Preliminary Analysis of Source Term and Consequence Assessment of Hypothetical Fuel Assembly Meltdown Accident for CLEAR-I

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INTRODUCTION

The Chinese Academy of Sciences (CAS) launched an engineering project to develop Accelerator Driven Subcritical System (ADS) and lead-based fast reactors name the 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 and environment impact assessment is vital to characterize the safety of the reactor design [5]. In this summary, source term calculation and consequence assessment was carried out for hypothetical fuel assembly meltdown accident of CLEAR-I, which included released nuclides selection, aerosol diffusion and consequences assessment for individual effective dose and lifetime thyroid dose of population surrounding the reactor.

DESCRIPTION OF THE ACTUAL WORK

Model and assumption for Source Term Calculation

Reactor Configuration

The seventy fuel assemblies were arranged in an annular array of four rows in the core. The inner row surrounds the neutron source (Spallation Target) assembly. The sixty-one fuel pins were loaded for each fuel assembly, in which the uranium enrichments was 19.75%. The configuration of the reactor was shown in Fig. 1. The primary coolant system was composed mainly of the Lead-bismuth eutectic (LBE) coolant and the cover gas Argon above the coolant to prevent primary coolant from contacting the air directly.

The lead-bismuth acted as an external source to the sub-critical system. The energy of incident proton was 250 MeV and the maximum fluence was 10 mA.

Accident Assumptions

In this accident, there were a series of assumptions and conditions, as follows:

(1) The hypothesis of seven fuel assemblies with maximum power was supposed according to fast reactor of CEFR and ALFRED. After the accident, all fission products from molten assembly entirely released into coolant. However, only volatile element was considered in the following to calculate their releasing into cover gas and environment impact assessment.
(2) The accident happened at the end of reactor lifetime under the full power (10 MW).
(3) Assuming that all fission gas release into cover gas, but the retention effect of LBE coolant should be considered for short-life radionuclides.
(4) 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 [6, 7].
(5) Finally, assuming all cover gas was released into reactor containment and building. These radioactive materials were discharged by chimney through emergency ventilation system during eight hours after accident. It takes no account of radioactive materials transport and deposited in this process.

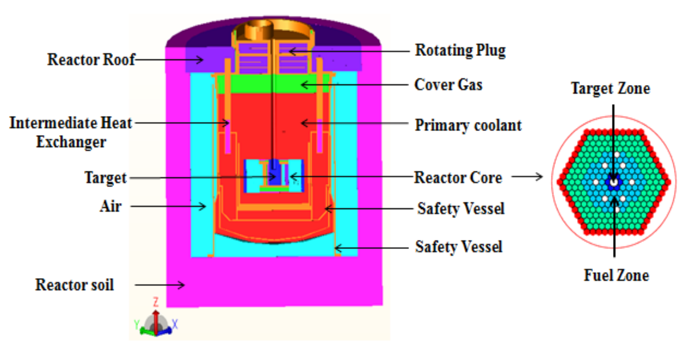

Fig. 1 Configuration of CLEAR-I

Evaporation model of volatile radionuclides

As the concentrations of volatile radionuclides in LBE coolant are extremely low, the LBE solution could be thought of as an ideal solution. Raoult's law was used 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.

This model is applied for the evaporation of volatile polonium and fission product in the primary coolant.

Calculation codes and data libraries

The neutronics model created by CAD/Image-Based Modeling Program for Nuclear and Radiation System (SuperMC/MCAM) was used for neutron transport calculation [8-11]. The neutron transport and material activation were conducted by CAD based Multi-Functional 4D Neutronics & Radiation Simulation System (VisualBUS) [12]. It has beeen applied in design and analysis of fusion, fission and hybrid systems [13-16].

The neutron flux was estimated using SuperMC with HENDL3.0 data library [17, 18]. The radionuclide inventory was calculated by the Inventory Code FISPACT2007 with data library EAF-2007 [19].

RESULTS

Accidental Radioactivity Release

The result in Table I was amount of radionuclide released into the environment during the first two hours and next six hours. Release amount equals inventory of radionuclide from cover gas and radionuclide from molten assembly after Hypothetical Fuel Assembly Meltdown Accident.

These radionuclides was calculate by VisualBUS for an equilibrium calculations. They were selected as volatile elements for environment impact assessment.

