R&D Progress of China Lead-Based Reactor

Yican Wu*, FDS Team

Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China

* *E-mail contact of main author: yican.wu@fds.org.cn*

Abstract. In 2011, the Chinese Academy of Sciences (CAS) launched an engineering project to develop an accelerator-driven subcritical system (ADS) for nuclear waste transmutation. The China LEAd-based Reactor (CLEAR), proposed by the Institute of Nuclear Energy Safety Technology (INEST), was selected as the reference reactor for ADS development, as well as for the technology development of the Generation IV lead-cooled fast reactor. The conceptual design of CLEAR-I with 10 MW thermal power has been completed. KYLIN series lead-bismuth eutectic (LBE) experimental loops have been constructed to investigate the key technologies. In order to validate and test the key components and integrated technology of the lead-based reactor, the lead alloy cooled non-nuclear reactor CLEAR-S, the lead-based zero power nuclear reactor CLEAR-0, and the lead-based virtual reactor CLEAR-V are under realization.

Key Words: China LEAd-Based Reactor (CLEAR), accelerator-driven system (ADS), Lead-bismuth eutectic (LBE), technology R&D

1. Introduction

An accelerator-driven subcritical system (ADS) is considered for construction in China to be an innovative nuclear power system due to its excellent capability for nuclear waste transmutation and its potential benefits for nuclear energy sustainability. Due to its features—a hard neutron spectrum, high neutron flux, and good capability for the transmutation of minor actinide (MA) and long-lived fission products (LLFP)—the ADS has exhibited great superiority in achieving nuclear waste transmutation and energy multiplication. Moreover, it can significantly reduce potential radiological hazards caused by nuclear waste and improve the utilization of nuclear resources [1–2]. Based on these considerations, the Chinese Academy of Sciences (CAS) launched a Strategic Priority Research Program named the “Future Advanced Nuclear Fission Energy-ADS Transmutation System.” This program aims to develop and master all the key technologies of the ADS through three phases of R&D [3].

In the first phase, an ADS research facility will be built, consisting of a proton accelerator, a heavy metal spallation target, and a subcritical reactor. The China LEAd-based Reactor (CLEAR) proposed and developed by the Institute of Nuclear Energy Safety Technology (INEST/FDS Team), CAS [4–5] was selected as the reference reactor system of CAS ADS project. According to the development plan of the CAS ADS project, the reactor correspondingly consists of three phases, with the goals of developing a 10 MWth lead-based research reactor, a 100 MWth lead-based engineering demonstration reactor, and a 1000 MWth lead-based commercial prototype reactor. During the first phase, a 10 MW lead-bismuth cooled research reactor named CLEAR-I will be designed and built to carry out experiments on neutronics, thermal hydraulics, and safety characteristics. Moreover, the lead-based reactor technologies of construction, operation, control, and system coupling will be verified in the first phase.

This paper gives a brief introduction and description of the CLEAR-I reactor and presents the R&D progress on heavy liquid metal loops, key technologies, safety analysis and environmental impact assessment.

2. Technical characteristics and current status of the lead-based reactor

The lead-based fast reactor, which is one of the Generation IV nuclear systems, is considered to be the most promising reactor option for the ADS system. According to the latest technology roadmap released by the Generation IV International Forum (GIF), the lead-cooled fast reactor (LFR) is expected to be the first demonstration and commercialization nuclear system of all the Generation IV systems [15]. The lead-based breeding (e.g., lithium-lead alloy) blanket is also being studied extensively for nuclear fusion reactor research around the world, due to its high heat removal, adequate tritium breeding ratio, relatively simple design, and potential attractiveness in terms of economy and safety.

Lead or lead alloy (lead-based) materials have low neutron absorption and moderation characteristics, resulting in good nuclear waste transmutation and fuel-breeding capability. Due to the low melting temperature and high boiling temperature of lead-based materials, a lead-based reactor can be operated under normal pressure, drastically lowering risks due to potential loss-of-coolant accidents (LOCAs) and increasing the electricity production efficiency. Fire and/or explosion risk issues can also be eliminated due to the chemical inertia of lead-based materials. Passive safety characteristics can be enhanced by passive decay heat removal, which is realized by the excellent heat and natural circulation capabilities of the coolant [6]. Thus, the lead-based reactor is considered to be the reference technology in most ADS programs around the world.

