Homogenous (Th,Pu)O$_2$ Fuel Utilization on High Temperature Test Reactor 30MWt

Anni Nuril Hidayati$^1$, Abdul Waris$^{2*}$, Dwi Irwanto$^2$, and Asril Pramutadi$^2$

$^1$Department of Physics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesa 10 Bandung 40132, Indonesia
$^2$Nuclear Physics & Biophysics Research Division, Department of Physics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jl. Ganesa 10 Bandung 40132, Indonesia

*awaris@fi.itb.ac.id

Abstract. HTTR (High Temperature Test Reactor) is one of the Generation IV nuclear reactor that has been built in Japan. This study will discuss about several neutronic aspect on HTTR 30 MWt such as effective multiplication factor (k-eff) whole of active core, conversion ratio, spectrum of neutrons and the power distribution of the reactor core at the beginning and at the end of the period by using homogenous (Th,Pu)O$_2$ fuel assembly. 3D triangular geometrical type of active core has been selected for neutronic calculation by using SRAC2006 code with nuclear data bases JENDL4.0 which is developed by JAERI. The results shows that core optimum when (Th,Pu)O$_2$ with PuO$_2$ fraction is 6.7% and will give the optimum k-eff during the operation time. The spectrum neutron result shows that (Th,Pu)O$_2$ is dominant at fast energy. The power distribution results show that it can be stable for long operation period, both at beginning of life (BOL) and end of life (EOL).

Keywords: HTTR, (Th,Pu)O$_2$, SRAC 2006, JENDL 4.0

1. Introduction
The high temperature gas-cooled reactor (HTGR) is one of the Generation IV of nuclear power reactors that has the capability of producing high temperature heat up to 1000°C. HTGRs have been developed and operated in several countries [1]. Japan Atomic Energy Research (JAERI) has developed and operated the High Temperature Test Reactor (HTTR) that is one of HTGR type of reactor since 1998 [2, 3]. The purpose of HTTR development is to enlarge the nuclear energy utilization to many fields such as water desalination and hydrogen production for the future energy source. In general, both HTGR and HTTR have inherent safety features with more economic advantages [1].

Various test data of the HTTR such as neutronic analysis and thermal hydraulics properties give some benefits for HTGR technology establishment in the future. The HTTR’s first loading fuel was uranium oxide (UO$_2$) in 1998 and achieved the flattening power reactor by optimizing the specifications of the burnable poisons. Also other evaluation which relates with fuel performance on fission product release and degradation of the coating layers to contain the fission products and other aspect including residual heat removal system. All those evaluations were done by using experimental
data for validation of computational data result [3]. Other recently work is an analysis of HTTR neutronic performance through several nuclear data such as JENDL3.3, JENDL4.0, JEFF3.1, with enriched uranium oxide fuel assembly [4]. This paper discusses about the preliminary study on neutronic aspects of HTTR 30MWt with (Th, Pu)O$_2$ fuel type in homogeneous composition. Study on thorium utilization in nuclear reactors become very interesting since it has 3-4 times more abundance and produce less nuclear high level wastes compared to uranium fuel [5, 6].

2. Design and Methodology

In this study, several neutronic aspects of (Th, Pu)O$_2$ homogeneous fuel of HTTR 30 MWt such as multiplication factor, conversion ratio, active core power distribution and neutron spectrum have been evaluated. PuO2 has been utilized for starting the reactor since Thorium (Th) is not a fissile material. 3D triangular (XYZ) geometrical type of active core has been selected for neutronic calculation by using CITATION SRAC2006 code [7] with nuclear data library of JENDL 4.0 [8] which is developed by JAERI. For the neutronic calculation, it is needed to divide the active core into several grids. In this case it will be divided into 48 grids of X, 24 grids of Y and 7 layers for Z so that each fuel assembly will be divided into six grids.

General specifications of the HTTR are listed in table 1:

| Parameter                    | Specification |
|------------------------------|---------------|
| Thermal power                | 30MW          |
| Outlet coolant temperature   | 950°C         |
| Inlet coolant temperature    | 395°C         |
| Primer coolant pressure      | 4MPa          |
| Core structure               | Graphite      |
| Coolant material             | Helium        |
| Direction coolant flow       | Downward      |
| Equivalent core diameter     | 2.3m          |
| Active core height           | 2.9m          |
| Average power density        | 2.5 W/cm$^3$  |
| Burnup period                | 600 days      |
| Number of fuel blocks        | 150           |
| Number of fuel columns       | 30            |
| Number of pairs of CRs       |               |
| In core                      | 7             |
| In reflector                 | 9             |

The HTTR does not have a high output power and power density because it is a research and test reactor which classified as a research reactor or a zero power reactor. The reactor core consists hexagonal fuel blocks, replaceable reflector blocks and control rod guide blocks which has graphite as the material core support structure. Inside core, there are five layers (axial) of fuel assembly which originally consist of several enriched uranium oxide between 3%-9% [9]. Some fuel rods (30 or 33)
are attached in a fuel assembly with 360mm across flats and the height is 580mm. Each fuel rod consists of some compact cylinder that contains TRISO-coated fuel particles. In a TRISO particle there is a (Th,Pu)O$_2$ fuel kernel used in this calculation which is surrounded by triple-isotropic layer of carbon and silicon-carbide for preventing from chemical attack and deformation caused by heat. Mixing of (Th,Pu)O$_2$ in a fuel kernel consists of ThO$_2$ and PuO$_2$ itself and the percentage of PuO$_2$ has been treated as well as using UO$_2$ in the original design of HTTR [9] around 3.4% until 17%. Meanwhile the isotopes of Plutonium which are used: Pu-238, Pu-239, Pu-240, Pu-241, Pu-242 with each isotope has percentage different from other based on reactor grade plutonium data. B$_4$C/C was selected as a burnable poison for controlling neutron population in active core of HTTR [9] and keeps the power at a stable point.

