Neutronics Experimental Verification for ADS with China Lead-based Zero Power Reactor

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Abstract. An Accelerator Driven System (ADS) project for nuclear waste transmutation has been launched by Chinese Academy of Sciences (CAS) since 2011. China LEAd-based Reactor (CLEAR) was selected as the reference reactor for the CAS ADS project and was designed and developed by Institute of Nuclear Energy Safety Technology (INEST), CAS. According to the research and development roadmap of CLEAR, a 10 MWth lead-bismuth cooled pool-type research reactor named CLEAR-I coupled with a proton accelerator will be constructed at the first stage.

In order to verify the nuclear physics performances and the coupling techniques for the ADS system, a multifunctional lead-based zero power reactor (CLEAR-0) has been built, which is driven by a high intensity D-T fusion neutron generator (HINEG). A brief introduction on the design objective, experiment functions and system description for CLEAR-0 is given in this paper. The recent R&D progress on core design and coupling system is also presented. The first stage of CLEAR-0 is scheduled to couple with the first phase of HINEG and be finished for construction in the end of 2016, series of core characteristic experiments will be carried out in CLEAR-0. The testing data will be used to validate the calculation method, program and database used in the nuclear design, and also to support the safety analysis and license application for CLEAR-I.

Key Words: Accelerator Driven System (ADS); zero power reactor; China lead-based research reactor; CLEAR-0.

1. Introduction

Lead-based reactor, lead-cooled or lead-bismuth (LBE) cooled reactor, was considered as one of the most important candidates of the Generation-IV nuclear energy systems and Accelerator Driven sub-critical Systems (ADS)[1-2]. Chinese Academy of Sciences (CAS) has launched an an ADS demonstration project since 2011 through three stages[3]. China LEAd-based Reactor (CLEAR), which was developed by Institute of Nuclear Energy Safety Technology (INEST), CAS, was selected as the reference reactor in CAS ADS project. According to the development of the ADS project, the China lead-based research reactor (CLEAR-I) with 10 MWth[4] coupled with a proton accelerator (~250 MeV/~10 mA) will be designed and constructed in the first stage. Experiments of neutronics, thermal hydraulics and safety characteristic of lead-based reactors will be carried out in CLEAR-I, and technologies of construction, operation, control and system coupling will also be verified in the first phase.

Based on the huge efforts on investigating structural materials[5,6], liquid metal technology [7-10], sub-critical system design [11], and advanced nuclear analysis software [12,13] , the conceptual design of CLEAR-I has been completed[2,9] and the preliminary engineering is still on-going.

CLEAR-I is an innovative lead-bismuth cooled dual-mode reactors, and there are many challenge technology research requirements such as structure materials verification, thermal hydraulics phenomena investigation, instrumentation and chemistry control technology, neutronics and reactor operation control technology, etc. With these considerations, two experiment facilities have been designed to meet the experimental requests for technology development and license application. One is for non-nuclear experiment, named CLEAR-S [14,15], the other one is a lead-based zero power reactor, named CLEAR-0.

As a nuclear experiment facility, CLEAR-0 has been built to achieve the neutronics experiment data for applying the license of CLEAR-I, and its design is determined by the requirement of versatility in applications and the desire to test as much as possible developing technologies.

This paper gives a brief introduction on the design objective, experiment functions and system description for CLEAR-0. The recent R&D progress on core design and coupling system is also presented. Series of core characteristic experiments will be carried out in CLEAR-0. The testing data will be used to validate the calculation method, program and database used in the nuclear design, and also to support the safety analysis and license application for CLEAR-I.

2. Objectives and Functions

The main goal of CLEAR-0 is to build a lead based zero power nuclear facility, which is able to perform critical and subcritical dual-mode physical experiments for Lead-Based reactors. The main objectives of CLEAR-0 are listed below:

(1) An experiment platform on key physical issues, control and operation technologies for CLEAR-I construction and operation permission application.