By taking advantage of this technology's relatively good technical maturity, excellent characteristics, and extensive and attractive application prospects for both fission and fusion energy systems, a number of lead-based reactor engineering projects are ongoing worldwide, such as the SVBR-100 [7] and BREST-OD-300 projects [8] in Russia, the MYRRHA ADS project [9] in Belgium, and the ELFR and ALFRED projects [10] in the European Union. Furthermore, various design and technology development activities are being conducted in the United States, Japan, and Korea.

3. China lead-based research reactor (CLEAR-I)

3.1. Design characteristics

CLEAR-I is a lead-bismuth cooled research reactor for the ADS research facility. The experimental objectives are expected to be achieved step by step, such as loading different types and amounts of fuel or adjusting the intensity of the proton beam, while the design and construction is implemented in the meantime. The main design principles are defined to meet the project objectives, including technical feasibility, safety and reliability, experimental flexibility, and later-upgrade sustainability.

(1) Technology feasibility: Relatively mature fuel for the initial loading, materials, and components technologies are adopted to reduce the technology gap and the cost of the reactor construction.

(2) Safety and reliability: Due to the neutronics features, the favorable thermal-physical and low chemical reactivity properties of lead-bismuth eutectic (LBE), the reactor has a negative temperature reactivity coefficient and passive decay heat removal capability.

These features significantly improve the inherent safety of CLEAR-I, effectively avoiding the possibility of a Fukushima-like accident.

(3) Experimental flexibility: Its dual operation mode ensures that CLEAR-I can be operated in either subcritical or critical conditions. A remote refueling system is designed to make sure with different core configurations and different fuel types can be tested conveniently.

(4) Technology sustainability: UO_2 has been adopted as the first loading fuel; advanced fuels (MOX, TRU, etc.) and MA-based fuels will be tested in later steps in order to validate the transmutation technology.

Based on the above design principles, the innovative dual operation mode lead-bismuth research reactor CLEAR-I was designed and developed. Therefore, the ADS system coupling test and the lead-based reactor critical operation test can be carried out in the same structural platform. Thus far, the detailed conceptual design of CLEAR-I is complete and the preliminary engineering design is underway. The LFR is one of the most promising concepts for Gen IV implementation base on GIF Road Map 2014, and due to its unique and innovative design features, CLEAR-I has been selected into the LFR catalogue by the International Atomic Energy Agency (IAEA) [11] and the GIF [12].

3.2. Design description of CLEAR-I

Fig. 1 shows the overall 3D view of CLEAR-I. The primary cooling system is a pool-type configuration with a 600 tons LBE inventory inside, and the operation pressure is close to atmospheric pressure. The coolant is circulated by two primary pumps. Four primary heat exchangers are directly immersed in the pool. The reactor vessel, which is the boundary of the primary system, is designed as a double wall shell, and hung at the top. The secondary coolant is pressurized water at 10 MPa, and the inlet/outlet temperatures of the heat exchanger for the secondary coolant are 250 ℃ and 270 ℃, respectively. The final heat sink is an air cooler. The control rod drive mechanism (CRDM) is designed as two independent systems with different physical principles. The in-vessel fuel handling system (IVFHS) consists of double rotating plugs, a transfer machine, and a rotor lift machine.