Figure 1. Vertical cross-section of HTTR [9, 10].

Figure 1 shows that the active core of HTTR is surrounded by replaceable reflector in the bottom and top of it. Meanwhile each layer is surrounded by permanent reflector blocks. Also for the control rods must be designed for providing a reactor shutdown margin more than 0.01Δk/k. All of those systems are inside the reactor pressure vessel. Because of non-commercial reactor, HTTR must not release high power so that the maximum average burnup in a fuel element has to be below 33,000MWd/t [9].
Table 2. General Specification of HTTR [11]

| Isotope   | Percentage (%) |
|-----------|----------------|
| Pu-238    | 1.30           |
| Pu-239    | 60.30          |
| Pu-240    | 24.30          |
| Pu-241    | 9.10           |
| Pu-242    | 5.00           |

3. Result and Discussion

Figure 2 and 3 show the effective multiplication factor and conversion ratio for (Th,Pu)O$_2$ loaded fuel in 30MWt HTTR. At first, several parametric surveys have been done in the previous work. Fresh mixing fuel between ThO$_2$ and PuO$_2$ has been added in a fuel kernel with percentage of PuO$_2$ between 3.4%-17%. Other parameter that has been reviewed was percentage of natural Boron in B$_4$C/C. Natural B that has B-10 and B-11 is a neutron absorber that can absorb a lot of neutron in the beginning of reactor operation. Original HTTR used 2% and 2.5% of natural B and there was and impurity that has been added in the burnable poison at 37ppm of B so that overall the percentage of Carbon in a burnable poison between 97.5% until 98% [9]. Eventually, the population of neutron became less than at the first step of operation. Core 1h, 2h and 3h explain about PuO$_2$ percentage that being used in the active core calculation. Core 1h used 11.5% of PuO$_2$ and 2% natural B in burnable poison while Core 2h give the result when 7.9% PuO$_2$ was loaded into the core and the burnable poison has 2.5% of natural B. other result is Core 3h which has 6.7% of PuO$_2$ and used 2% natural B in burnable poison. Based on three results that are explained before, the most optimum result occurs when HTTR was loaded by 6.7% of PuO$_2$ for two year. This fact may due to the excess reactivity of reactor core is lower than others.

![Figure 2. Effective multiplication factor result of (Th,Pu)O$_2$ Homogenous fuel in HTTR](image1)

![Figure 3. Conversion Ratio result of (Th,Pu)O$_2$ Homogenous fuel in HTTR](image2)

After two years operations of HTTR, each kind of core give different result about conversion ratio. Higher the percentage of PuO$_2$ in kernel will give higher energy or power but less for producing other fissile material. So that, for Core 3h will give higher conversion ratio even though the excess reactivity is lowest. The neutron spectrums in the Figure 4 are showing the result that for every percentage of PuO$_2$ fewer than 20% will have fast-energy dominant energy. It because the eta value of Plutonium is higher in the fast-energy rather than in thermal energy. It is about 2.87 released neutrons/absorbed neutron in fast energy and for thermal and epithermal energy, each reaction with Plutonium can release 1.91 and 1.77 neutron [12]. Other result is power distribution in hot channel of HTTR active
core. Figure 5, 6 and 7 shows that there is no much different result from the Beginning of Life (BOL) and the End of Life (EOL). The stability of power in HTTR active ore could reach when all aspect get the optimal value. The average of power distribution is 2.18W/cm³.

![Graph showing neutron flux distribution](image1.png)

**Figure 4.** Neutron flux distribution of (Th,Pu)O₂ Homogenous fuel in HTTR

![Graph showing power distribution for grid X](image2.png)

**Figure 5.** Power distribution for hot channel of grid X in (Th,Pu)O₂ Homogenous fuel HTTR 6.7% of PuO₂

![Graph showing power distribution for grid Y](image3.png)

**Figure 6.** Power distribution for hot channel of grid Y in (Th,Pu)O₂ Homogenous fuel HTTR 6.7% of PuO₂
Figure 7. Power distribution for hot channel of grid Z in (Th,Pu)O$_2$ Homogenous fuel HTTR 6.7% of PuO$_2$

4. Conclusion
Several neutronic aspects of 30MWt HTTR using (Th,Pu)O$_2$ homogenous fuel arrangement for two years operation have been analysed with SRAC2006 and JENDL 4.0. The results shows that core optimum when (Th,Pu)O$_2$ with PuO$_2$ fraction is 6.7% and will give the optimum k-eff during the operation time. The spectrum neutron result shows that (Th,Pu)O$_2$ is dominant at fast energy. The power distribution results show that it can be stable for long operation period, both at Beginning of BOL and EOL. The average of power distribution is 2.18W/cm$^3$.

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