shows that heavy water coolant gives better conversion ratio than light water coolant. It shows high conversion ratio can be obtained by light water coolant and it shows heavy water coolant has capability to obtain breeder reactor. Transuranium composition is higher for plutonium recycling case and heavy water coolant such as more MA production and more plutonium production is estimated to have more fuel-breeding capability. Neptunium and curium compositions are almost the same for both coolants, while plutonium and americium have a significant increase of composition for heavy water coolant. More even mass plutonium isotopes such Pu-238, Pu-240 and Pu-242 are obtained for plutonium recycling scheme, which can be also as fertile material to increase fuel breeding capability and to obtain higher level proliferation resistant. Heavy water coolant gives higher even mass plutonium and less odd mass plutonium than light water coolant.

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