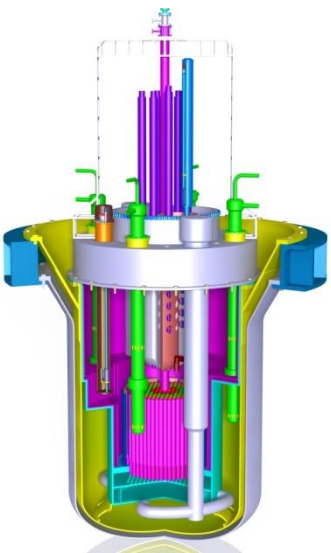


FIG. 1. *3D view of the CLEAR-I reactor.*

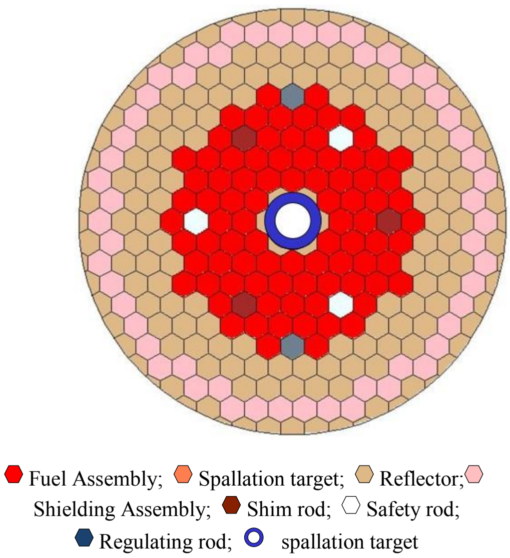


FIG. 2. *The reactor core layout in critical mode.*

The reactor core consists of fuel, shielding, and inner-to-outer reflector assembly in the radial direction, and 8 control rods are configured at specified positions, shown in *Fig. 2*. Each fuel assembly (FA) is surrounded by a hexagon wrapper containing 61 pins. The reactor core is designed in both subcritical and critical conditions. The neutronics analysis of the core was performed with the Super Monte Carlo Simulation Program for Nuclear and Radiation Process (SuperMC) [13], and the results show that the reactivity coefficients are negative.

4. R&D of key technologies and test facilities

Considering the engineering realization requirements of CLEAR-I as well as the technology continuity, the R&D activities were mainly focused on heavy liquid metal coolant technology, the reactor key components, structural material and fuel, reactor operation, and control. KYLIN series LBE experimental loops were constructed to perform structural material corrosion experiments, thermal-hydraulic tests, and safety experiments. Key components including the main pump, heat exchanger, CRDM, and refuelling system for principle verification have been fabricated and tested.

In order to comprehensively validate and test the key component prototypes and the integrated operating technology of the lead-based reactor, the lead-based non-nuclear reactor CLEAR-S, the lead-based zero power nuclear reactor CLEAR-0, and the lead-based virtual reactor CLEAR-V are being constructed.

4.1. Multi-functional lead-bismuth loop KYLIN-II and diverse testing

KYLIN-II is a large multi-functional lead-bismuth experiment loop platform with height 13 m, shown in *Fig. 3*. It has three independent loops, including a material test loop, thermal-hydraulics loop, and safety loop. The objective of KYLIN-II is to carry out the LBE process technology test, structural materials corrosion experiment, FA flow and heat transfer investigation, forced and natural circulation experiment, components prototype proof test, and heat exchanger tube rupture accident investigation. The highest temperature of the material test loop is 1100 °C. The maximum velocity in the thermal-hydraulics loop test section is 10 m/s. The highest pressure and temperature in the secondary water loop of safety loop is 25 MPa and 550 °C, respectively, in order to investigate the heat exchanger tube rupture phenomenon and validate the numerical tools.

FIG. 3. *Multi-functional lead-bismuth loop KYLIN-II.*

4.1.1. LBE process technology

LBE process technology is one of the key issues for the stable operation of a lead-based reactor, due to its dramatic impact on the heat transfer performance of the fuel pin and heat exchanger, the corrosion of structural and cladding material, and the potential risk of blocking the FA or narrow flow channel.

Innovative technologies were developed, such as, electromagnetic induction smelting and online LBE purification, oxygen concentrations in LBE measurement and control, and Po210 purification technology.

The oxygen sensors and oxygen concentrations control maintain stable condition, running for more than 6000 h in the KYLIN-II material test loop, shown in *Fig. 4*. The oxygen concentrations are steadily controlled in the allowable range, from 10^{-6} to 10^{-8} wt%.

