Annals of Nuclear Energy 60 (2013) 383–395

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Decay heat removal without forced cooling on a small simplified PBR with an accumulative fuel loading scheme

Dwi Irwanto, Toru Obara *

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, 2-12-1-N1-19 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

ARTICLE INFO

Article history:
Received 22 May 2012
Received in revised form 27 April 2013
Accepted 17 May 2013
Available online 17 June 2013

Keywords:
Decay heat
Passive safety
Accumulative fuel loading scheme
Pebble bed reactor
Temperature distributions

ABSTRACT

In this study, we analyzed the passive safety features of a small simplified pebble bed reactor with an accumulative fuel loading scheme for decay heat removal after reactor shutdown without a forced cooling system. The accumulative fuel loading scheme has unique characteristics that make it different from Multipass or Once Through Then Out (OTTO) fuel loading schemes. In this fueling scheme, significant changes of power distributions occur in a limited area at the top of the reactor core, where new fuel pebbles are inserted during reactor operation. We analyzed three different reactor conditions: different heights of the active core at the beginning, middle, and end of life as a consequence of the accumulative fuel loading scheme. In the analysis of a depressurized loss-of-flow accident, it was assumed that no natural circulation was possible, so that heat would be transferred through conduction and radiation with the last heat sink being the ground. Our analysis obtained temperature distributions inside the reactor core for each condition. The maximum temperature achieved in our simulation was 1287 °C, which is lower than the safety limit of 1600 °C.

1. Introduction

A small Pebble Bed Reactor (PBR) is one of the most promising reactor systems to adopt passive safety features, specifically, the coating of fuel particles, which limits the release of radioactive material into the environment, and the use of a large amount of graphite as a moderator and reflector, giving the core a high heat capacity, which leads to a very slow transient response. The high temperature limit of this system, as high as 1600 °C, is another major advantage, given that most of the fission products can be maintained below this temperature limit by SiC layer(s). PBRs also offer even further advantages in their small excess reactivity during reactor operation, and in the fact that the moderator material (graphite) has a small absorption cross-section. In a PBR system, helium gas is used as a coolant because it is chemically and neutronically inert and always in a single-phase state.

The two most typical fuel loading schemes in a PBR are the Multipass and Once Through Then Out (OTTO) schemes. In the Multipass fueling scheme (Reutler et al., 1983), fuel pebbles are inserted several times from the top and are unloaded from the bottom. In this mode, power profiles remain almost constant during reactor operation and are shaped like a cosine function. In the OTTO fueling scheme (Mulder et al., 1996), fuel pebbles are inserted only once during reactor operation and are discharged from the bottom of the core. This makes the power distributions high at the top of the core and low at the bottom of the core. However, beside the Multipass and OTTO fuelling schemes, there is also the accumulative fuel loading scheme (Teuchert et al., 1991), in which the reactor core starts with its lower layers partially filled with fuel pebbles, leading to the first criticality. At various time intervals, one fuel layer after another is added, depending on the requirements of criticality and compensation for burnup. This fuel loading scheme has unique characteristics compared with those previously mentioned in two important ways. First, significant changes of power distributions occur only in a limited area at the top of the reactor core, where new fuel pebbles are inserted during reactor operation. And second, the height of the reactor core is always changing and increasing during reactor operation.

The small simplified PBR is a high-temperature helium gas-cooled type with a graphite moderator and a small thermal power of 110 MW. The main feature of this reactor is the simplification of its design, which was achieved by removing the pebble unloading devices from the system and using the accumulative fuel loading scheme, allowing the reactor to be constructed, operated and maintained more easily and at a lower cost. Neutronic analyses of small simplified PBRs with an accumulative fuel loading scheme have been performed and discussed in previous studies using uranium and mixed thorium-uranium fuel. In the study using uranium fuel (Irwanto and Obara, 2011), the optimal uranium fuel configuration was obtained by parametric surveys and, using this value, a 110-MWt simplified PBR using an accumulative fuel concept was

---

* Corresponding author. Tel./fax: +81 3 5734 2380.
E-mail address: tobara@nr.titech.ac.jp (T. Obara).

