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

Nuclear Design for Series Lead Based Reactors in China

Yican Wu, Minghuang Wang*, Qi Yang, Chao Liu, Bo Chang, Chao Lian, Jieqiong Jiang, FDS Team
Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China
*Corresponding author: minghuang.wang@fds.org.cn

1. Introduction

The lead cooled fast reactor (LFR) features a fast neutron spectrum, high temperature operation, and cooling by molten lead or lead-bismuth eutectic (LBE), low-pressure, chemically inert liquids with very good thermodynamic properties. According to the latest technology roadmap of Generation IV system proposed by the GIF organization in 2014, the LFR is expected to be the first Generation-IV nuclear system to achieve industry demonstration and commercial application [1].

To catch up with the development of advanced reactors, the Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences · FDS Team has conducted many studies on the lead based reactors, involving in the subcritical reactor for accelerator driven system (ADS) [2], small modular reactor for ocean energy supply [3], miniature reactor for driving small electric-equipments and many other reactor concepts for hydrogen production [4], tritium production, etc.

In this paper, the basic objects for those concepts were introduced briefly. Conceptual designs were presented with preliminary analysis by using the Super Monte Carlo Simulation Program for Nuclear and Radiation Process SuperMC [5].

2. Nuclear Design of ADS Subcritical reactor

ADS system has attracted many countries' attention due to its high waste transmutation ability and inherent safety. Chinese Academy of Sciences (CAS) had launched an engineering project to develop the ADS system. The lead-based reactors were proposed as the subcritical reactor of ADS by INEST FDS Team and series of reactor conceptual designs were carried out for technology demonstration.

The thermal power in the reactor core is targeted at 10 MW. To couple with 250 MeV, 10 mA proton accelerator and spallation target, the reactor is designed as dual-mode operation with subcritical mode for ADS technology test and critical mode for LFR technology test. Considering the technology feasibility, the most widely used UO_2 (^{235}U enrichment: 19.75% w.t.) fuel is chosen as preliminary fuel material. The coolant is lead-bismuth eutectic (LBE) with low neutron moderation which allows greater spacing between fuel pins.

For critical mode, to maintain the highest k_{eff} with the fewest fuel loading, the height of the active zone is set as 800 mm and the diameter of each fuel assembly is about 120 mm, the total number of fuel assemblies is about 86 to keep the k_{eff} being 1.016. The surrounding LBE works as both coolant and reflector. Besides, to prevent the assembly floating in LBE environment, the depleted uranium is placed at the bottom of fuel assembly. The core center is reserved for target coupling. After 10 years operation, the k_{eff} will be 1.016 at the end of life (EOL).

For subcritical operation, the target will be incorporated and the fuel assemblies outside will be replaced by reflect assemblies until the k_{eff} decreases to about 0.97. Fig.1 shows the core layout. With fuel depletion, the k_{eff} will be about 0.92 at EOL by 10 years operation.

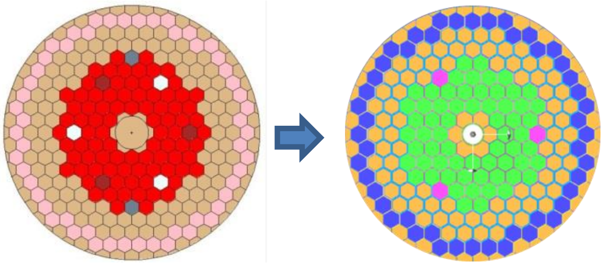
Critical mode Subcritical mode

Fig. 1. Core configuration.

Table I. Key parameters for critical/subcritical core

Parameters	Critical mode	Subcritical mode
Number of Fuel Assemblies	86	63
Fuel Load, t	4.07	3.07
k_{eff} (BOL/EOL)	1.016/1.008	0.970/0.920
Average Neutron Flux, n/cm^2/s	1.00E+14	1.35E+14
Mean neutron energy, keV	479	469
Power Peak Factor for BOL (radial/axial)	1.43/1.23	1.46/1.27
Power Peak Factor for EOL (radial/axial)	1.41/1.26	1.52/1.28
Mean Discharge Burnup (10 years), MWd/kg-HM	5.098	6.478

3. Nuclear Design of Small Modular Reactor

Small reactors are reactors with an equivalent electric power less than 300 MW(e) and have the ability to fabricate major components of the nuclear steam supply system in a factory environment and ship to the point of use. To supply energy in the ocean environments, such as islands far from the land or offshore oil drilling platform, INEST·FDS Team has proposed a small modular reactor cooled by lead-bismuth and named CLEAR-SR. As a small reactor, CLEAR-SR is designed integral with all main components inside the vessel, as shown in Fig.2.