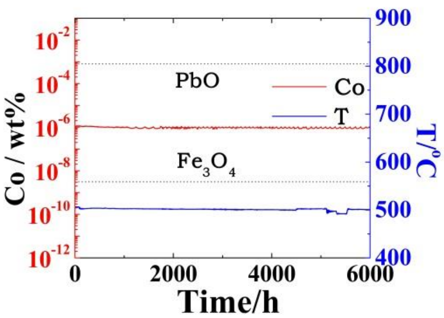
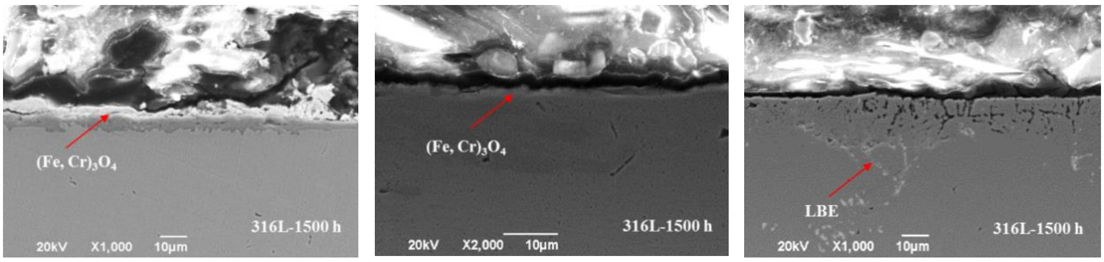


FIG. 4. *Oxygen steadily controlled in the LBE loop.*

4.1.2. Compatibility assessment of structural and cladding materials

In order to investigate and solve the compatibility issues of the lead-based reactor, such as high-temperature corrosion and LME (liquid metal embrittlement), a series of corrosion and mechanical property testing have been done.

Corrosion tests with different oxygen concentrations were carried out. Severe dissolution corrosion was observed in the case of low oxygen concentration. The protective oxide that forms on the steel surface in the case of relatively high oxygen concentration can enhance the anti-corrosion property of the steel. A long-term corrosion simulated operating condition with 1×10^{-6} to 3×10^{-6} wt% dissolved oxygen was test for CLEAR-I. *Fig. 5* shows cross-section appearance of Type 316L stainless steel at 500℃ in stagnant LBE with different oxygen concentrations.



(a) 10^{-4}wt% (b) 10^{-6}wt% (c) 10^{-8}wt%

FIG. 5. *Cross-section appearance of 316L steel in stagnant LBE with different oxygen concentrations.*

4.1.3. Fuel assembly technology

The experimental investigation of cladding tube corrosion and mechanical properties under a liquid lead-bismuth environment, and experimental study on synergic effects between liquid lead-bismuth corrosion and neutron irradiation were completed. The key technologies of the FA fabrication and structural design have been obtained, shown in *Fig.6*. A series of simulated assemblies were fabricated to investigate the flow, heat transfer, and structural stability features. The experimental results have already been obtained for the structural design optimization of the FA.

(a) (b) (c)

FIG. 6. *(a) Flowing test assembly; (b) Heat transfer test assembly; and (c) Structural stability test assembly.*

4.1.4. Reactor in-vessel components

Mechanical pumps have been developed and their performance has been tested in the KYLIN-II loop, and research into ceramic materials and coating technology is being conducted. A prototype heat exchanger has already been fabricated and was successfully tested in the KYLIN-II loop. The processing technology of a double wall heat transfer tube was verified. Moreover, the heat transfer performance was evaluated.

(a) (b) (c) (d)

FIG. 7. *(a)CRDM Prototypes in air; (b)CRDM Prototypes in LBE; (c) IVFHS Prototypes in air; and (d) IVFHS Prototypes in LBE.*

Prototypes of CRDM (Control Rod Drive Mechanism) for testing in air and LBE were accomplished, as shown in *Fig. 7(a)* and *(b)*. A series of tests were carried out both in air and

LBE, including tests on the rod position and velocity control, rod drop, driving motor, and grippers' applicability. Furthermore, the life test in LBE is still in progress.

Prototype IVFHS (In-Vessel Fuel Handing System) has been developed with double rotating plugs and a split-type centre column design. Testing in air and LBE were accomplished, as shown in *Fig. 7(c)* and *(d)*. Based on the simulation analysis and experimental validation of the principle prototype, the double rotating plugs scheme of the IVFHS was proved to be reasonable and feasible. A full-scale engineering prototype for the key technologies validation of the refuelling mechanism in an LBE environment is completed, and the testing is ongoing.

4.2. Lead-based reactor integrated test facilities

Based on the diverse test of key technologies described above, three integrated test facilities are being built, including the lead-based non-nuclear reactor CLEAR-S, the lead-based zero power nuclear reactor CLEAR-0, and the lead-based virtual reactor CLEAR-V, shown in *Fig. 8*. These test facilities are aimed to satisfy the integrated testing requirements of the key components and technologies for CLEAR-I.

