Proceedings of the Reactor Physics Asia 2015 (RPHA15) Conference
Jeju, Korea, Sept. 16-18, 2015

Design Concept Study for Innovative High Temperature Gas-Cooled Reactors

Toru Obara*, Dwi Irwanto, Tomonori Nakashima, Taiki Onoe, Piyatida Trinuruk, Topan Setiadipura,
Sambuu Odmaa, Hai Quan Ho, Irwan Liapto Simanullang,
Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology
Ookayama, Meguro-ku, Tokyo 152-8550, Japan
*Corresponding author: tobara@nr.titech.ac.jp

1. Introduction

High Temperature Gas-Cooled Reactors (HTGR) are more advantageous than conventional water-moderated thermal reactors. The thermal efficiency of these reactors is higher than that of light water reactors, and their high output temperature can be utilized for other industrial purposes such as hydrogen production and district heating. Several studies have been performed to design innovative HTGR concept. There two types of HTGR's, one is prismatic HTGR and the other is Pebble Bed Reactor (PBR). The research activities have been performed for the both type of reactors in Tokyo Institute of Technology. The purpose of the activities were to make clear the innovative HTGR concepts which can achieve passive safety, effective utilization of uranium resources, high nuclear proliferation resistance, reduction of amount of spent fuel, and improvement of safety in final disposal of spent fuel. This paper aims to summarize current research activities about innovative HTGR's in Tokyo Institute of Technology.

2. Monte Carlo-based Pebble Bed Reactor Fuel Management Code [1]

A Pebble Bed Reactor (PBR) with a moving fuel core provides flexibility in the fuel management of the core, including the advantage of online refueling. On the other hand, depletion analysis of this moving fuel core is especially challenging because the analysis must account for the movements of the fuel as well as the changes of nuclide composition. The purpose of this study was to develop an MC-based depletion code for PBR fuel management analysis. The code, named Monte Carlo burnup analysis code for PBR (MCPBR), enables a simulation of the Once-Through-Then-Out (OTTO) cycle of a PBR from the running-in phase to the equilibrium condition. In MCPBR, a burn up calculation based on a continuous-energy Monte Carlo code, MVP-BURN, is coupled with an additional utility code to be able to simulate the OTTO cycle of PBR. MCPBR has several advantages in modeling PBRs, namely its Monte Carlo neutron transport modeling, its capability of explicitly modeling the double heterogeneity of the PBR core, and its ability to model different axial fuel speeds in the PBR core.

3. Burnup Pebble Bed Reactors with ROX Fuel [2]

In the disposal of spent fuel from HTGR's, geological disposal without reprocessing is the most promising option because the complicated processes for highly radioactive material can be avoided. In this case, fuel material with high chemical stability is desired because it can be expected to improve the performance of the spent fuel element in the geological disposal. Rock-like oxide (ROX) fuel has been studied at the Japan Atomic Energy Agency (JAEA) as a new once-through type fuel concept, which has high chemical stabilities under geological condition can be expected in the direct disposal of the spent ROX fuel without further processing. The purpose of this study was to show the possibility of using ROX fuel in a small pebble bed reactor and to analyse the burnup performance. This study utilized the OTTO scheme for refuelling the fuel pebbles during operation to avoid using the fuel-handling system (FHS), a complicated system associated with the multi-pass cycle. The ROX fuel reactor showed lower FIFA than the UO_2 fuel reactor at the same heavy-metal loading, about 5-15%. However, the power peaking factor and maximum power per fuel ball in the ROX fuel core were lower than that of UO_2 fuel core. This effect makes it possible to compensate for the lower-FIFA disadvantage in a ROX fuel core. All reactor designs had a negative temperature coefficient that is needed for the passive safety features of a Pebble Bed Reactor.

