Preliminary Analysis of Source Term for Primary Coolant System of China Lead-based Research Reactor (CLEAR-I)

Tongqiang Dang*, Lanfang Mao, Haixia Wang, Qian Guo, Yican Wu, FDS Team

Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China
**Email: tongqiang.dang@fds.org.cn*

INTRODUCTION

The Chinese Academy of Sciences (CAS) launched an engineering project to develop ADS system and lead-based fast reactors named China LEAd-based Reactor (CLEAR) series. On the first stage of this project, the China Lead-based Research Reactor with 10 MWth (CLEAR-I)，developed by Institute of Nuclear Energy Safety Technology (INEST) will be built [1]. CLEAR-I was designed to test heavy liquid metal fast reactor technology and accelerator driven subcritical operation for ADS system [2-4].

The radioactive source term assessment is vital to characterize the safety of the reactor design [5]. In this summary, source term calculation was carried out for the primary coolant system of CLEAR-I. Radioactive source terms of the primary coolant system include the fission products (FP), activation products, activation corrosion products and activated cover gas. It plays an important role in estimating radiation dose of worker and public during maintenance and decommissioning.

DESCRIPTION OF THE ACTUAL WORK

Model and Codes for Source Term Calculation

Reactor Configuration

The core consists of seventy fuel assemblies arranged in an annular array of four rows. The inner row surrounds the neutron source (Spallation Target) assembly. The fuel assemblies are all the same, each loaded with sixty-one fuel pins which have the same cross section and fuel composition with enrichments (19.75%). The configuration of the reactor is shown in Fig. 1. The primary coolant system is composed mainly of the Lead-bismuth eutectic (LBE) coolant and the cover gas Argon.

The lead-bismuth target is the external source in the subcritical system. The energy of incident proton is 250MeV and the maximum fluence is 10mA.

Contents for Source Terms Calculation

The primary coolant system is composed mainly of the Lead-bismuth eutectic (LBE) coolant and the cover gas Argon. The primary coolant is 55.5% bismuth and 44.5% lead in weight and the cover gas is Argon that prevent primary coolant from air directly.

The source terms in the primary coolant system is based on an assumption of fuel clad failure and its own activation, and calculated by mechanism models [6]. The source terms of LBE coolant and cover gas were shown as following.

The source term of LBE coolant includes:
(1) The activation of liquid lead-bismuth eutectic.
(2) The leakage of fission products due to the fuel cladding failure.
(3) The radioactive corrosion products of structure materials.

The source term of cover gas includes:
(1) The activation of Argon.
(2) The evaporation of the LBE activation product polonium (^{210}Po).
(3) The releases of fission gas (Kr, Xe) and volatile fission products (I, Cs, Sr, Te, etc.) due to the fuel cladding failure into cover gas.

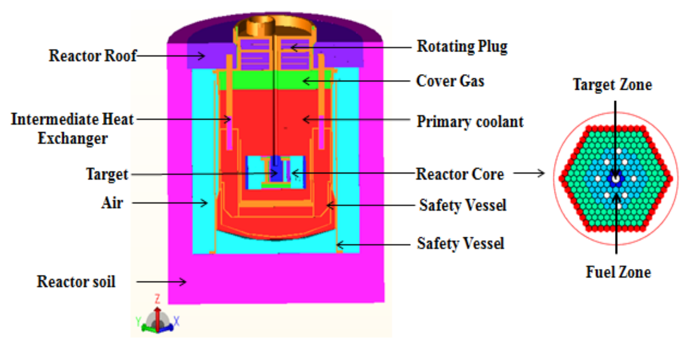

Fig. 1 Configuration of CLEAR-I

Calculation model for volatile radionuclides

As the concentrations of volatile radionuclides in LBE coolant are extremely low, the LBE solution could be thought of ideal solution. So we use the Raoult's law to evaluate their evaporation from LBE coolant to cover gas. Raoult's law is shown in equation 1.

$$P_i = P_i^* \cdot x_i \qquad (1)$$

Where P_i is the partial pressure of the component i in the solution, P^*_i is the vapor pressure of the pure component i, and x_i is the mole fraction of the component i in the solution.