4.2.1. Lead-based non-nuclear reactor CLEAR-S

CLEAR-S is a heavy liquid metal pool-type integrated test facility. It will be used to test the 1:1 prototype components for CLEAR-I. There are seven FPS (fuel pins simulator) with 61 pins inside, the same number as in CLEAR-I, and the pins are heated by electric power. One main pump prototype, one main heat exchanger and DHR (Decay Heat Remove) prototype, reactor internals are configured in the reactor vessel with the RVACS (reactor vessel air-cooling system) surrounding outside. CLEAR-S is mainly used to carry out the testing of core heat transfer and flow distribution, the main pump and heat exchanger prototype, the decay heat removal technology, and the pool-type lead-bismuth process technology, as well as to verify the operating and commissioning technology. Moreover, thermal-hydraulics investigations including forced/natural circulation flow, coolant mixing, thermal stratification, and transient safety in the pool will be conducted in order to verify the thermal-hydraulics design and safety analysis programs.

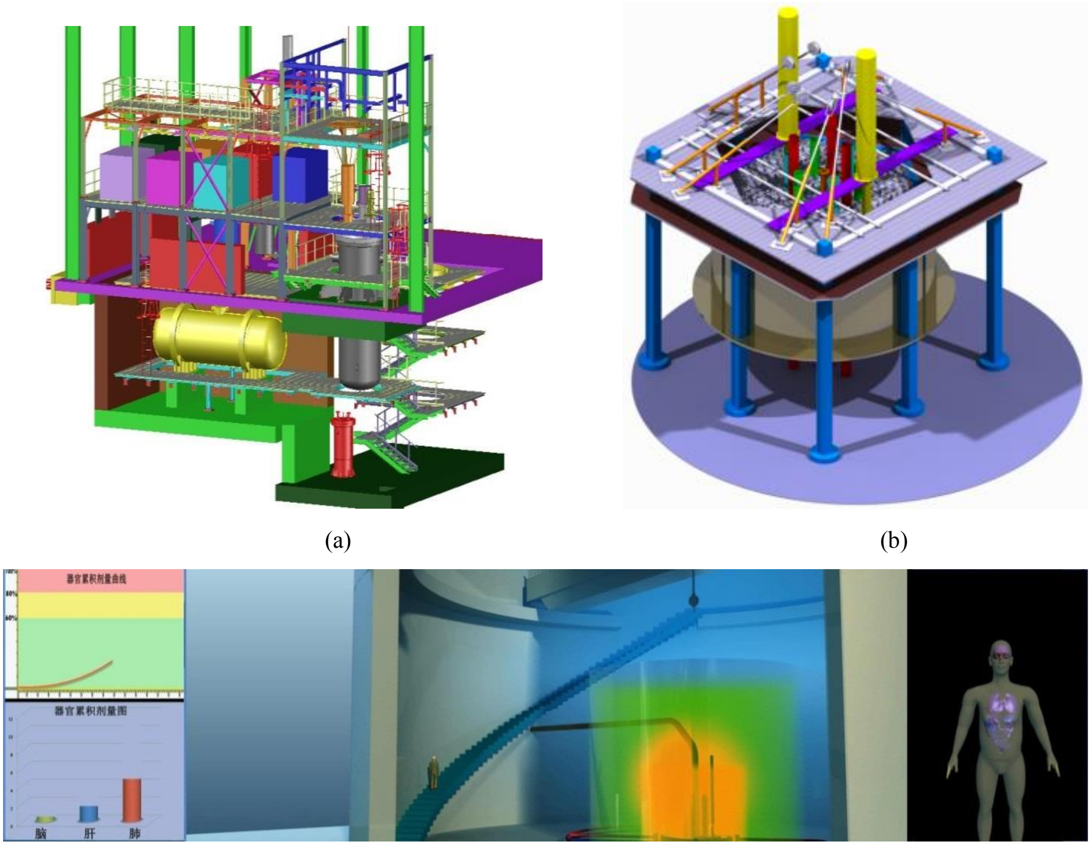
4.2.2. Lead-based zero power nuclear reactor CLEAR-0

CLEAR-0 has the same fuel type, coolant, and core configuration as CLEAR-I and its neutron flux distribution and energy spectrum are similar to those of CLEAR-I. The objective of CLEAR-0 is to carry out core characteristic experiments, such as measurements of critical mass, neutron flux density, neutron energy spectrum, the void effect worth of the control rod value. The results will be used to validate the calculation method, program, and database used in the nuclear design of CLEAR-I. Thus far, the engineering design and construction of CLEAR-0 is complete and the key technologies development is underway.

