Fuel Breeding Analysis On Low Moderated Fuel Ratio Based On Actinides Closed Water-Cooled Thorium Reactor

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Abstract. Utilization of spent nuclear fuel and some fuel breeding capabilities of nuclear fuels to extend the sustainability aspect of nuclear fuel become more important issues to be optimized. Thorium fuel utilization based on water-cooled reactor is one of the possible options to be used and optimized as well as uranium fuel utilization. Some schemes of accumulated spent nuclear fuels can be used as recycled fuel in water-cooled reactor based on thorium fuel. In the present analysis, fuel sustainability aspect of nuclear fuel will be evaluated, which is based on a water-cooled reactor. As a fuel basis, thorium is used with can be mixed with additional recycled spent nuclear fuels. Some minor actinides (MA) as recycled fuels are used as doping material to be loaded to the water cooled reactors with thorium fuel as fuel basis and heavy water as moderator and coolant. The evaluation has been made by adopting a computational simulation of an equilibrium burnup analysis method, which was coupled with cell calculation of computer code of SRAC with JENDL.32 as nuclear data library. Several survey parameters have been evaluated to evaluate some effect of MA doping rate, different moderation ratio and power density levels to the reactor performance including fuel-breeding capability and void reactivity coefficient. Effect of some actinide composition to fuel breeding capability as well as safety aspect, which is based on void reactivity coefficient have been investigated. Fuel breeding capability can be obtained by the present reactor systems; as well as negative void reactivity has been show for more moderator ratio and less power density. Low portion of moderation to fuel ratios (MFR) are used to have a better fuel breeding capability as well as some contribution from recycled fuel of minor actinides (MA) and less power density. A negative void reactivity can be obtained in this system and it becomes less negative for doping MA and more power density as well as a positive void reactivity coefficient value for much less moderation ratio.

1. Introduction
Sustainability aspect of nuclear energy is basically coming from the optimum fuel utilizations of existing nuclear fuel resources, nuclear fuel management of the reactor including fuel cycle program and fuel breeding program. Fuel optimization programs can be improved and those optimized system of nuclear sustainability shown a similar trend with the renewable energies as a sustainable energy source [1]. One of the important issues, which is corresponding to nuclear fuel cycle, is nuclear proliferation resistance issues. The issue comes from the production of good quality of weaponable grade of spent nuclear fuel such as plutonium. A reduction strategy of the proliferation resistance level, it has been introduced some barriers such as matrial 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 $^{238}$Pu, $^{240}$Pu and $^{242}$Pu and in case of thorium cycle will depend on $^{232}$U. For decades some thorium fuel technologies have being 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. Some key important parameters are evaluated such as doping composition of minor actinide (MA), volume ratio of moderator to fuel (MFR) and fuel cell power density which have some significant impact to the reactor performances such as criticality, fuel breeding ratio and void reactivity coefficient.

2. Parameter and Method

Analyses on nuclear fuel sustainability and void reactivity coefficient have been done based on heavy water as coolant and thorium as main fuel cycle. 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 using 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 material of minor actinide (MA) based on large 3000 MWt power output and heavy water as coolant and moderator. Employed MFR of 0.3 as very low moderation ratio and 1.0 as a moderate size for less moderation ratio 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) effect was used for comparative analysis, which is based on no MA doping and with about 1 % MA doping. A burnup of discharged fuel has been set to be 36 GWd/t as nearly a burnup level of standard LWR of PWR.

| Parameters                          | Values/Type          |
|-------------------------------------|----------------------|
| Thermal Power Output [MWt]          | 3000                 |
| Coolant                             | D₂O                  |
| Fuel Cycle Option                   | Actinides closed Cycle |
| Supply Fuel Composition             | Th + MA (Doping)     |
| Cladding                            | Zircaloy-4           |
| Fuel pellet diameter [cm]           | 1.31                 |
| Fuel pin outer diameter [cm]        | 1.45                 |
| Moderator to Fuel Ratio (MFR) [ - ] | 0.3 and 1.0          |
| Fuel Power Density [W/cc]           | 140 and 280          |
| Burn-up [GWd/t]                     | 36                   |
| MA Content [%]                      | 0 and 1              |

A regular blanket fuel diameter of the Shippingport of about 1.452 cm was used as fuel pin diameter based as a basic fuel parameter size [2,6-7]. A system for fuel cycle scheme has been used as a closed fuel cycle that all actinides are returned to the reactor. While only fission product (FPs) are sent into final disposal stream. The reactor will kept the heavy metal inside the core as all heavy metal closed cycle scheme concept. To evaluate fuel sustainability based on fuel conversion or fuel breeding capability of the reactors as well void reactivity coefficient, an iterative equilibrium method of burn-up calculation code (Equilibrium Cell Iterative Calculation System: ECICS) was used. The code was coupled by 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. A void reactivity coefficient was used also to evaluate the reactor criticality safety in case some voided condition of coolant are occur and affect to the criticality condition.

