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Design concepts of small CANDLE reactor with melt-refining process

Van Khanh Hoang, Jun Nishiyama, Toru Obara*

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

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A B S T R A C T

The innovative CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production) burnup strategy has several advantages over conventional fast reactor designs: namely, the reactor characteristics do not change with burnup, it is possible to withdraw the burnup reactivity control mechanism, there is no need for orifice control along with burnup, and it is easy to extend reactor life by increasing the core height and using natural uranium as fresh fuel. Maintaining the fuel cladding integrity of a CANDLE reactor during operation is one of the key technological challenges that still need to be addressed. The introduction of the melt-refining process has shown great potential for solving this challenge in the high-burnup condition of large CANDLE reactors. The purpose of the present study was to design a small CANDLE reactor with the melt-refining process. With metallic fuel of natural uranium (90 wt% U, 10 wt% Zr), ODS cladding material, and lead-bismuth eutectic (44.5 wt% Pb, 55.5 wt% Bi) coolant, a 300-MWt reference core of 1.3-m radius and 2.2-m length can realize CANDLE burning. The results of our analysis demonstrate that it is possible to design a small CANDLE reactor with the melt-refining process. The analysis focused on the impacts of core homogenization, melt-refining, and the cooling and waiting times of the fuel. From the equilibrium analysis, the burning region velocity, neutron flux distribution, power density distribution, and core nuclide number density distribution were obtained. Applying the melt-refining process reduced the burning region velocity from 0.70 cm/year to 0.59 cm/year. Meanwhile, the minimum effective neutron multiplication factor and core averaged discharged fuel burnup were increased from 1.0047 to 1.0235, and from 435.2 GWd/t to 523.7 GWd/t, respectively.

1. Introduction

The CANDLE (Constant Axial shape of Neutron flux, nuclide densities and power shape During Life of Energy production) burnup concept was first proposed by (Sekimoto et al., 2001). In a CANDLE reactor, the constant shapes of neutron flux, nuclide number densities and power density distributions shift in the axial direction. The CANDLE reactor core can be divided into roughly three regions: the breeding region composed of fresh fuel, the burning region which produces the main portion of power in the core, and the spent fuel region containing fission products. During operation, the main portion of the neutrons and energy are produced by fission of the fissile materials in the burning region. In the front side of the burning region, the fertile materials absorb leaked neutrons from the burning region to transmute into fissile materials. Therefore, the distribution of fissile materials shifts to the burning region. The spent fuel region is the region left behind by the burning region, composed mainly of fission products and depleted fuel. In this way, the burning region moves along the core axis.

The CANDLE reactor has several general advantages such as (Sekimoto and Yan, 2008):

- Possible to use natural or depleted uranium as the replacement fuel.
- High burnup can be achieved; it is possible that about 40% of fuel undergoes fission.
- It does not require any control mechanism for burnup.
- High-level optimization of the radial power distribution is possible since the radial power distribution does not change with time.
- The core characteristics do not change as burnup progress.
- It is not necessary to adjust the flow rate with orifices as burnup progress. Since the radial power profile does not change with burnup, the required flow rate for each coolant channel does not change.
- The lifetime of a nuclear reactor can be lengthened by simply increasing the core height.
- The risk of a criticality accident in transportation and storage of the fresh fuel is small because of the use of natural or depleted uranium, which makes the infinite neutron multiplication factor (k_∞) of fresh fuel after the second cycle less than unity.

* Corresponding author.
E-mail address: tobara@lane.iir.titech.ac.jp (T. Obara).

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Nomenclature

BOC	Begin of fuel-movement cycle
EOC	End of fuel-movement cycle
FMC	Fuel-movement cycle [days]
MRR	Melt-refining region
LDU	Load-and-discharge unit
Tc	Cooling time before melt-refining process [days]
Tw	Cooling time after melt-refining process [days]

A CANDLE reactor can achieve 40% burnup of spent fuel without reprocessing and enrichment (Sekimoto et al., 2001). To realize a long-life CANDLE core, it is important to maintain fuel cladding integrity under ~40% burnup (Sekimoto, 2010). Several solutions to overcome this challenge have been proposed. The first is the recladding method, investigated by (Nagata and Sekimoto, 2007). In this method, fuels in the process of burning are removed from the core, gaseous fission products are also removed from these fuels, and the fuels are recladded. Then, they are reloaded into their previous position in the core. The effects of recladding in this method were small; the shape of each burnup distribution was almost the same, and burnup was increased by 1%. Another solution to maintain fuel cladding integrity is to apply the melt-refining process introduced by (Abdul Karim et al., 2016), (2017). The melt-refining process was developed in an EBR-II reactor project (Hesson et al., 1963). In this process, fuel pins are decladded, all volatile and gaseous fission products are substantially removed, and at least 95% of the reactive fission products are removed; no separation will occur for noble fission products in the melt-refining (Hesson et al., 1963). They investigated the possibility of introducing this process into a large-scale CANDLE reactor (Abdul Karim et al., 2016), (2017), and were able not only to maintain fuel cladding integrity in the high-burnup condition, but also to improve the burnup performance of the large-scale CANDLE reactor. In previous studies (Greenspan and Heidet, 2011), (Heidet and Greenspan, 2012), performed by Ehud Greenspan and Florent Heidet, respectively, the melt-refining process was also applied successfully to large-scale breed and burn reactors to extend the lifetime of the fuel and achieve high burnup. This raises the question of whether it is possible to apply the melt-refining process to a small CANDLE reactor, which generally requires high neutron economy.

