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Development strategy and conceptual design of China Lead-based Research Reactor

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ABSTRACT

Chinese Academy of Sciences (CAS) launched an engineering project to develop an Accelerator Driven System (ADS) for nuclear waste transmutation since 2011, and China LEAd-based Reactor (CLEAR) proposed by Institute of Nuclear Energy Safety Technology (INEST) is selected as the ADS reference reactor. In this paper, the development strategy and conceptual design of China Lead-based Research Reactor are proposed. The Chinese ADS development program consists of three stages, and during the first stage, a 10 MW_{th} lead-based research reactor named CLEAR-I will be built with subcritical and critical dual-mode operation capability for validation of ADS transmutation system and lead cooled fast reactor technology. Major design principles of CLEAR-I are oriented at technology feasibility, safety reliability, experiment flexibility and technology continuity. Followed by the development strategy and design principles, CLEAR-I design options and conceptual design scenarios are presented.

1. Introduction

Nuclear power is playing an important role and will progressively replace fossil fuels in the world energy supply (Armaroli and Balzani, 2011). However, the nuclear fuel supply and spent fuel accumulation issues will restrict the healthy development of nuclear energy (Poinssot and Gin, 2012). Thus innovative nuclear systems such as fast reactor and Accelerator Driven System (ADS) are expected to resolve these problems in the near term (IAEA, 1997; OECD/NEA, 2002; Rubbia et al., 1995).

The ADS consists of a subcritical reactor, proton accelerator and heavy metal spallation target. High-intensified and high energy protons impinge on heavy metal spallation target to produce spallation neutrons, which can interact with surrounding nuclear fuel in subcritical reactor. The subcritical reactor has an array of nuclear fuel elements without the possibility of sustaining a chain reaction. The neutrons are produced by the interaction of the charged particles with the target materials and their numbers are multiplied in the actinide fuel materials through the fission process. The nuclear reaction of the subcritical reactor can be stopped by turning off the charged particle beam in the case of an accelerator source. The neutron balance can be regulated so that the reactor would be below criticality for the discontinuity of the additional neutrons yielded by the spallation reactions (Nifenecker et al., 2010). ADS has exhibited its great superiority in achieving long-lived radioactive nuclear wastes transmutation and energy multiplication (OECD/NEA, 2002). Because of the inherent advantages, ADS became the research focus during recent years in China, including low activation materials (Huang et al., 2014; Wu et al., 2002; Wu et al., 2009), liquid metal technology (Wu et al., 2007a; Wu et al., 2012), subcritical system design (Wu et al., 2011), and advanced nuclear software (Wu et al., 2009, 2015).

To improve the efficiency of nuclear waste transmutation and Minor Actinides (MA) burning, the high energy and high flux neutrons in the reactor are required. As consequence liquid metal cooled fast reactors have a higher sustainability than thermal reactor (Gulevich et al., 2008). Liquid lead or lead-alloy (lead-based) coolant has many unique nuclear, thermal-physical and chemical attributes, so lead-based reactor is considered as one of the most promising ADS reactors (Hamid et al., 2012; Saito et al., 2006; Song et al., 2007) and the heat source for hydrogen production (Gulevich et al., 2008).

Chinese Academy of Sciences (CAS) launched an engineering project to develop ADS system for nuclear waste transmutation from 2011, and China LEAd-based Reactor (CLEAR) was selected as the reference reactor in CAS ADS project (Zhan and Xu, 2012). During the first stage, a 10 MW lead–bismuth cooled research reactor named CLEAR-I coupled with a 250 MeV/10 mA proton linac and heavy metal spallation target, will be designed and built. It would serve as the verification technological platform for ADS system and lead cooled fast reactor technology, being able to be applied as the research facility for fundamental science and neutron irradiation (Wu et al., 2007b; Wu et al., 2007c).