3. Results and Discussions

3.1. MA Doping effect to fuel breeding capability

As mentioned in the previous section, the effect of MA material, which is loaded into the reactor, will be analysed. It used a comparative doping rate for non-doping MA case and for MA doping case of 1 % doping rate. The obtained results of the MA doping effect to the fuel conversion capability in the reactor as well as breeding gain are shown in **figure 1 and 2**. All obtained results of fuel conversion capabilities for both non-MA doping and MA doping cases are higher than unity. It means the reactor a fuel-breeding capability. Fuel breeding capabilities are becoming higher for doping material of MA as shown in figure 1. The result shows that MA doping can make the fuel breeding level increases during the reactor operation. It because of some additional fissile materials are produced from converted MA material during reactor operation. Obtained results to estimate the increase of some additional gain of fissile material of fuel breeding condition, it can be used a fuel breeding gain concept and the results are shown in **figure 2**. Fuel breeding of the reactor has some more than 1.16 % of breeding gain for non-doping MA case which means the Initial condition for thorium reactor without additional MA material as doping obtained higher than unity and it increases for MA doping case which is estimated of about 1.25 % of additional fissile materials were produced during reactor operation. Breeding gain can be achieved from some increasing fissile materials during reactor operation. These fissile materials are produced from conversion process from uranium to plutonium such as U-238 into Pu-239 and to other plutonium from capturing neutrons and also from conversion process of minor actinides (MA) into plutonium, which are mainly into even mass plutonium. These MA materials are estimated to be some fertile materials or intermediate materials from fertile to fissile after capturing neutrons.

![Figure 1](image1.png) **Figure 1** Fuel conversion ratio for Doping MA

![Figure 2](image2.png) **Figure 2** Fuel breeding gain for Doping MA

Some Doping MA materials are effective to increase plutonium production. 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. Those even mass plutoniums are estimated to gives
some contribution to better fuel breeding condition as well as a 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].

3.2. Effect of very less MFR effect to fuel breeding capability
One of the reasons to have better fuel breeding capability was the hardening neutron spectrum during reactor operation. When neutron spectrum becomes harder, the potential to increase fuel conversion from capturing neutron by fertile material into fissile material become well. More neutrons are captured by fertile materials when the spectrum faster or harder. It can be estimated, if the volume ratio of moderator to fuel becomes smaller, the spectrum becomes harder because of less capability of water to moderate the neutron spectrum of the reactor. To estimate the hardening spectrum effect to the fuel conversion process, some less Moderator to fuel ratio have been used for less MFR of 1.0 and very less MFR of 0.3. MFR of 1.0 is adopted to have less moderator capability of water, which is equal to a half moderator to fuel ratio (MFR) of standard PWR. In addition, MFR of 0.3 is used to estimate the moderator ability for very low level of capability as well as in term of geometrical effect of MFR. Obtained results of fuel conversion ratio and breeding gain have been shown in Figure 3 and 4 for different MFR values. All employed MFRs of 1.0 and 0.3 obtain more than unity which mean fuel-breeding capability is achieved for both MFRs. MFR of 1.0 give slightly more than unity and it increases with less MFR, which is shown by MFR of 0.3 that gives better fuel conversion capability, which is shown by Figure 3. In term of breeding gain or excess fuel breeding, MFR of 1.0 obtain about 2 % breeding gain and it becomes higher for MFR of 0.3 which produced almost 16% of breeding gain as shown in Figure 4. The results show that MFR of 0.1 gives a breeding capability and it will be better when the MFR is reduced. We can make the optimization for intender breeding gain, for example when we need a breeding gain of about 10 %, we can find a suitable MFR to be used for the reactor system as well as if we want to have a maximum MFR to be adopted to have a sustainable fuel breeding condition, which shows fuel breeding of about 1.0. Different MFR analysis gives a significant fuel breeding effect especially for less MFR condition. Less MFR give harder neutron spectrum and it will make the reactor more fuel breeding capability.

