Thorium Fuel Utilization Analysis on Small Long Life Reactor for Different Coolant Types

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Abstract. A small power reactor and long operation which can be deployed for less population and remote area has been proposed by the IAEA as a small and medium reactor (SMR) program. Beside uranium utilization, it can be used also thorium fuel resources for SMR as a part of optimalization of nuclear fuel as a “partner” fuel with uranium fuel. A small long-life reactor based on thorium fuel cycle for several reactor coolant types and several power output has been evaluated in the present study for 10 years period of reactor operation. Several key parameters are used to evaluate its effect to the reactor performances such as reactor criticality, excess reactivity, reactor burnup achievement and power density profile. Water-cooled types give higher criticality than liquid metal coolants. Liquid metal coolant for fast reactor system gives less criticality especially at beginning of cycle (BOC), which shows liquid metal coolant system obtains almost stable criticality condition. Liquid metal coolants are relatively less excess reactivity to maintain longer reactor operation than water coolants. In addition, liquid metal coolant gives higher achievable burnup than water coolant types as well as higher power density for liquid metal coolants.

1. Introduction

Nuclear reactor utilization have been improvised to increases their reactor fuel capability for decades and one of the innovative reactor design to fulfill the requirement is reactor type for small power reactor and for long operation which can be deployed for small population densities and remote area as well as less transmission or grid. Long life reactor operation have been proposed by the IAEA as SMR program for a small and medium reactor to be used for some specific purposes which is basically based on thermal reactor and fast reactor types [1]. Beside uranium utilization, thorium fuel resources for SMR can be used as a “partner” fuel with uranium fuel. Thorium fuel technology has being developed well not only for conventional reactor but also provided the thorium breeder reactor programs to meet the global nuclear energy contribution as well as Uranium fuel technology. Better capability of thorium fuel is mainly coming from the superiority of fissile U-233 which shows higher eta-value in comparing with other fissile materials such as U-235 and Pu-239, except for higher energy regions, Pu-239 becomes more superior than others although U-233 still shows high eta-value. In addition, some advantages of thorium are estimated such as better breeding capability in thermal and epi-thermal neutron energy region, better fuel stability and better proliferation resistance level in comparison to uranium cycle [2-6]. Plutonium production in the spent fuel based on thorium fuel is very small compared with uranium fuel cycle, because of its nuclide chain, that affect to very low plutonium production as well as very low MA production as long-lived heavy nuclides. A comparative analysis on small long life reactor based on thorium fuel cycle for several reactor coolant types and several power output has been evaluated. In addition, several key parameters are analysed to evaluate
its effect to the reactor performance such as reactor criticality, excess reactivity, reactor burnup achievement and power density profile.

Table 1 General Parameters

| Parameters                  | Values/Type                   |
|-----------------------------|-------------------------------|
| Thermal Power Output [MWt]  | 100 - 500                     |
| Coolant                     | H2O, D2O, Na and Pb-Bi        |
| Fuel                        | Oxide Type                    |
| Blanket                     | Nat Thorium                  |
| Core                        | U233-Th                       |
| Fuel Pellet Radius [cm]     | 0.6                           |
| Volume Fraction             | 45 / 15 / 40                  |
| (Fuel/Clad/Cool) [%]        |                               |
| Core Operation Time [Years] | 10                            |

2. Methods and Parameters

To maintain the reactor criticality condition, some approaches have been done such as reactor size as geometrical reactor core approach, required fissile material and fuel cycle types as well as coolant types. Active core arrangement and fuel shuffling and refuelling schemes are also would be optimized for reactor operation, especially for long-life reactor core operation. One of the efficient and effective reactor operations is by adopting longer reactor operation with one batch fuel system, which can be called as a long-life reactor operation without any refuelling and shuffling processes [7-9]. The idea for designing a long-life reactor core operation for different reactor coolant types which based on water-cooled liquid metal cooled types as well as for several power reactor output. General parameters are shown in Table 1 as a basic reactor design parameters. Small power outputs of 100 to 500 MWt are adopted as small reactor power types based on the IAEA definition.