In addition, the High-Intensity D-T Fusion Neutron Generator (HINEG), which can be coupled with CLEAR-0 for the verification of neutronics physics and the control technology of the ADS, was developed at INEST. HINEG is also a significant neutronics experimental platform for R&D nuclear technology and safety, including the validation of neutronics methods and software, radiation protection, materials activation, and irradiation damage, as well as the neutronics performance of components. The first phase, named HINEG-I, was completed and started commissioning since December 2015, with an intensity of 1.1×10^{12} n/s.

4.2.3. Lead-based virtual reactor CLEAR-V

CLEAR-V has been developed based on the Virtual4DS (Virtual Nuclear Power Plant for Digital Society) system, and will be accomplished soon. Analysis models and modules of neutron physics, radiation shielding, thermal hydraulics, structural mechanics, safety, and environmental impact are included in CLEAR-V. This virtual reactor can be used for lead-based reactor design and safety assessment, can check the consistency of the transient coupling of sub-systems, and can provide solutions for reactor optimization. Thus, it can effectively prevent significant issues caused by dynamic coupling failure between design phases. Furthermore, CLEAR-V can be used as a full-scope training simulator for operator training.



(a) (b)

(c)

FIG. 8. *(a) Lead-based non-nuclear reactor CLEAR-S; (b) Lead-based zero power nuclear reactor CLEAR-0; and (c) Lead-based virtual reactor CLEAR-V.*

5. Safety analysis and environmental impact assessment

Computer codes are indispensable tools in the process of CLEAR-I's design and safety assessment. Therefore more than 20 computer codes has been developed including code for neutron physics SuperMC, thermal hydraulics code for accident analysis NTC, reliability and probabilistic safety assessment code RiskA, and also codes for structural mechanics, radiation shielding and environmental impact assessment, etc. Moreover the validation and verification of these codes has also been carried out or in progress including code-to-code benchmark and comparison with experimental data. Different methods have been adopted including domestic activities and international joint-activities, such as IAEA and OECD/NEA benchmarking activities.

SuperMC, which has been used for CLEAR-I's nuclear design, has already been benchmarked by the IAEA international standard benchmark cases, and the calculation results match well with the experimental data and other codes. More comprehensive benchmarks will be conducted through CLEAR-0 experiments. The experimental results obtained from the KYLIN-II thermal-hydraulics loop and the OECD/NEA Lead Alloy Cooled Advanced Nuclear Energy Systems (LACANES) benchmark activities have already been used to validate the computational fluid dynamics (CFD) and the system analysis program for simulating the fuel pin flow and heat transfer as well as the loop natural circulation. Furthermore, the simulation capability in the pool-type configuration system case will be validated by CLEAR-S and by other pool-type experimental facilities. NTC has been validated by the results from the heat exchanger tube rupture experiment in the KYLIN-II safety loop.

Moreover, a systematic safety assessment and environmental impact assessment was carried out based on the current CLEAR-I design. The Integrated Safety Assessment Methodology (ISAM) proposed by GIF was adopted in the safety assessment. The impacts of whole core transients, blockages, heat exchanger tube rupture, neutron source fluctuation, and radioactivity release accidents were analysed using several different codes (e.g., RELAP, NTC, and FLUENT). Results demonstrated that the radioactivity releases were within acceptable limits and also with a large margin in all considered conditions, proving the inherently safe design and effectiveness of the engineered safety features. In addition, the level 1 probabilistic safety assessment (PSA) was carried out, which provided feedback for optimization of the weak points of the design.

Due to the lack of LFR-related regulation, an LFR design criteria and licensing study was carried out under GIF and through international collaboration. LFR safety design criteria were written and the LFR safety white paper was published jointly. Meanwhile, a completed CLEAR-I design criteria have been established.