The purpose of the present study was to design a small CANDLE reactor with the melt-refining process. The reference core analysis is given in Section 2. The core burnup analysis with the melt-refining process is presented in Section 3. A discussion is given in Section 4. Section 5 provides concluding remarks and points to future work.

2. Reference core analysis

2.1. Description of the reactor

Table 1 presents the design parameters of the reference core. Fig. 1 shows the basic axial configurations of the core. It uses metallic fuel with 10% (wt%) Zr content, and natural uranium as a fresh fuel. Oxide-dispersion-strengthened (ODS) steel was chosen for the cladding material. Lead–bismuth eutectic (LBE) (44.5–55.5%) was employed as a coolant to allow high neutron economies in the hard spectrum (Sekimoto and Suud, 1995). In the present design, the core inlet coolant temperature was set to 600 K and the outlet temperature to 800 K; these are values used previously by H. Sekimoto for a small CANDLE reactor (Sekimoto and Yan, 2008). Fig. 2 provides the schematic fuel cell layout. The fuel cell has hexagonal geometry with a fuel pellet radius of 0.39 cm, cladding thickness of 0.06 cm, and fuel pin pitch of 1.08 cm. The height of the plenum is set at 45 cm. The heights of the lower-end plug and upper-end plug are 50 cm and 5 cm, respectively.

Table 1
Core design parameters.

Design parameters	Values
Thermal power [MWt]	300
Core height [cm]	220
Core radius [cm]	130
Reflector thickness [cm]	50
Fuel type [-]	U-Zr
Coolant material [-]	Pb-Bi
Cladding material [-]	ODS
Bond material [-]	Pb-Bi
Fuel rod pitch [cm]	1.08
Fuel pellet radius [cm]	0.39
Cladding inner radius [cm]	0.45
Cladding outer radius [cm]	0.51

2.2. Methodology of neutronic analysis

The neutronic analysis was performed using SRAC (Okumura et al., 2007) and COREBN (Okumura, 2007) code systems. The reference core calculation method is described in Fig. 3. The cell burnup calculation evaluated the macroscopic cross-section of 21 energy groups with burnup on an infinite system of fuel pins using the collision probability (PIJ) module of the SRAC2006 code system based on the latest SRAC nuclear data library, JENDL-4.0 (Shibata et al., 2011). In the previous study, performed by (Abdul Karim et al., 2016), the calculation using the nuclear data library of JENDL-4.0 gave an effective multiplication factor (k_{eff}) higher than that achieved using the data library of JENDL-3.3 (Shibata et al., 2002). The nuclear data library of JENDL-4.0 was chosen in this study since there is a vigorous effort to improve the

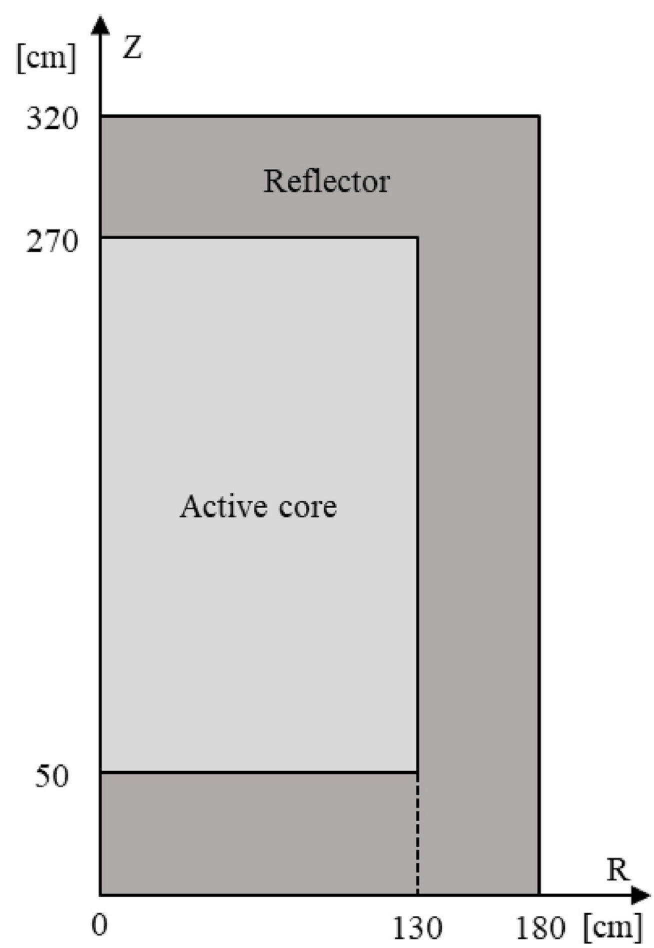

Fig. 1. Basic axial configuration of the core.