The reactor system are based on thorium oxide fuel for different coolant types such as light water and heavy water coolants as representative of thermal reactor coolant types or water-cooled type as well as for liquid metal-cooled reactor types, it has been used some coolants such as sodium-cooled and lead-bismuth-cooled as coolant. Natural thorium is loaded into blanket regions and some required fissile content of U-233 and thorium are loaded into core regions as driver fuel regions. To analyse the reactor core optimization, an established code of SRAC-CITATION and JENDL-33 have been used for core optimization analysis and nuclear data library for two-dimensional core arrangement of radial and axial directions (R-Z) [10]. Reactor operation period is arranged to be 10 years as long-life reactor core operation. Adopting sufficient inner blanket region as well as core fuel regions in order to increase inner fuel conversion capability has done maintaining the reactor criticality condition for long-life core operation. Excess reactivity is used to analyse the surplus or additional neutron production during reactor operation, which related to reactor criticality. This neutron excess or excess reactivity can be used as one of the safety parameter for reactor operation which is considering the criticality safety point of view. Burnup level has been evaluated to estimate the reactor capability to burn the fissile material which can contribute to the reactor operation as well as reactor power production during operation period.

3. Results and Discussions

In the present study, small power output of nuclear reactor with several coolant materials are evaluated based on thorium fuel with some additional fissile material of U-233 in the core regions as driver fuel for long-life reactor operation for about 10 year reactor operation. In this section, some important parameters are shown and discussed such as reactor criticality, excess reactivity, burnup level and power density for different coolant types and several power output levels.
3.1. Reactor criticality

As a basic nuclear reactor analysis for the operation, the evaluation of reactor criticality becomes a key factor and it should be maintain more than unity to keep the reactor in operation. The study intend to maintain the reactor operation up to 10 years period which means the reactor should be maintain to be critical condition during intended period of 10 years operation without any refuelling and shuffling processes. Some basic approaches have been done for obtaining the reactor to be in a critical condition such geometrical arrangement and fuel type optimizations as well as fuel content optimization. Several coolants have been adopted for the evaluation based on different typical reactor that are exist and in operation for research and commercial reactor facilities which is generally divided into two general reactor types that is thermal reactor and fast reactor types. Typical coolant types of thermal reactors are light water (H2O coolant) and heavy water (D2O) coolants. Liquid sodium or sodium and liquid Pb-Bi coolants are adopted for typical fast reactor types.

Figure 1 Reactor criticality for different coolant types
BOC : Beginning of cycle (0 year)
MOC: Middle of cycle (5 years)
EOC : End of cycle (10 years)

Obtained results of reactor criticality are shown in Figures 1 and 2 for different coolant types and power reactor outputs. Several coolant types have been employed as well as some different power outputs for the evaluation to analyse its effect to the reactor criticality condition during reactor operation. Figure 1 shows all reactor systems based on different coolant types obtain reactor operation for 10 year operation times which shows reactor criticality are always higher than unity. Light water coolant obtains higher criticality condition from the beginning of operation in comparison to other coolants. Water coolant types gives higher criticality than liquid metal coolants (Liquid sodium and liquid Pb-Bi coolants) at BOC and MOC, while at the end of operation or EOC almost all coolants obtain same level of criticality. Liquid metal coolant of coolant for fast reactor system gives less criticality at the BOC and increases at the MOC and it reduces for EOC. This condition shows that fast reactor system or liquid metal coolant system obtain almost stable criticality condition since the beginning of cycle and small increases at MOC. While water cooled types (light water and heavy water coolants) are obtained high at BOC and it reduces with increasing the time. Different power outputs give some different criticality conditions are shown in Figure 2 for sodium coolant type. All power output can maintain its reactor operation up to 10 years period. Based on the obtained results shows that the highest criticality condition is expected coming from the highest power output, which is shown at MOC period.
3.2. Excess reactivity

Criticality condition is not only used as reactor operation condition, but also to evaluate the safety condition based on excess reactivity from criticality of the reactors. Excess reactivity is defined as some surplus neutron population or criticality that exceed more than unity. This excess criticality will be used to estimate the safety from criticality point of view. Less excess reactivity or in ideal condition when the criticality reaches to a unity is the best condition. When abnormality condition occurs, some control rod should be used to compensate the excess criticality to push the reactor sub critical and if the excess reactivity is less, then it is easier to make the reactor shutdown and less control rod action. Less excess reactivity is also estimated the reactor stability from neutron population during reactor operation. Obtained results of excess reactivity are shown in Figures 3 and 4 for different coolant types and power reactor outputs.