![Figure 3 Fuel conversion ratio for different MFR values.](image1)

![Figure 4 Fuel breeding gain for different MFR values.](image2)
3.3. Fuel cell power density effect to fuel breeding capability

Reactor power output and operation are basically one of the options which is contributed to an economical point of view which also relates to capability to burn or burnup level of fuel as well as the length of reactor operation. Fuel pin cell evaluation, which regards to power density of the fuel, has been evaluated to analyse these effect to the fuel breeding capability. Power density level will shows how effective the power is produced during operation and how many fuel are burnt during that process and what is the effect of power density level to the fuel breeding capability. Obtained results of power density effect to the fuel breeding capability and fuel breeding gain are shown in Figure 5 and 6 for different power density of 140 and 280 W/cc. It shows less power density gives better fuel conversion capability. Power density of fuel for 140 W/cc obtains breeding condition than power density of 280 W/cc which gives less than unity for fuel breeding ratio. Breeding gain of about 3% is given by power density of 140 W/cc and it becomes negative breeding gain for 280 W/cc which means breeding gain cannot be achieved because of fuel conversion ratio is less than unity. Less power density shows less power production is estimated to gives better fuel conversion capability while higher power density means more power production gives smaller fuel conversion ratio. It is because some fuels are converted to fissile material more for less burnt fuel to produce the power. It can be estimated to have a certain fuel power density to have some fuel breeding gain.

![Figure 5 Fuel conversion ratio for different fuel power density](attachment:conversion_ratio.png)

![Figure 6 Fuel breeding gain for different fuel power density](attachment:breeding_gain.png)

3.4. MA Doping effect to void reactivity coefficient

Different fuel loadings in the reactor will affects to reactor behaviour including reactivity coefficient in term of void condition as void reactivity coefficient. A comparative analysis has been done to evaluate the MA doping effect to the void reactivity coefficient behaviour. A non-doping MA case and 1% MA doping case are evaluated to estimate their effect. Obtained results of MA doping effect to void reactivity coefficient are shown in Figure 7. The figure shows all results give a negative value of void reactivity coefficient for both non-MA doping and MA doping cases. It shows MA doping case achieves less negative void reactivity coefficient than non-MA doping case. It is estimated that more MA material are inserted into the reactor will give the reactor more fission reaction when voided condition than non-MA doping case. Some converted materials into plutonium or trans-plutonium have some contributions to make less void coefficient.
As mentioned in the previous section, an effect of different moderation ratio was evaluated to the fuel conversion ratio condition. In this section, these MFR different effects will be evaluated to have some significant effect to void reactivity coefficient. Obtained results of MFR effect to void reactivity coefficient are shown in Figure 8 for MFR of 1.0 and MFR of 0.3. Void coefficient of both MFRs are totally different which shows a negative void coefficient value for MFR of 1.0 and a positive value of void coefficient for MFR of 0.3. MFR 1.0 obtains negative coefficient was estimated because of the neutron spectrum is still can be thermalized and some contribution of fissile material to make less criticality or less fission reaction in voided condition. While very low MFR of 0.3 gives less thermalization factor and harder spectrum is achieved as well as some fissile materials will have some more criticality or fission reaction during voided condition. It can be estimated in certain MFR values a condition will have a threshold value for void reactivity coefficient to become positive or negative
values. A negative value of void reactivity coefficients is more preferable to be adopted instead of a positive value, because of some safety concern of criticality condition.

### 3.6. Fuel cell power density effect to void reactivity coefficient

In this section will be shown and discussed some void reactivity coefficient from different fuel power density in the fuel cell. Obtained results of power density differences to the void reactivity coefficient are shown in Figure 9. It shows that all power density conditions give a negative value of void coefficient. It shows less power density gives more negative void coefficient, while higher power density obtains less void coefficient. It is estimated that more power density obtains harder neutron spectrum and some produced fissile material will make more fission reaction when voided condition in comparing with less power density condition. More power density also can be estimated to be more power is produced that gives less void reactivity for more power reactor. More power reactor also can be used for more nuclear materials especially fissile material is burnt in the reactor.

### 4. Conclusions

Some nuclear fuel sustainability analyses have been done based on heavy water-cooled thorium reactor system and the fuel recycled composition which all actinide compositions except fission products are recycled into the reactor. Some key important parameters are evaluated such as doping composition of minor actinide (MA), volume ratio of moderator to fuel (MFR) and fuel cell power density which have some significant impact to the reactor performances such as criticality, fuel breeding ratio and void reactivity coefficient. As a fuel basis, thorium is used with can be mixed with additional recycled spent nuclear fuels. Some minor actinides (MA) as recycled fuels are used as doping material to be loaded to the water cooled reactors with thorium fuel as fuel basis and heavy water as moderator and coolant. Effect of some actinide composition to fuel breeding capability as well as safety aspect, which is based on void reactivity coefficient have been investigated. Fuel breeding capability can be obtained by the present reactor systems; as well as negative void reactivity has been show for more moderator ratio and less power density. Low portion of moderation to fuel ratios (MFR) are used to have a better fuel breeding capability as well as some from contribution from recycled fuel of minor actinides (MA) and less power density. A negative void reactivity can be obtained in this system and it becomes less negative for doping MA and more power density as well as a positive value of void coefficient for much less moderation ratio.

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