(2) To perform experiments to validate the software, database, methods of physical design and analysis, to validate the nuclear design and control technologies of CLEAR-I;

(3) To perform experiment research on reactor physics theoretical model, software and database, nuclear measuring methods, control and operation technologies for other advanced reactor, such as lead-based fast reactor, fusion-fission hybrid reactor.

Two features have been design for CLEAR-0 to achieve the objectives:

(1) **Flexibility of the core:** The core of the CLEAR-0 is structured designed to fit the requirements of both critical and subcritical operations. All of the core components can be arrange flexible, include fuel assemblies, moderator assemblies, detector ducts, control rods and so on. CLEAR-0 also designed some auxiliary supporting structure for ion beam pipe auxiliary support and installation.

(2) **Multi-protection of Safety:** Two independent shutdown systems have been design for CLEAR-0, include safety rod device and the core collapse reactor shut down device and advanced control system. These devices can ensure the safety of the CLEAR-0 in harsh conditions.

3. Design description

The reactor proper of CLEAR-0 consists of the container, the core structure, reactor core component, roof platform, control rod drive mechanism supporting structure, top auxiliary supporting structure, and the bottom supporting structure of the container, core collapse

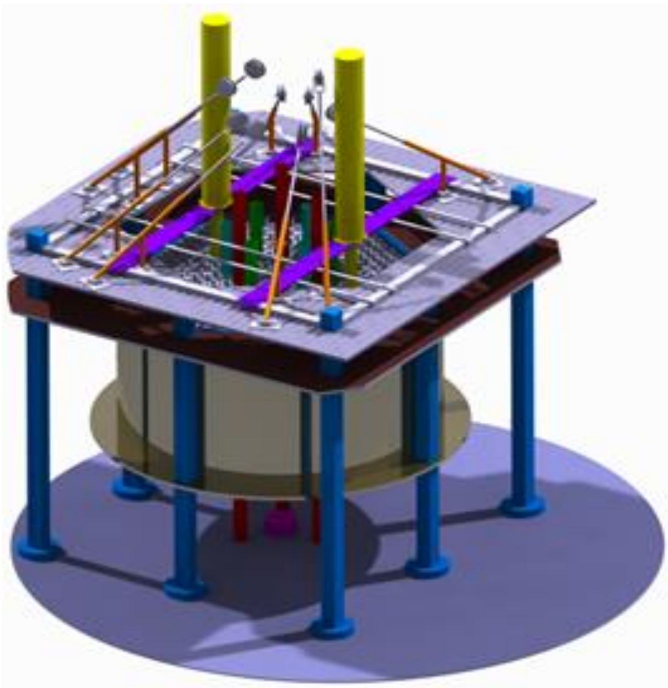

FIG. 1. The global view of the present design of CLEAR-0

TABLE I: DESIGN OPTIONS OF CLEAR-0

	Items	CLEAR-0
Reactor Core	neutron flux	~1×10^8 n/cm^2·s
	Coolant simulant	Solid Lead-Bismuth
	Fuel	19.75% enrichment UO_2
External Neutron Source	Neutron yield	10^{12} n/ s
	Target	T-Ti/Water cooling

shutdown mechanism. The global view of the present design of CLEAR-0 is showed in *FIG. 1.*. The main design options and considerations are listed in TABLE I.

3.1. Core Design

To simulate the neutronics performance of CLEAR-I, the core of CLEAR-0 is designed as the same layout of CLEAR-I but with solid lead alloy. Considering the technology feasibility, the most widely used UO_2 (^{235}U enrichment: 19.75% w.t.) fuel was chosen as fuel material. Same as CLEAR-I, CLEAR-0 is also able to be operated at both critical and subcritical modes. *FIG. 2.* shows the corresponding core layouts of two modes. For critical mode, the central areas of the core is reserved for measurements and tests, two independent control systems are designed for reactivity adjustment and shutdown. For subcritical mode, accelerator with targets are inserted into the core center to provide external neutrons, the fuel assemblies at outer rounds are replaced with solid lead alloy which also works as reflector, the control assemblies are decreased to three just for reactivity adjustment during experiments.