![Figure 3 Excess reactivity for different coolant types](image3)

![Figure 4 Excess reactivity for different power outputs](image4)

![Figure 5 Average burnup for different coolant types](image5)

![Figure 6 Average burnup for different power outputs](image6)
Figure shows that larger excess reactivity are obtained by water cooled type (H2O and D2O coolants) and liquid metals coolant types (Na and Pb-Bi coolants) are obtained less. Higher excess reactivity of water-cooled type is estimated from the BOC period that more neutron populations are needed to maintain the reactor operation along 10 years periods. This reactivity condition is a typical type of water-cooled reactor for long-life operation. In case of liquid metal coolant, which is working as coolant for fast reactor system are relatively less excess reactivity to maintain longer reactor operation period for both sodium and Pb-Bi coolants. This condition can be estimated from the neutron spectrum characteristic that liquid metal has harder spectrum with relatively higher fissile content in core region. While blanket region can maintain internal fuel conversion by capturing produced neutron from core regions, which affects to a reduction factor of neutron population. At the same time some converted fertile materials in the blanket regions becomes fissile materials, which can be used for reactor operation longer. In case of water-cooled reactor, blanket regions does not significantly absorb the neutron from core regions and slowly reduce the excess reactivity at the BOC and gradually criticality reduces because of fissile material are reduces from caused by fission reaction. In case of different power output, it shows that higher power output obtains higher excess reactivity, which is shown at MOC period of operation. Based on the obtained results, it gives the excess reactivity less than 12% for water-cooled coolant types (H2O and D2O coolants) and less than 1.5% for liquid metal coolant types (Na and Pb-Bi coolants)

3.3. Reactor burnup

Obtained results based on the analyses of the different coolant and power output effects to the reactor burnup are shown in Figures 5 and 6. Liquid metal coolant gives higher achievable burnup than water coolant types which obtains higher than 60 GWd/t and more than 80 GWd/t along 10 years operation period for liquid sodium and liquid Pb-Bi coolants, respectively. While water coolant type obtains less than 60 GWd/t of reactor burnup for 10 years operation period. This phenomenon can be estimated from the neutron spectrum point of view that harder neutron spectrum work better to make more fission reaction which means more fuel material in the reactors are burnt during reactor operation for the same period of time. Liquid Pb-Bi gives harder spectrum than liquid sodium and those liquid metal coolants are relatively harder in term of neutron spectrum. Higher power output gives better burnup value, and it shows a gradual trend of increasing burnup, which is depending on the increase of reactor power. More power reactor output means the reactor produces more power from fission reaction in the reactor cores and more fission reactor affects to the increasing burnup.

![Figure 7 Maximum Power Density for different coolant types](image)
3.4. Reactor power density
To evaluate the performance of reactor power density, a maximum power density value is adopted to show the optimum power density is produced during reactor operation. Obtained results of the study are shown in Figure 7 for different coolant cases. It shows that the highest maximum power density is obtained by liquid Pb-Bi coolant followed by liquid sodium coolant and water coolant types. In General, power density profile is decreasing for longer reactor operation which is shown in the results, except for liquid Pb-Bi which shows some increasing power at the EOC than MOC, although it still less than BOC. Liquid metal obtains higher maximum power density than water coolants. This condition is estimated from the capability to make more fission reaction in the reactor, which can produce more power output as well as power density during reactor operation.

4. Conclusions
A small long-life reactor based on thorium fuel cycle for several reactor coolant types and several power output has been evaluated in the present study. Several key parameters are used to evaluate its effect to the reactor performances such as reactor criticality, excess reactivity, reactor burnup achievement and power density profile. An established code of SRAC-CITATION and JENDL-33 as nuclear data library have been used for core optimization analysis based on two dimensional reactor core arrangement of radial and axial directions (R-Z) for 10 years period of reactor operation period is arranged to be 10 years. Water-cooled types give higher criticality than liquid metal coolants (Liquid sodium and liquid Pb-Bi coolants). Liquid metal coolant of coolant for fast reactor system gives less criticality especially at BOC and increases in small changing, which shows that fast reactor system or liquid metal coolant system obtain almost stable criticality condition. Larger excess reactivity is obtained by water-cooled type (H2O and D2O coolants) than liquid metals coolant types (Na dan Pb-Bi coolants). This reactivity condition is a typical type of water-cooled reactor for long-life operation. In the case of liquid metal coolant for fast reactor system are relatively less excess reactivity to maintain longer reactor operation period for both sodium and Pb-Bi coolants. In addition, liquid metal coolant gives higher achievable burnup than water coolant types as well as higher power density for liquid metal coolants.

Acknowledgments
We would like to acknowledge and extend our gratitude to desentralisasi research program of ministry of research, technology and higher education and the Asahi foundation for the grant and international conference publication

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