HTTR 30MWth Reactor with Homogenous (Th,U)O$_2$ Fuel

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Abstract. (Th,U)O$_2$ fuel has been utilized for neutronic analysis of HTTR 30 MWt which is a high-temperature test reactor with helium gas as a coolant that has been built in Japan. HTTR has a Triple-isotropic Coated Fuel Particle (TRISO CFP) type of fuel. Homogenous fuel of (Th,U)O$_2$ in the active core reactor give some different results for neutronic analysis such as effective multiplication factor (k-eff) each block fuel and whole of active core, conversion ratio, and spectrum of neutrons. The calculation was calculated by using neutronic SRAC2006 code and based on JENDL4.0 nuclear data which has been developed by JAERI. The results show that the optimum core may be obtained when (Th,U)O$_2$ has 60% of ThO$_2$ and 16.8% enrichment of UO$_2$. The spectrum neutron shows that (Th,U)O$_2$ fuel results in a softer spectrum.

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

1. Introduction
Since 1990s Japan has operated a High Temperature Gas Cooled Reactor (HTGR), named as High Temperature Test Reactor (HTTR) 30 MWth. This reactor can be categorized as the Generation IV nuclear reactor system [1]. The first criticality has been attained on November 10, 1998, and achieved the full power of 30MW along with the reactor outlet coolant temperature of 850°C on December 7, 2001 originally used UO$_2$ as the loaded fuel. The ultimate goal of HTTR development is being a leader for producing heat source of a hydrogen production system by 2015 [1-3]. Hydrogen production will completely cut the carbon dioxide emission and give cleaner energy system. Other purpose of HTTR development is to be used for water desalination [1].

The previous evaluation that has been conducted by JAERI in order to know HTTR characteristic was focused on core physics in relation with thermal response and control system, thermal analysis for fuel, reactor internals and high temperature components, 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 [1]. For inherent safety purpose, the maximum fuel temperature is necessary to be well-maintained as low as possible under normal operation and any anticipated operation occurrences. The maximum fuel temperature should not exceed fuel design limit of 1600°C during any anticipated operation occurrences [4]. For the fuel scale protection, HTTR has a fuel design feature using Triple Isotropic Coated Fuel Particle (TRISO-CFP) for keeping the kernel from...
corrosion and other outside chemical attack. Various evaluation such as neutronic analysis and thermal hydraulics properties of the HTTR can be utilized for HTGR technology establishment in the future. Recently, study on thorium utilization in nuclear reactors become attractive since it has 3-4 times more abundance and produce less nuclear high level wastes compared to uranium fuel [5,6].

In this paper, several neutronic aspects of HTTR 30MWt with (Th,U)O₂ fuel are presented.

2. Design and Methodology

Neutronic design for any type reactors actually depends on nuclear fuel which is loaded into active core, geometrical design, period of reactor operation, desired thermal and electrical output power, reactor core temperature. Table 1 presents the general information about the design characteristics of the reactor core [7].

| 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/cm³           |
| 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                   |

As a research nuclear reactor, The HTTR does not have a high output power and power density compare with other commercial thermal nuclear reactor. Many TRISO-coated fuel particles which has 1mm diameter is arranged to become a fuel compact with 39mm height, inside and outside diameter are 10mm and 26mm. 30% in fuel compact is the fuel particle while the rest value contains graphite as moderator. In a TRISO particle, anything can replace the UO₂ as the original fuel that was used in HTTR. Here, other innovation has been performed with using (Th,U)O₂ fuel kernel which is surrounded by triple-isotropic layer of carbon and silicon-carbide for preventing from chemical attack and deformation caused by heat. Other countries that have tried using this fuel mixture are Germany with Pebble Bed HTGRs, namely AVR 15MWe and THTR 300MWe were successfully operated till the late 1980s after which they were terminated. HTGRs of USA, namely Peach Bottom (40 MWe) and Fort St. Vrain (330 MWe). The HTGR in UK, namely the Dragon reactor, has also used coated fuel particles of mixed thorium uranium oxide and di-carbide in graphite matrix [8]. Mixing of (Th,U)O₂ in a fuel kernel consists of ThO₂ and UO₂ itself and the comparison value between those two
fuel are 50%-50%, 60%-40% and 25%-75%. Thorium dioxide is chemically more stable and has higher radiation resistance than uranium dioxide. Even though thorium is a non-fissile material, it can produce a fissile material that is U-233.

**Figure 1.** Reactor core structure of HTTR [1]  
**Figure 2.** Fuel block scheme of HTTR [9]

| Parameter                        | Type I  | Type II |
|----------------------------------|---------|---------|
| Density (g/cm³)                  | 1.79    | 1.79    |
| Natural Boron concentration (wt%)| 2       | 2.5     |
| Diameter (mm)                    | 14      | 14      |
| Boron-10 (wt%)                   | 19.9    | 19.9    |

Several fuels compact is arranged to be a fuel rod, then placed to a hexagonal fuel block which has 360mm across flats and the height is 580mm. The reactor core consists hexagonal fuel blocks, replaceable reflector blocks and control rod guide blocks. The structure of core is mostly built with graphite. Inside core, there are five layers (axial) of fuel assembly and surrounded by reflector for preventing neutron leakage into outside reactor. One fuel block at least has 30 until 33 fuel rods and 3 rod of burnable poison. B4C/C was selected as a burnable poison for controlling neutron population in active core of HTTR. Table 2 and table 3 show the burnable poison specification.