0306-4549/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2013.05.022

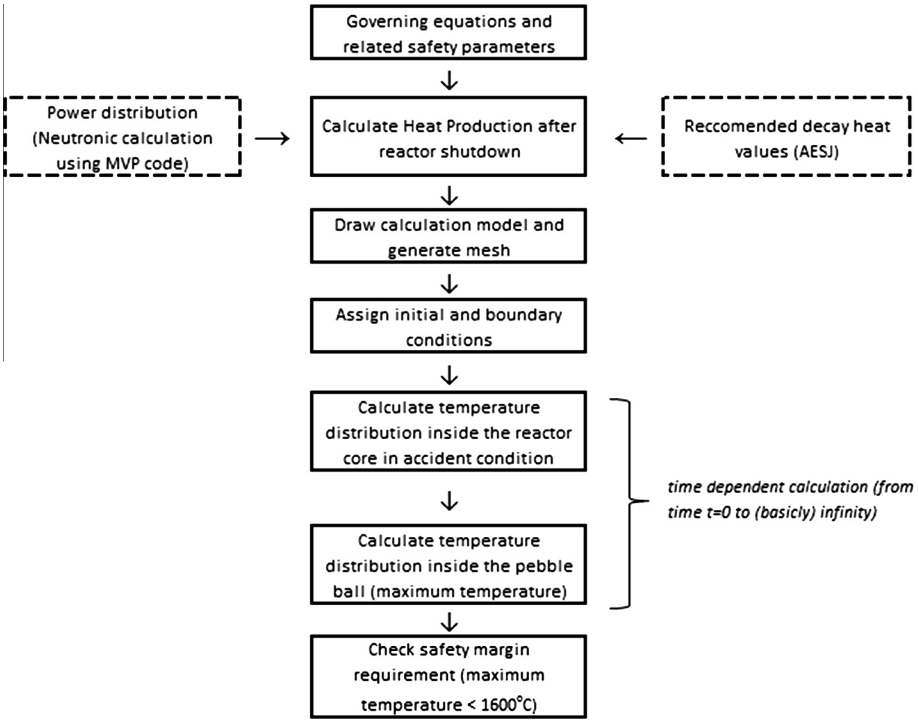

Fig. 1. Flowchart of the calculation procedures.

Table 1
Comparison of the two thermal conductivity values considered in the accident analysis.

Temperature (°C)	Thermal conductivity (W/m/K)	
	German correlation (Eq. (3))	GE correlation (Eq. (6))
550	5.1	5.5
650	6.6	6.9
750	8.2	8.5
850	9.9	10.3
950	11.7	12.1
1000	12.6	13.1
1050	13.5	14.1
1100	14.5	15.1
1200	16.4	17.3
1300	18.4	19.6

analyzed. The analysis confirmed that the reactor could be operated for 20.8 years with average and maximum burnup values of 135 GWd/t and 152 GWd/t, respectively; these values are significantly higher than those of the low enriched uranium (LEU) design and could be competitive with those of other high temperature gas reactor (HTGR) designs such as the GTHTR300. With respect to fuel economy, the requirement of natural uranium per year of operation can be reduced to about 23% for reactors with an optimized fuel configuration compared with that of the LEU design. Moreover, in a study on the use of mixed thorium–uranium fuel (Irwanto and Obara, 2012), optimization of the thorium fuel configuration for the accumulative fuel loading concept was performed and implemented on a 110-MWt simplified PBR. This reactor could be operated for 21.4 years with average and maximum burnup values of 140 GWd/t and 182 GWd/t, respectively, which is significantly higher than those of reference cases using only uranium as fuel. These reactor designs have a low power density of 6 W/cc at the beginning of reactor life, allowing a less complicated emergency core cooling system (ECCS) design. The primary pressure was 6 MPa, with inlet and outlet temperatures of 500 °C and 811 °C, respectively. The thermodynamic cycle efficiency was assumed to be 45%. The analysis indicated that simplification of the PBR's design and operation could be accomplished, reducing the requirement for total natural uranium during reactor operation by 33.3%

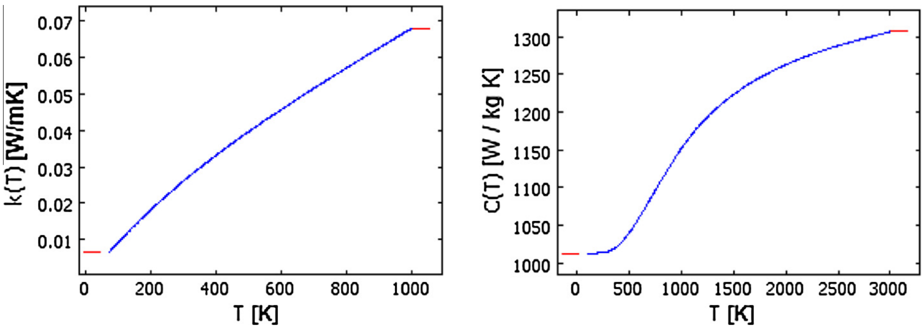

Fig. 2. Thermal conductivity and specific heat of air as a function of temperature.