Methods for source terms calculation

The main calculation methods for primary coolant system were shown in the following:

(1) The source terms for normal operation calculations were based on long-term operation under the full power (10MW). The refueling cycle and lifetime of the reactor are 10 years and 30 years, respectively.
(2) The radioactivity of the fuel zone and other material was calculated.
(3) The fission products could diffuse into the pellet-clad gap, and then release into LBE coolant. Because of the complexity of the releasing mechanism, we use the escape rate to describe this release process.
(4) To calculate the source terms of FP in the primary coolant, the escape rate was used to describe the release behavior of FP from fuel pellet to primary coolant, and assuming the fuel cladding damage rate was 0.1%.
(5) Assuming that all fission gas release into cover gas, but the retention effect of LBE coolant should be considered for short-life radionuclides.
(6) Using the Raoult's law as the calculation model to calculate the activation product ^{210}Po of LBE and the volatile FP (I, Cs, Sr, Te, etc.) released into the primary coolant [7, 8].
(7) To calculate the activation corrosion products in the LBE coolant, we only considered the core part of the reactor, because the neutron flux, temperature, flow velocity and corrosion area were all the highest.
(8) Without considering the coolant purification.

Calculation codes and data libraries

The neutronics model created by CAD/Image-Based Modeling Program for Nuclear and Radiation System (MCAM) was used for neutron transport calculation [9-12]. The neutron transport and material activation were conducted by CAD based Multi-Functional 4D Neutronics & Radiation Simulation System (VisualBUS) [13]. It has been applied in design and analysis of fusion, fission and hybrid systems [14-17].

The neutron flux was estimated using MCNP with HENDL3.0 data library [18, 19]. The radionuclide inventory was calculated by the Inventory Code FISPACT2007 with data library EAF-2007 [20].

RESULTS

According to our calculations for the source term of the primary coolant system, the total radioactivity and concentration of radionuclides were listed in Table I. for LBE coolant and Table II. for cover gas.

Table I. The source terms of LBE coolant

Nuclides	Specific Activity/Bq/kg	Nuclides	Specific Activity/Bq/kg
^{210}Bi	1.05×10^{10}	^{132}Te	3.26×10^{7}
^{210}Po	1.05×10^{10}	^{140}La	4.50×10^{7}
^{89}Sr	3.20×10^{7}	^{140}Ba	4.50×10^{7}
^{95}Zr	4.61×10^{7}	^{63}Ni	2.00×10^{6}
^{131}I	2.30×10^{7}	^{51}Cr	1.06×10^{8}
^{132}I	3.30×10^{7}	^{58}Co	2.80×10^{8}
^{133}I	4.81×10^{7}	^{60}Co	1.64×10^{6}
^{135}I	4.54×10^{7}	^{55}Fe	7.20×10^{9}
^{134}Cs	3.43×10^{7}	^{59}Fe	3.50×10^{9}
^{137}Cs	8.56×10^{6}		

Table II. The source terms of cover gas

Nuclides	Concentration Bq/l	Nuclides	Concentration Bq/l
^{41}Ar	3.20×10^{6}	^{131}I	6.28
^{37}Ar	8.14×10^{4}	^{132}I	9.07
^{85}Kr	6.02×10^{7}	^{133}I	13.2
^{85m}Kr	5.90×10^{8}	^{135}I	12.5
^{87}Kr	1.17×10^{9}	^{134}Cs	0.773
^{88}Kr	1.51×10^{9}	^{137}Cs	19.3
^{131m}Xe	1.90×10^{7}	^{210}Po	33.9
^{133}Xe	3.10×10^{9}	^{3}H	3.92×10^{7}
^{135}Xe	3.06×10^{9}		

In the present work, the generation and migration of radionuclides were analyzed, and through the calculation models, the source term calculation was completed for the primary coolant system of CLEAR-I. Based on these results, we could obtain the following conclusions:

(1) The source terms of primary coolant system mainly comes from the releasing of FP, the activation of LBE and Argon, and the corrosion of structure materials.
(2) For the primary coolant, bismuth-210 and polonium-210 are the main radionuclides. Though polonium-210 is volatile, most of ^{210}Po were still restrained in the primary coolant, and little diffused into the cover gas.
(3) For the cover gas, the main radioactive source term is fission gas released from breakage of fuel assembly. These radionuclides would be released into containment due to the leakage of cover gas. These data can give guidance for the ventilation design of the containment.

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