LBE-cooled natural-circulation small modular reactor without on-site refueling

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1. Introduction

Liquid lead-bismuth eutectic has outstanding property as a fast reactor's coolant: natural circulation ability, shielding capability of chemically stable and fair neutron spectrum for transmutation. Based on this, a lead-bismuth coolants fast reactor, PASCAR (Proliferation-resistant, Accident-tolerant, Self-sustainable, Capsular, Assured Reactor) was designed by NUTRECK (Nuclear Transmutation Energy Research Center of Korea).

2. Design goal and constraints

The first design goal is to achieve 20-year cycle length with 100MWt full power operation. Second, geometrical configurations are required to satisfy a pressure loss low enough to permit full heat transport capability by only natural circulation in both normal and abnormal conditions. Third, the 20-year operation has no more than 1$ reactivity swing to reduce transient overpower initiator and remove burnable poison rods.

In addition, the design aims at incorporating four engineering features: (1) underground reactor buildings; (2) whole core refueling; (3) shop-fabrication; and (4) passive decay heat removal by LBE natural circulation associated with reactor vessel auxiliary cooling system (RVACS).

Design constraints are explained in Table I.

Table I: Design constraints of PASCAR

Category	Failure mode	Design definition	Limit value
Thermal limit	Fuel melting	Peak fuel centerline temperature < fuel melting temperature	1000 (^{o}C)
Mechanical limit	Clad collapse	Stress imposed on clad < 2/3 yield strength	240 (MPa)
	Creep rupture	Creep strain < ductility limit	1 (%)
	Clad fatigue	Ratio of applied cycles to cycles to failure < limit value	0.05
Chemical limit	Fuel cladding chemical interaction	Fuel/cladding interface temperature < eutectic U-Fe reaction temperature	700 (^{o}C)
	Cladding oxidation	Ratio of oxide layer thickness to cladding thickness < limit percentage	10 (%)
Radiation limit	Cladding embrittlement	Fast neutron fluence (> 0.1 Mev) < limit value	4.0×10^{23} (n/cm^{2})

3. Calculation methods

The neutronic analysis was performed by using REBUS-3 that is a multi-group diffusion-depletion analysis program [1]. This code could calculate flux solutions of homogenized nodes or mesh cells using DIF3D module without thermal-hydraulic feedback effects [2]. The core characteristics were obtained by solving nodal diffusion theory methods for a square geometry option in REBUS-3. All following calculations used a 24 energy-group structure and TRU burn-up chains from Th-232 to Cm-245. A neutron cross section library with 80 groups for neutron and 24 groups for gamma rays based on JEFF3.0, ENDF/B-VI.8, and JENDL3.3 were utilized as an input of TRANSX producing transport tables in binary cross sections [3]. The final cross section for REBUS-3 was weighted by a preliminary regional neutron flux calculated by a discrete-ordinates transport code, DANTSYS [4]. Kinetic parameters were determined by FREK developed by the Reactor Physics Laboratory of SNU [5]. FREK, still without burn-up and depletion calculation, could also incorporate three dimensional thermal expansion effects for power and temperature transient behaviors modeled by an internal thermal-hydraulic calculation module.

Detailed thermal-hydraulic analysis and transient evaluation were performed by Multi-dimensional Analysis Reactor System (MARS) developed by the Korea Atomic Energy Research Institute [6]. Although MARS was originally intended to use a safety analysis of light water reactor, we modified its physical properties and heat transfer correlations to be applicable to LBE-cooled reactors while maintaining numerical methods, namely, MARS-LBE. For power information, MARS received steady-state power distributions from REBUS-3 while this code obtained kinetic parameters from FREK.

4. Performance evaluation

PASCAR, 100MWt equivalent to 35MWe, has been designed for a 60-year system life with 20 years refueling cycle, having sufficiently small reactivity swing and low radial power peaking. PASCAR operates by using natural circulation of LBE at an average temperature range of 320-420^{o}C in order to limit the corrosion of structural materials to an acceptable level throughout the 60 years of system design lifetime. Table II shows the design parameter of PASCAR including steady state results.