4. Pebble Bed Reactor with Accumulative Fuel Loading Scheme [3,4,5]

Despite the many advantages to PBR design, there are also drawbacks to this reactor concept, such as the FHS design, which can be complicated. FHS has functions that must be controlled to manage the fuel pebbles during operation. As a result, this study seeks to simplify the reactor design by removing the FHS. Teuchert, proposed a new concept of fuel management in PBR design [6]. At the start-up, the reactor cavity is filled with some amount of fuel balls, and under operation new fuel balls are filled in little by little until the cavity is fully filled. Due to the very slow movement of the fuel, this concept has been called the “Peu à Peu” method. For ease of understanding, in this study the method is called an accumulative fuel loading scheme. The purpose of this study was to establish the reactor concept which can achieve high burnup performance. A new code was developed based treat the accumulative fuel loading scheme. The code had two main functions: (1) to obtain the effective multiplication factor and to find the exact step when the reactor become sub-critical. This information would be used to decide the time to add fresh fuel; and (2) to identify the atomic number density data before the reactor became subcritical. In this calculation, the pebble balls were inserted in a stepwise procedure and the axial zone of the core was divided into several fuelling zones. This study was performed using PBR 110 MWt with a core radius of 200 cm and height of 1026 cm. Initial core height was set to 146 cm. The analysis results showed that, by the use of 20% enriched uranim, the reactor could be operated for 13.3 years with a maximum burnup of 178 GWd/t. However, large excess reactivity occurred in the initial condition. The next step of this study is to optimize the fuel composition in the initial condition to reduce the excess reactivity and also to introduce the burnable poison to eliminate excess reactivity.

5. Burnup Performance of High Temperature Gas-Cooled Reactor with SiC Coating on Graphite Structures [7]

Although graphite has advantageous properties for use in reactor cores, its mechanical and thermal properties can easily be degraded by oxidization, especially in accidents, which might expose it to a high oxidation environment and high temperature. To combat fragility at the surface caused by graphite oxidation, improved oxidation resistance was introduced by material coating. Silicon carbide (SiC) is a prospective coating material due to its capability to enhance mechanical strength, resist corrosion in aggressive environments, resist thermal shock, and retain all fission products within coated particle when implemented in TRISO fuel particles as a coating layer. The purpose of this study was to present a HTGR concept with SiC coating on the graphite structure and to investigate the impact of a SiC coating layer on the neutronic properties of the HTGR. A 100-MW_{th} prismatic HTGR of 20 wt% enriched uranium was designed. The effect of a coating layer of SiC was confirmed from the neutronic point of view; adding a small amount of SiC instead of graphite as a coating layer can have a small impact on the neutronic characteristic by slightly decreasing the reactivity and shortening the fuel burnup life cycle because of the large neutron absorption cross section of silicon in SiC. It was concluded that under normal operation, the effect of a SiC coating is acceptable, besides the proven performance with regard to the oxidation resistance and mechanical properties.

6. Particle Type Burnable Poisons for Prismatic High Temperature Gas-Cooled Reactors [8,9,10]

A small and passive-safe HTGR can be an attractive reactor for use in remote areas or small islands if it has long-life core. In the design of long-life small prismatic HTGRs, it is necessary to use highly enriched uranium to increase the fissile inventory. At the same time, it is necessary to load an effective burnable poison (BP) to compensate for excess reactivity during the core life. The purpose of this study was to show that it is possible to use BP particles to reduce the excess reactivity in long-life HTGR and thereby avoid prompt critical accidents. Especially, the effect of the use of two types of BP particles to flatten the reactivity curve is considered. Numerical calculations were performed to show that it is possible to minimize the excess reactivity in a long-life prismatic HTGR. By the optimization of BP materials, which depends on the core design, the particle diameter, the density, and the combination of different BP materials, it may be possible to make the excess reactivity less than 1$ for some core design, in which prompt super critical condition can be avoided in the case of withdrawal of all control rods. For the practical use of BP particles, further analysis of the changes in power peaking and temperature coefficient is required.

7. Neutronic analyses of a small, long-life HTGR for passive decay-heat removal [11,12,13,14]

Generally, conventional HTGRs are designed to remove core heat by multiple methods using active and passive cooling systems. The feasibility of passive decay-heat removal depends largely on the reactor’s size, power or power density, and the initial temperature of the reactor regions. However, there is little general knowledge of the relationships among the above parameters and the ability of the core to passively reject decay heat. The purpose of study was to carry out criticality and burnup analysis for a small prismatic 100 MW_t HTGR whose dimensions was decided based on the condition for design parameters, by which the reactor can achieve passive decay heat removal after shutdown, and to perform necessary optimization using burnable poison particles to suppress excess reactivity and using control rod insertion to flatten the reactivity swing during operation as well as to check fuel maximum temperature and temperature coefficient of reactivity in view point of safety issue. Performing the criticality and burnup analyses by using the proper composition of B_4C particles with a diameter of 0.2 cm with the volume ratio of 140 and Gd_2O_3 particles with diameter of 0.2 cm with the volume ratio of 490 which are uniformly distributed in the proposed reactor core with coated fuel particles having 20 wt% enrichment of uranium, the maximum excess reactivity can be suppressed from 32.7 $\%\Delta k/k$ to 3.06 $\%\Delta k/k$ with 18.6 years of core life. The optimization for core configuration by using non-uniformly distributed fuel and burnable poison particles was done successfully, and the maximum excess reactivity is effectively reduced more till 0.78 % and the change in Power Peaking Factor during long operation of the core was flattened well.

