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Burnup optimization of Small Natural Circulation Lead Cooled Fast Reactor

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ABSTRACT

SNCLFR-100 (Small Natural Circulation Lead Cooled Fast Reactor with 100 MW_{th}), proposed by University of Science and Technology of China (USTC), is a typical modular fast reactor with an array of heterogeneous square fuel assemblies using MOX as the main fuel located in the core, and a preliminary conceptual design has been presented. To extend the full power operating time of the core to 10 years without refueling and improve the transmutation capability of the core, the design optimizations were carried out in this paper, including changing compositions of the fuel, adjusting the relative portion of Pu and U, and changing the type of structure material in the core. In addition, relevant parameters were also optimized. Compared to the original design, the neutron flux distribution became flatter, and the power peak factor of the core dropped from 1.40 to 1.37. The MA transmutation ratio of the optimized core came out to be 2.73%. At the same time, the worth of control rods and the negative reactivity coefficients showed the core has inherent safety.

1. Introduction

The lead-cooled fast reactors have been selected as one of the possible options for Generation IV reactors by the US Department of Energy (DOE) in 2002. Small modular reactor (SMR) has also attracted particular attentions in recent years due to its attractive advantages such as reduced capital costs and enhanced safety behavior. Several small module natural circulation lead or lead-alloy cooled fast reactors (LFRs) have been developed in the past decades. In 1990s, Rubbia (Rubbia et al., 1995) proposed to use a natural circulation LFR to serve as a sub-critical reactor for an Accelerator Driven System (ADS) in European Organization for Nuclear Research (CERN). In 2000s, Sienicki (Sienicki et al., 2008, 2011) developed several small modular natural circulation LFR concepts in Argonne National Laboratory (ANL), including SSTAR (Sienicki et al., 2008; Smith et al., 2008) and SUPERSTAR (Sienicki et al., 2011). In 2011, Seoul National University designed a lead-bismuth-cooled small modular reactor called PASCAR (Choi et al., 2011) which was designed to be the first generation of small modular reactor system as a long-life robust power unit (Hwang et al., 2008, 2008). At the same time, China has also carried out series of research on the lead cooled fast reactor (Wenlong and Hushan, 2012; Chen et al., 2016, 2014, 2015).

SNCLFR-100 is a Small Natural Circulation Lead Cooled Fast Reactor with 100 MW_{th}, which is one of the potential candidates for LFR development, and a preliminary conceptual neutronics design study for the SNCLFR-100 was presented (Chen, 2015). Although the conceptual design satisfied the design criteria, the full power operating time of the core is still to be optimized for the target of 10 years while the MAs were mixed into the fuel.

In this paper, the design was optimized by changing compositions of the fuel, adjusting the relative portion of Pu and U, and changing the type of structure material in the core, in order to achieve a full power operation for ten years without refueling. Although MA transmutation support ratio is proportional to MA fraction in fuel, the core performance will be affected significantly by the addition of MA into fuel, which limits MA percentage in fuel. At the same time, benefiting from these adjustments, the neutron flux distribution and power distribution of the core became flatter, and the power peak factor of the core would be lower than previously calculated value. In addition to the power peak factor, neutron flux and power distribution, other parameters including excess reactivity, shutdown margin, were also optimized. These parameters had achieved better values than those the original scheme. Finally, the worth of control rods and the negative reactivity coefficients showed the optimization scheme meet safety design requirements.

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2. The reference design

2.1. Reactor material and structures

The core of SNCLFR-100 is loaded with 204 fuel assemblies, 36 control rod assemblies, 48 reflective layer assemblies and 84 shield layer assemblies. There are three fuel zones. And each fuel zone has control rod assemblies. The height of active region of the core is 100 cm, and its equivalent diameter is 350 cm (Chen, 2015). Some key technical parameters of SNCLFR-100 reactor are shown in Table 1.

The core arrangement of SNCLFR-100 is in Fig 1, and the control rods which are numbered as shown were divided into primary control system and secondary control system. The original core design parameters are in Table 2.

The fuel assembly is a 9 × 9 pins lattice. Additionally, a fission gas plenum region above the fuel is considered to confine the fission gases, and its height is assumed to be 100 cm. The control assembly is similar to the fuel assembly while the middle 9 fuel rods (3 × 3) of the fuel assembly were replaced by one control rod.