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Nomenclature

ADS	Accelerator Driven System
CLEAR	China LEAd-based Reactor
CLEAR-I	China Lead-based Research Reactor
CLEAR-II	China lead-based engineering demonstration reactor
CLEAR-III	China lead-based commercial prototype reactor
CLEAR-0	China lead-based zero power reactor
RVACS	Reactor Vessel Air Cooling System
FA	fuel assembly
CRDM	control rod drive mechanisms
CAS	Chinese Academy of Sciences
LBE	Lead–Bismuth Eutectic
LFR	lead cooled fast reactor
MOX	Mixed OXide
V&V	Validation and Verification
HX	heat exchanger
SMR	small modular reactor
DU	depleted uranium
PP	primary pump

In this paper, the development strategy of China LEAd-based Reactor and conceptual design of CLEAR-I reactor will be presented. The conceptual design consists of the design on neutronics, thermal–hydraulics and mechanics and the safety assessment.

2. China ADS and lead-based reactor development strategy

The Chinese ADS development program consists of three stages. In the first stage an ADS research facility, which consists with the CLEAR-I, a proton accelerator (250 MeV/10 mA) and spallation target, will be built-up. The second stage will be foreseen the construction of an ADS demonstration facility, which consists of a 100 MW_{th} nuclear system (China lead-based engineering demonstration reactor, named CLEAR-II) coupled with a proton accelerator (~600 MeV/~10 mA). For the third stage, the ADS commercial prototype facility will be built-up, which consists of a 1000 MW_{th} magnitude reactor (China lead-based commercial prototype reactor, named CLEAR-III) coupled with a proton accelerator (~1500 MeV/~10 mA). As a pre-testing facility, a multifunctional lead-based zero power reactor (CLEAR-0) will be operated to get the neutronics experiment data for applying series license of CLEAR reactors.

CLEAR-I was designed to be operated in a dual ways: critical operation mode for technology test of lead cooled fast reactor (LFR) and subcritical operation mode for ADS operation technology validation. CLEAR-II will be conceived as an engineering demonstration reactor for nuclear waste transmutation using ADS, as pilot-plant of lead-alloy cooled small modular reactor (SMR), and it also could be used as high neutron flux irradiation facility for nuclear fuel and fusion reactor materials, the reactor technology will also benefit for the hydrogen production based on direct contact of gaseous hydrocarbons and evaporated water. CLEAR-III is the commercial prototype reactor of nuclear waste transmutation system.

The technologies of CLEAR series reactor design and development will benefit not only ADS and lead-based fast reactors, but also lead–lithium blanket development of fusion reactor and fusion driven subcritical system, especially in the design and analysis codes, the structural materials, the transmutation fuel element technologies, and the safety assessment technologies.

3. Design options of CLEAR-I

CLEAR-I is designed as a research platform for ADS and lead–bismuth cooled fast reactor verification. The design objectives of CLEAR-I are listed below.

(1) Technology validation of ADS coupling operation and power control.
(2) Verification and Validation (V&V) of numerical tools for design and licensing support.
(3) Neutronics, thermal–hydraulics, and safety characteristics research for ADS and LFR.
(4) Fuel, structural material and component tests for ADS and LFR.
(5) Fundamental study for neutronics and material science.

CLEAR-I is designed as a flexible test platform for different operation modes and different nuclear fuel tests. According to the experimental objects and implementation procedures, the deeply subcriticality and low power mode will be operated on the first step, and then the power will be increased by adding fuel assemblies or increasing proton intensity step by step. The major principles of conceptual design have been approached, including technology feasibility, safety reliability, experiment flexibility and technology continuity.

(1) Technology feasibility

Proven fuel, materials and components are selected, and coolant operation temperature is kept below the critical thresholds.

(2) Safety reliability

Based on the excellent thermal-physical and chemical properties of LBE, the reactor is conceived to have a negative reactivity coefficient. A passive decay heat removal system is proposed.

(3) Experiment flexibility

CLEAR-I can be run in both subcritical and critical operation modes, and adopts a remote refueling system to guarantee the achievement of any core configuration, allowing the installation of innovative fuel test rig.

(4) Technology continuity

The reactor structure, key components and main systems have the same characteristics of the demonstration reactor. Advanced nuclear fuel assemblies can be tested in CLEAR-I.

With the guideline of abovementioned principles, the design options of CLEAR-I are preliminarily determined, as shown in Table 1.

4. Design description of CLEAR-I

4.1. Reactor core design

Reactor core includes spallation target, fuel assemblies, reflection assemblies, and shielding assemblies. The whole core is enclosed by core barrier with heat shielding on the inner surface