6. Summary

In 2011, CAS launched an engineering project to develop the ADS for nuclear waste transmutation. CLEAR-I was selected as the reference reactor for the China ADS project, and was designed and developed by the INEST/FDS Team, CAS. CLEAR-I has subcritical and critical dual-mode operation capability for the validation of both ADS coupling and operation technology as well as of LFR technology. Thus far, a preliminary engineering of CLEAR-I is completed. CLEAR-I has also been selected as the reference reactor design by the IAEA and GIF. KYLIN series LBE experimental loops were constructed to perform structural material corrosion experiments, thermal-hydraulic tests, and safety experiments. The key component prototypes including the main pump, heat exchanger, CRDM, refuelling system, and FA have been fabricated and tested for principle verification. A series of integrated test facilities, including CLEAR-S, CLEAR-0, and CLEAR-V, are being constructed to validate and test the key components and the integrated operating technology of the lead-based reactor. Systematic design and analysis programs have been set up, and the safety analysis has established the inherent safety features of CLEAR-I.

Lead-based reactor R&D may play a very important role in the development of fission application GIF LFRs in the near future, fusion application in the far future, and hybrid fusion-fission reactors in the transition period from fission to fusion energy. Also, due to its attractive properties, the lead-based reactor is an excellent technology to benefit the global power supply and establish safe and sustainable nuclear energy development.

Acknowledgments

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences Grant No.XDA03040000, and the National Magnetic Confinement Fusion Energy Program of China Grant No. 2014GB112000, etc. The authors would like to thank the members of the FDS team for their great help in this research.

References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Accelerator driven systems: Energy generation and transmutation of nuclear waste. Status report, IAEA-TECDOC-985. Vienna (1997).

[2] OECD/NEA, Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles A Comparative Study. 2002.

[3] Wenlong Zhan, Hushan Xu, Advanced Fission Energy Program-ADS Transmutation System, Bulletin of Chinese Academy of Sciences, 2012, 27, 375-381.

[4] Yican Wu, Yunqing Bai, Yong Song, et.al. Development strategy and conceptual design of China Lead-based Reaserch Reactor, Annals of Nuclear Energy, 2016, 87, 511-516.

[5] Yican Wu, Yunqing Bai, Yong Song, et.al. Conceptual Design of China Lead-based Research Reactor CLEAR-I, Chinese Nuclear Science and Engineering, 2014, 34(2), 201-208.

[6] Yican Wu, Minghuang Wang, Qunying Huwang, et.al. Development Status and Prospects of Lead-based Reactors, Nuclear Science and Engineering, 2015, 35(2), 213-221.

[7] Vladimir Petrochenko, Georgy Toshinsky, Oleg Komlev. SVBR-100 Nuclear Technology as a Possible Option for Developing Countries, World Journal of Nuclear Science and Technology, 2015, 5, 221-232.

[8] V.S. Smirnov. Lead-Cooled Fast Reactor BREST– Project Status and Prospects. International Workshop on Innovative Nuclear Reactors Cooled by Heavy liquid metals: Status and Perspectives, 2012, Pisa, April, 17-20.

[9] Hamid Aït Abderrahim, Peter Baeten, Didier De Bruyn, et. al. MYRRHA – A multi-purpose fast spectrum research reactor, Energy Conversion and Management, 2012, 63(11), 4–10.

[10] A. Alemberti, D. De Bruyn, G. Grasso, et. al. The European Lead Fast Reactor Strategy and the Roadmap for the Demonstrator ALFRED, International Conference on FAST REACTORS AND RELATED FUEL CYCLES: Safe Technologies and Sustainable Scenarios - FR13, 4–7 March 2013, Paris, France.

[11] IAEA, Status Of Innovative Fast Reactor Designs And Concepts, October, 2013.

[12] Technology Roadmap Update for Generation IV Nuclear Energy Systems, Issued by the OECD Nuclear Energy Agency for the Generation IV International Forum, January, 2014.

[13] Yican Wu, Jing Song, Huaqing Zheng, et al. “CAD-based Monte Carlo Program for Integrated Simulation of Nuclear System SuperMC” , Annuals of Nuclear Energy, 82, pp. 161 (2015).

[14] Lei Yang, Wenlong Zhan. New concept for ADS spallation target: gravity-driven dense granular flow target, Science China Technological Sciences, 2015, 58(10), 1705-1711.

[15] GIF. Technology Roadmap Update for Generation IV Nuclear Energy Systems, January, 2014.