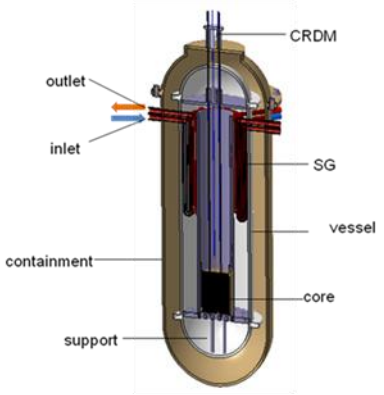

Fig. 2. Reactor layout of CLEAR-SR.

The core is located at the lower part and UN with ^{235}U enrichment 19.75% is chosen as fuel because of its higher melting point (2850 ℃), higher thermal conductivity and advantageously increased density (14.32g/cm^3). Fig.3 shows the core arrangement. The ratio of height to diameter of core is determined through the optimization analysis of loading amount and power distribution. Considering the weak slowing-down and absorption power of LBE, the assembly is designed with larger diameter of rod and lattice pitch, which can reduce the loading amount and improve the natural circulation power in emergency.

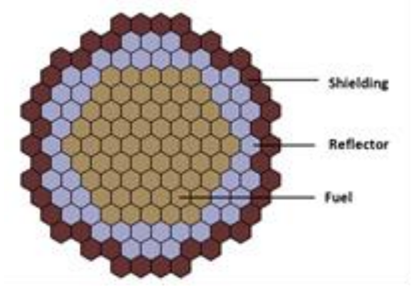

Fig. 3. Core layout of CLEAR-SR.

Some preliminary neutronics analysis has been conducted with SuperMC to assess the performance of core during its operation, as given in Table II. From the results, CLEAR-SR shows negative temperature reactivity coefficients, void coefficients and expansion coefficients. According to burn-up analysis, CLEAR-SR has a long fuel cycle about 13 years and the burnup of the fuel assembles was ~63MWd/t HM at the end of a fuel cycle.

Table II. Reactivity coefficients of CLEAR-SR core

Coefficients / unit	BOC	EOC
Fuel Doppler (pcm/K)	-0.17	-0.07
Coolant temperature (pcm/K)	-5.29	-6.20
Void coefficient (pcm/%void)	-37.65	-22.54
Radial expansion (pcm/%)	-595.62	-646.46
Axial expansion (pcm/%)	-298.84	-353.35

4. Summary

Recently, energy demand drive nuclear energy development in China, and diversified application of nuclear energy could become a trend with the further development of economy, such as for ocean development, for solve freshwater problem and so on. Based on the development of lead-based coolant technology, INEST·FDS Team has finished many conceptual designs for various advanced reactors.

In this paper, the nuclear design for the critical/subcritical core of ADS and the core of small modular reactor CLEAR-SR is introduced briefly. With the Super Monte Carlo Simulation Program for Nuclear and Radiation Process SuperMC, preliminary neutronics analysis for these reactors were conducted to verify the theoretical feasibility of the design.

Besides the reactor for ADS and small modular reactor CLEAR-SR, INEST·FDS Team has also conducted many conceptual design for other advanced reactors based on the development of lead based coolant technologies. It includes the CLEAR-Mini which is table-sized reactor or basketball-size reactor for solar battery in the space exploration and small electric-equipments, the CLEAR-H which combines the nuclear reactor and SOEC (solid oxide electrolysis cells) technology for hydrogen production, the CLEAR-T which is accelerator driven subcritical reactor to produce tritium for the fusion reactors, etc.Further studies will be carried on to achieve further development of nuclear energy in the future.

Acknowledgements

This work is supported by the Strategic Priority Science & Technology Program of the Chinese Academy of Sciences (NO. XDA03040000). We would further like to thank the great help from the other members of FDS Team in this research.

References

1. Zhang J, Kapernick R J, McClure P R, et.al, Lead-bismuth eutectic technology for Hyperion reactor, Journal of Nuclear Materials, 441, 644 (2013).
2. Wu Y, Bai Y, Song Y, et al, 2014. Design and R&D Progress of China Lead-Based Reactor, 22nd

International Conference on Nuclear Engineering. American Society of Mechanical Engineers: V003T06A051-V003T06A051.

3. Wang M, Lian C, Li Y, etc. Preliminary Conceptual Design of a Lead-bismuth Cooled Small Modular Reactor (CLEAR-SMR), International Journal of Hydrogen Energy, DOI: 10.1016/j.ijhydene.2015.03.097
4. Yuan B, Wang M, Jiang J, et al, Preliminary Neutronics Design and Analysis for Accelerator Driven Subcritical Tritium Production Reactor ADS-T. Nuclear Science and Engineering, 33,175 (2013).
5. Wu Y, Song J, Zheng H, et al. CAD-Based Monte Carlo Program for Integrated Simulation of Nuclear System SuperMC. Ann. Nucl. Energy(2014), http://dx.doi.org/10.1016/j.anucene.2014.08.058 .
6. Wu Y, FDS Team. CAD-based Interface Programs for Fusion Neutron Transport Simulation. Fusion Eng. Des., 84, 1987 (2009).