Table II: Design parameters of PASCAR

Design factor	Design value
Inner fuel U/TRU/Zr (wt%)	75.50/14.50/10.0
Outer fuel U/TRU/Zr (wt%)	69.86/20.14/10.0
Fuel rod O.D./Clad thickness (mm)	12/0.85
Clad/Bond/Liner material	Al-containing ferritic steel/Pb/V
Assembly array type	8 by 8 ductless square lattice
Core thermal/ Electric power (MWt)/(MWe)	100/35
Cycle length (EFPY)	20
Average/peak linear heat rate (kW/m)	9.47/15.32
Average/peak power density (MWD/kg)	69.96/89.25
Circulation type	Natural convection
Core inlet/outlet coolant temperature (°C)	320.0/420.0
Coolant mass flow rate in primary side (kg/s)	6901.0
Secondary feed-water/outlet-steam temperature (°C)	252.0/356.0
Water mass flow rate in secondary side (kg/s)	51.6
Maximum fuel temperature (°C)	507

In safety analyses, two controlled transient scenarios (UTOP and ULOHS) were considered. Fig. 1 and Fig. 2 show the results for these analyses.

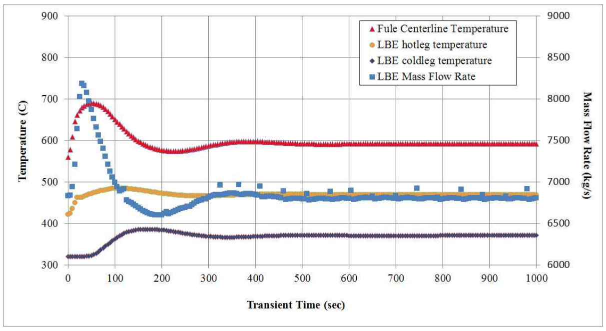

Fig. 1. UTOP results (MFR, temperature)

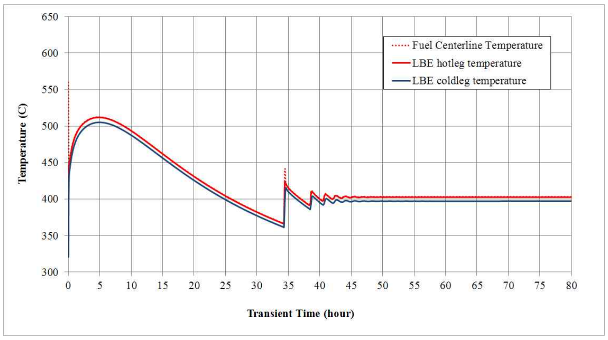

Fig. 2. ULOHS results (temperature)

5. Conclusion

Considering needs for inexpensive small power reactors for remote areas, PASCAR has been developed as a small modular reactor to meet the design principles on proliferation-resistance, safety, and economy. This paper includes optimization studies minimizing a burn-up reactivity loss as well as both steady-state and transient performance evaluations for neutronics and thermal-hydraulics. The reactor using U-TRU-Zr metallic fuels is intended to be operated by only natural circulation of LBE coolant. For proliferation resistance, the core has been judiciously designed for 20 years cycle with a whole core refueling at a multilateral nuclear fuel cycle center, eliminating needs for fuel access at on-site. Excellent accident-tolerance has been achieved by the pump-less design removing concerns over loss of flow accident and by chemically inert coolant ensuring no fire or explosion events. Two accident analyses demonstrate inherent safe shutdown capability enough to guarantee safety margin for fuel melting with negative reactivity feedback and passive decay heat removal, ensuring sufficient safety margin for fuel melting. Corrosive environment is significantly mitigated by low peak outlet temperature and travelling peak power location. Economic viability is improved to be acceptable by taking advantage of standardized design for shop fabrication and modular construction at remote sites as well as uses of superheated steam. Because long-term operation needs reduced core specific power density to satisfy limits of neutron irradiation and peak excess reactivity even forced-convection systems [7], this naturally circulation concept could be competitive in market niches of either in single unit or in cluster deployments at least long burning reactors without on-site-refueling.

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