Table I. Radioactive source terms after Hypothetical Fuel Assembly Meltdown Accident

Nuclides	Radioactivity from cover gas (Bq)	Radioactivity from molten assembly （Bq）	Release amount (Bq)	
			0-2 hours	2-8 hours
^{41}Ar	9.61×10^{9}	——	2.40×10^{9}	7.21×10^{9}
^{85}Kr	4.47×10^{11}	1.50×10^{14}	3.76×10^{13}	1.13×10^{14}
^{87}Kr	2.94×10^{9}	2.77×10^{15}	6.91×10^{14}	2.07×10^{15}
^{88}Kr	1.35×10^{10}	3.55×10^{15}	8.87×10^{14}	2.66×10^{15}
^{131m}Xe	1.47×10^{9}	7.21×10^{13}	1.80×10^{13}	5.41×10^{13}
^{133}Xe	2.06×10^{12}	7.70×10^{15}	1.93×10^{15}	5.78×10^{15}
^{135}Xe	1.32×10^{11}	7.63×10^{15}	1.91×10^{15}	5.72×10^{15}
^{90}Sr	0	5.17×10^{2}	1.29×10^{2}	3.88×10^{2}
^{131}I	2.87×10^{3}	4.22×10^{10}	1.06×10^{10}	3.17×10^{10}
^{132}I	4.09×10^{3}	6.02×10^{10}	1.50×10^{10}	4.51×10^{10}
^{133}I	5.91×10^{3}	8.70×10^{10}	2.17×10^{10}	6.52×10^{10}
^{134}I	6.73×10^{3}	9.89×10^{10}	2.47×10^{10}	7.42×10^{10}
^{135}I	5.59×10^{3}	8.22×10^{10}	2.05×10^{10}	6.16×10^{10}
^{134}Cs	2.73×10^{3}	5.24×10^{8}	1.31×10^{8}	3.93×10^{8}
^{137}Cs	3.24×10^{4}	5.27×10^{9}	1.32×10^{9}	3.95×10^{9}
^{203}Hg	2.27×10^{5}	0	5.68×10^{4}	1.70×10^{5}
^{210}Po	1.20×10^{6}	0	3.00×10^{5}	9.00×10^{5}

Radiation Doses to the Public

MACCS2 was used to assess the accident consequences. The atmospheric transport, dispersion and disposition of radioactive material were treated using Gaussian plume model with Pasquill-Gifford dispersion parameters. Dose computation for public consider five exposure pathways: cloud shine, inhalation, ground shine, resuspension inhalation, and skin absorption.

The individual effective dose 7 days after accident was shown in Fig. 2. In the simulation, all airborne radioactivity were discharged into the atmosphere as the plume. MACCS2 divided the angular spatial grid into the 16 points of the compass, each 22.5° wide. The radial region around the reactor was divided into 34 areas at radial distances of 0.5, 1.0, 1.5, 2.0, …, 9.5, 10.0, 11.0, 12.0, 13.0, …, 23.0, and 24.0 km.

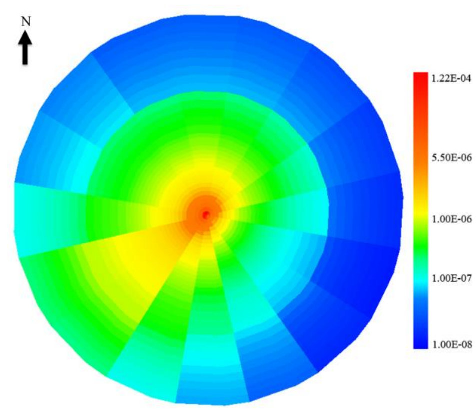

Fig. 2. Individual effective dose 7 days after accident at various distance (km) from the release point

SUMMARY

In the present work, the radioactive source term and individual effective dose were analyzed for Hypothetical Fuel Assembly Meltdown Accident. Based on these results, the following conclusions were obtained:

(1) The source terms were mainly derived from the releasing noble gas of fission product.

(2) The maximum public doses surrounding reactor was 1.22×10^{-4} Sv, which was appeared at 0.5 km from the release point. The value was about 3 orders of magnitude less than the dose limit (0.25 Sv during severe accident) stipulated in the Chinese National Standard GB6249-2011[8].

Another way, this level was less than emergency intervention level stipulated in Chinese Guide Rule HAD002/03.

(3) No emergency actionwould be required during such an accident because the consequences were not very severe.

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