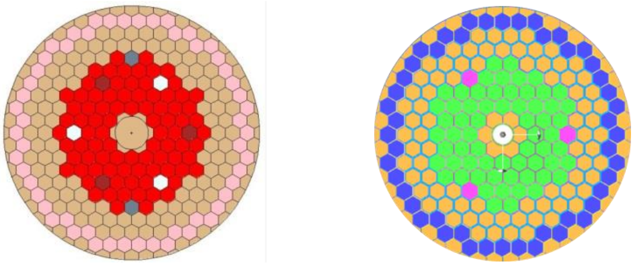

FIG. 2. Layout of core

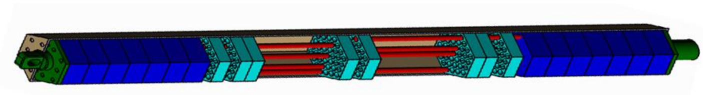

FIG. 3. The design geometry of FA for CLEAR-0

The fuel assembly (FA) configuration is shown in *FIG. 3.*. Each FA consists of fuel pins arranged in a triangular lattice with a pitch of 13.68 mm and a pin diameter of 12 mm. The active fuel length in each FA in CLEAR-I is 800 mm. In order to increase the flexibility of assembly, the active fuel is divided into two parts equally in CLEAR-0. Therefore, each fuel assembly (FA) includes 122 (61×2) fuel pins and the total length of fuel pellets in each pin is 400 mm. The fuel pins are arranged in a typical hexagonal wrapper with an assembly dimension of 120.7 mm plate-to-plate. Unlike one in CLEAR-I, the wrapper used in CLEAR-0 is divided into two parts which are bolted with operation head and bottom nozzle. Therefore, the fuel assembly could be assembled more conveniently. CLEAR-0 also chooses solid LBE block with hexagonal honeycomb shape to simulate the same coolant in CLEAR-I, as shown in *FIG. 3.*

3.2. Coupling

Two different neutron sources can be coupled with the subcritical core.

(1) The neutron tube: neutron tube diameter of 50 mm, its sealing components outside diameter is not more than 90 mm, placed in a special component inside the shell, as for the core center component activity area and a half high.

FIG.4. The design geometry of accelerator-based D-T neutron generator

(2) Accelerator-based D-T neutron generator (*see FIG.4.*): The high intensity D-T fusion neutron generator (HINEG) design to be able to couple with the core of CLEAR-0. Considering the feasibility to couple with accelerator, parts of components of the main safety piece can be flexibly got out, the center for socket with a diameter of 70 mm installation space. At the same time, the roof platform and auxiliary supporting structure is convenient for beam pipe auxiliary support and installation, in order to achieve coupling possible.

4. Verification experiment

The verification experiments plan to perform in CLEAR-0 include two phases. In the first phase, a natural uranium subcritical core will be coupled with HINEG. In this stage, experiments are focus on nuclear date evaluation and software validation for CLEAR-I. In the second phase, the 19.75% enriched fuel assemblies will be installed in CLEAR-0. The neutronics design and reactor control methods for CLEAR-I will be verified in this stage.

In this year HINEG coupling have successfully installed in CLEAR-0, which can produce up to 2 mA deuteron beam. The deuteron ion beam will bombs into a titanium-tritium or titanium-deuterium deposits water cooling target which located in the center of the subcritical core. The maximum neutron yield can reach to 10^{12} n/s. The target will be surrounded by 13 natural uranium fuel assemblies and 18 LBE assemblies.

Measurements of fission rate and neutron flux will be performed in early 2017. ^{235}U fission chamber will be set in different places to measure axial and radial fission rate of core. And activation foil sets, include Al, In, Au, will be used to determine neutron flux in both fuel and reflector region. The data acquired from experiments and Monte Carlo calculations will be compared with each other to validate the design of CLEAR-0 and to assess code for CLEAR-I development.