| Parameter                        | Specification |
|----------------------------------|---------------|
| Density (g/cm³)                  | 1.77          |
| Diameter (mm)                    | 14            |
| Impurity (natural Boron (ppm))   | 37            |
Table 4. Summary of neutronic properties of 'Fissile' (U-233, U-235 & Pu-239) and 'Fertile' (Th-232 and U-238) isotopes in thermal [average over Maxwellian spectrum at 300°C (0.05eV)] and Epithermal region [8]

| Nuclear Data                          | Th-232 | U-233 | U-235 | U-238 | Pu-239 | Pu-241 |
|---------------------------------------|--------|-------|-------|-------|--------|--------|
| Thermal Cross-section (barns)         |        |       |       |       |        |        |
| Absorption $\sigma_a$                | 4.62   | 364   | 405   | 1.73  | 1045   | 1121   |
| Fission : $\sigma_f$                  | 0      | 332   | 346   | 0     | 695    | 842    |
| $\alpha = \sigma_c / \sigma_f$       | 0.096  | 0.171 | 0.504 | 0.331 |        |        |
| $\eta_{th}$                          | 2.26   | 2.08  | 1.91  | 2.23  |        |        |
| Epithermal Resonance Integral (RI) barns ($\propto$ dilution) |        |       |       |       |        |        |
| $R_{Ia}$                              | 85.6   | 882   | 405   | 278   | 474    | 740    |
| $R_{If}$                              | 746    | 272   | 293   | 571   |        |        |
| $\alpha = R_{Ic} / R_{If}$            | 0.182  | 0.489 | 0.618 | 0.296 |        |        |
| $\eta_{epi}$                         | 2.1    | 1.63  | 1.77  | 2.29  |        |        |
| Neutron Yield $\nu$                  | 2.48   | 2.43  | 2.87  | 2.97  |        |        |
| Delayed Neutron Yield $\beta$        | 0.0031 | 0.0069| 0.0026| 0.005 |        |        |
| Capture:                              |        |       |       |       |        |        |
| 2 200 m/s value                      | 7.6    | 54    | 100   | 2.7   | 267    |        |
| Resonance integral                   | 85     | 140   | 144   | 275   | 200    |        |
| Neutron/fission (on average)         | 2.5    | 2.4   | 2.9   |       |        |        |

The numerical calculations have been performed by using CITATION module of SRAC2006 code [8] with JENDL4.0 nuclear data library [9,10] which is developed by JAERI. For the neutronic calculation, the active core has been divided into several grids. In this case it has been 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 so that the 3D triangular (XYZ) was chosen for the numerical grid representation.

### 3. Result and Discussion

Figures 3 and 4 show the effective multiplication factor and conversion ratio for (Th, U)O$_2$ loaded fuel in 30MWt HTTR. At first, several parametric surveys have been done in the previous work. Fresh fuel mixture between ThO$_2$ and UO$_2$ has been added in a fuel kernel with percentage of 50%-50% (graphic with index 50-50h), 60%-40% (graphic with index 60-40h) and 25%-75% (graphic with index 52-75h). Eventually, the three result show high multiplication factor results. Those can be like that because when fresh fuel mixture are loaded into active core, at first it will give high $k$$_{eff}$ and will go down at the second step because of burnable poison’s influence. Meanwhile, the new fissile material such as U-233, Pu-239 and Pu-241 are much created in this step and give the influence to the next step of reactor operation that make higher $k$$_{eff}$ than the previous step but no longer after that it will decrease a little by little. Other result is about conversion ratio for all three kind of loaded fuels will give no more than unity, or it can be said as there is no breeding activity yet the others fissile material are created though. All three results that are explained before, give the most optimum result when HTTR was loaded by 60% of ThO$_2$ mixed with 40% UO$_2$ which has 16.8% enrichment of uranium. It is pretty high enrichment of uranium but for long time of operation it will be good because the active
core still can produce the energy for more than two years for maintaining the low reactivity swing of the reactor.

Figure 3. Effective multiplication factor result of (Th,U)O$_2$ Homogenous fuel in HTTR

Figure 4. Conversion Ratio result of (Th,U)O$_2$ Homogenous fuel in HTTR

Figure 5. Neutron flux distribution of 60%-40% (Th,U)O$_2$ Homogenous fuel in HTTR

The neutron flux distribution is showed in the Figure 5. The neutron flux is influenced by what kind of fuel which is used. High uranium enrichment will give more thermal-energy dominant result. In the case of Th-232 as a fertile material, it will produce U-233 as fissile material with the eta value in thermal energy is 2.26, while the eta value for Pu-239 and Pu-241 are 1.91 and 2.23. This fact may become the reason for the neutron flux is dominant in the thermal energy. In other words, the neutron spectra become softer.

4. Conclusion
Several neutronic aspects have been analysed with SRAC2006 and JENDL4.0 in 30MWt HTTR using (Th,U)O$_2$ homogenous fuel arrangement for two years operation. The results shows that 60%-40% (Th,U)O$_2$ Homogenous fuel HTTR 16.8% of UO$_2$ will give the optimum k-eff during the operation time even for longer time period. The spectrum of neutron becomes softer spectrum.
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