8. Conclusion

Several studies have been performed for innovative small HTGR concepts which can achieve passive safety, effective utilization of uranium resources, high nuclear proliferation resistance, reduction of amount of spent fuel, and improvement of safety in final disposal of spent fuel. Important and useful concepts were proposed by the study. The further study is in progress for the more attractive reactor concepts.

References

1. Topan Sediadipura, Toru Obara, "Development of Monte Carlo-based pebble bed reactor fuel management code"Annals of Nuclear Energy, **71**, 313-321 (2014). DOI:http://dx.doi.org/10.1016/j.anucene.2014.04.010
2. Hai Quan Ho, Toru Obara, "Burnup performance of OTTO cycle pebble bed reactors with ROX fuel," Annals of Nuclear Energy,**83**, 1-7 (2015). DOI:http://dx.doi.org/10.1016/j.anucene.2015.04.001
3. Dwi Irwanto, Toru Obara, "Burnup Characteristics of a Peu a Peu Fuel-loading Scheme in a 110-MWt Simplified Pebble Bed Reactor", *Journal of Nuclear Science and Technology*, **48** [11], pp 1385-1395, (2011)
4. Dwi Irwanto, Toru Obara, "Burnup Characteristics and Fuel Cycle Economics of Mixed Uranium-Thorium Fuel in a Simplified Small Pebble Bed Reactor", *Journal of Nuclear Science and Technology*, **49** [2] , pp 222-229, (2012).
5. Irwan Liapt Simanullang, Toru Obara "IMPROVEMENT OF BURNUP ANALYSIS FOR PEBBLE BED REACTORS WITHANACCUMULATIVE FUEL LOADING SCHEME, *Proceedings of ICONE-23, 23th International Conference on Nuclear Engineering*, ICONE23-1627, May 17-21, 2015, Chiba, Japan, on CD-ROM (2015).
6. E.Teuchert, et al,"Simplification of the Pebble Bed High Temperature Reactor", *Proc. of SR/TIT*, Tokyo, Japan (1991).
7. Piyatida Trinuruk, Toru Obara, "Concept of prismatic high temperature gas-cooled reactor with SiC coating on graphite structures, *Annals of Nuclear Energy*, **63,** 437-445 (2013). DOI:http://dx.doi.org/10.1016/j.anucene.2013.08.019
8. Toru Obara, Taiki Onoe, "Flattening of burnup reactivity in long-life prismatic HTGR by particle type burnable poisons", *Annlas of Nuclear Energy*, **57**, 216-220 (2013).
9. Piyatida Trinuruk, Toru Obara, "Small, long-life high temperature gas-cooled reactor free from prompt supercritical accidents by particle-type burnable poisons", Journal of Nuclear Science and Technology, **50** (9), 898-912 (2013). DOI:http://dx.doi.org/10.1080/00223131.2013.815138
10. Piyatida Trinuruk, Toru Obara, **"**Particle-type Burnable Poisons for Thorium-based Fuel in HTGR", *Energy Procedia*, **71**, 22-32 (2015). DOI:http://dx.doi.org/10.1016/j.egypro.2014.11.851
11. Sambuu Odmaa, Toru Obara, "Possible design in long-life small prismatic HTGR for passive decay heat removal", *Nuclear Science and Engineering*, **177**, 97-109 (2014). DOI: http://dx.doi.org/10.13182/NSE13-22
12. Odmaa Sambuu, Toru Obara, "Above-ground HTGR design for passive decay heat removal" *Journal of Nuclear Science and Technology*, **52**, 857-871 (2015) DOI:http://dx.doi.org/10.1080/00223131.2014.986242
13. Odmaa Sambuu, Toru Obara, "Comparative study on HTGR Designs for Passive Decay Heat Removal", *Progress in Nuclear Energy*, Vol. 82, pp. 37-45 (2015). DOI:http://dx.doi.org/10.1016/j.pnucene.2014.07.013
14. Odmaa Sambuu, Toru Obara, "Neutronic and thermo-hydraulic analyses of a small, long-life HTGR for passive decay-heat removal", *Journal of Nuclear Science and Technology*, Published online DOI:http://dx.doi.org/10.1080/00223131.2015.1017546