The fuel comes from the reprocessing of PWR spent UO_2 fuel burnt up to 45 GWd/t, with a 4.5% initial enrichment in ^{235}U and 15 years of cooling period has been performed in Sobolev (2007), Van den Eynde et al. (2009), Bortot et al. (2011). The ratio of PuO_2 in three fuel districts of the core is also shown in Table 2. Compositions of U and Pu is in Tables 3 and 4 (Bortot et al., 2011).

2.2. Reactivity coefficients and kinetic parameters

The nature isotopic composition for Pb is reported in NIST (National Institute of Standards and Technology). The lead density depends on the temperature as (Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, 2007):

$$\rho[kg/m^3] = 11367 - 1.1944 \times T[K]$$

For 400 °C and 480 °C, this corresponds to 10.56 g/cm^3 and 10.47 g/cm^3 respectively.

The key core performances, reactivity coefficients, and kinetic parameters of SNCLFR-100 are shown as follows (see Tables 5 and 6):

Table 1
Design parameters

Design factor	Design value
Core thermal power	100 MW_{th}
Oxide fuel	MOX(PuO_2&UO_2)
Plant design lifetime	30 years
Primary coolant	Lead
Reflector material	15%T91 + 85%Pb (volumetric fraction)
Shield material	15%B_4C + 85%Pb (volumetric fraction)
Size of the reactor	Φ6 m × 10 m
Number of main heat exchanger device	4 × Shell and tube heat exchangers
1st circuit coolant	Pb
1st circuit inlet and outlet temperatures	400-480 °C
1st circuit operating pressure	0.1 MPa
Drive	natural circulation
Loop height	4 m
1st circuit coolant flow	8528 kg/s
2nd circuit coolant	H_2O
2nd circuit operating temperature	330–430 °C
2nd circuit operating pressure	18 MPa

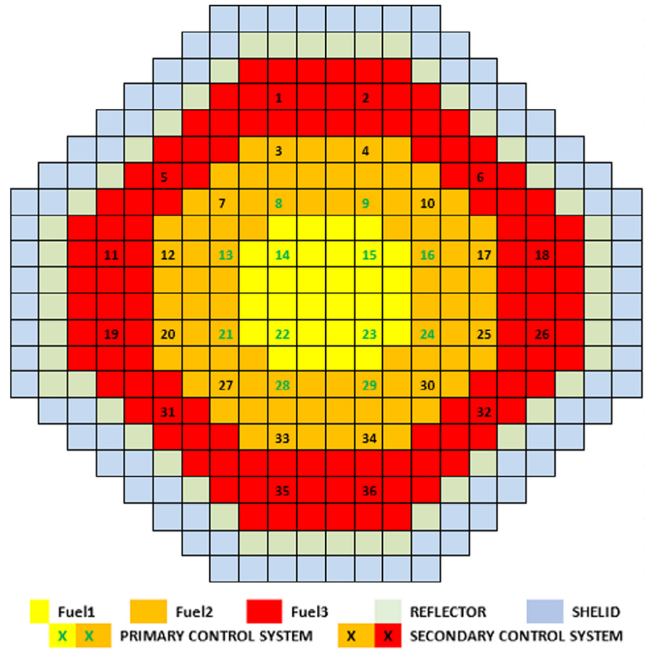

Fig. 1. SNCLFR-100 core layout with location of primary (green) and secondary (black) control system. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
SNCLFR-100 core design parameters.

Design factor		Design value
Number of fuel assemblies		204
Number of primary control assemblies		12
Number of secondary control assemblies		24
Number of reflection assemblies		48
Number of shielding assemblies		84
Total height of the core		3.4 m
Total core radius		1.73 m
Active core height		1 m
Active core radius		1.4 m
Density of PuO_2		11.5 g/cm^3
Density of UO_2		10.96 g/cm^3
Fuel	1st	$PuO_2$16% + $UO_2$84%
	2nd	$PuO_2$19% + $UO_2$81%
	3rd	$PuO_2$24% + $UO_2$76%
Fuel pellet diameter		9.8 mm
Clad material		T91
Clad thickness		0.1 mm
Fuel rod outer diameter		12.2 mm
Pin pitch		17.4 mm
Pitch to diameter ratio(P/D)		1.43

Table 3
Compositions of U.

Isotope	Fraction [wt.%]
^{234}U	0.0029
^{235}U	0.3989
^{236}U	0.0099
^{238}U	99.5882

3. Tools and modeling

Neutronics analyses have been performed with MCNP (Monte Carlo Team, 2003) and MCNPX used JEFF-3.2 (Evaluated File (JEF) Project, 2014) data library and the code for automatic generating