5. Conclusions

CLEAR-0 is the first multi-functional lead-based zero-power physical testing facility in China which uses an external neutron source to carry out the engineering verification for different nuclear reactors. The technical requirements for ADS are taken into account in CLEAR-0. Taking the advantage of the flexible core, robust safety and advanced control system, CLEAR-0 can model different type of advanced reactor, such as ADS, fusion-fission hybrid reactor and small modular lead-based reactors.

The first stage of CLEAR-0 is scheduled to be finished for construction and will be commissioning in the end of 2016, several neutronics experiments will be performed on the platform for design and licensing of CLEAR-I and R&D work of ADS.

Acknowledgements

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA03040000). We further thank the great help from other members of FDS Team in this research.

Reference

[1] Wu YC, Chen ZB, Hu LQ, et al. Identification of Safety Gaps for Fusion Demonstration Reactors. Nature Energy, DOI: 10.1038/NENERGY.2016.154.

[2] Alemberti A, Smirnov V, et al. Overview of lead-cooled fast reactor activities, J. Progress in Nuclear Energy, 2014, 77: 300-307.

[3] Zhan WL, Xu HS. Advanced Fission Energy Program-ADS Transmutation System, J. Bulletin of

Chinese Academy of Sciences, 2012, 27(3): 375-381.

[4] Wu YC, Bai YQ, et al. Conceptual Design of China Lead-based Research Reactor CLEAR-I , J. Chinese Journal of Nuclear Science and Engineering, 2014, 2: 201-208.

[5] Huang QY, Baluc N, Dai YQ, et al. Recent Progress of R&D Activities on Reduced Activation Ferritic/Martensitic Steels, J. Journal of Nuclear Materials, 2013, 442(1): S2-S8.

[6] Huang QY, Gao S, Zhu ZQ, et al. Progress in Compatibility Experiments on Lithium-Lead with Candidate Structural Materials for Fusion in China, J. Fusion Engineering and Design, 2009, 84:242-246.

[7] Wu YC, the FDS Team. Design Status and Development Strategy of China Liquid Lithium-Lead Blankets and Related Material Technology, J. Journal of Nuclear Materials, 2007, 367:1410-1415.

[8] Wu YC, FDS Team. Design Analysis of the China Dual-functional Lithium Lead (DFLL) Test Blanket Module in ITER, J. Fusion Engineering and Design, 2007, 82: 1893-1903.

[9] Wu YC, Huang QY, Zhu ZQ, et al. R&D of Dragon Series Lithium Lead loops for Material and Blanket Technology Testing, J. Fusion Science and Technology, 2012, 62(1): 272-275.

[10] Wu YC, Bai YQ, Song Y, et al. Development Strategy and Design Options of China Lead-based Research Reactor for ADS Transmutation System, J. Annals of Nuclear Energy, 2016, 87:511-516.

[11] Wu YC, Jiang JQ, Wang MH, et al. A Fusion-Driven Subcritical System Concept Based on Viable Technologies, J. Nuclear Fusion, 2011, 51(10):103036.

[12] Wu YC, Song G, Cao RF, et al. Development of Accurate/Advanced Radiotherapy Treatment Planning and Quality Assurance System (ARTS), J. Chinese Physics C (HEP & NP), 2008, 32(Suppl. II):177-182.

[13] Wu, YC, Song, J., Zheng, H., et al. CAD-based Monte Carlo program for integrated simulation of nuclear system SuperMC, J. Annals of Nuclear Energy, 2015, 82: 161–168.

[14] Wu, YC. CLEAR-S: an integrated non-nuclear test facility for China lead-based research reactor. J. International Journal of Energy Research, 2016.

[15] Wu, YC. Design and R&D Progress of China Lead-Based Reactor for ADS Research Facility, J. Engineering, 2016, 2(1):124-131.