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Experimental research on the radioactive dust in the primary loop of HTR-10

Feng Xie[a], Jianzhu Cao[a], Xiaogui Feng[a], Xuegang Liu[a,*], Jiejuan Tong[a], Haitao Wang[a], Yujie Dong[a], Zuoyi Zhang[a], S.K. Loyalka[b]

[a] Institute of Nuclear and New Energy Technology, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing 100084, China

[b] Nuclear Science and Engineering Institute, University of Missouri, Columbia, MO 65211, United States

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ABSTRACT

Presence of radioactive dust, and also potential for its release, are considered important issues as regards the safety of high temperature gas cooled reactors, especially the pebble bed types. To obtain data and insights into the quantity and characteristics of such dust, a sampling loop (with stainless steel powder filter elements to collect the dust) has been built in the helium purification system of HTR-10 enabling sampling of radioactive dust circulating in the primary loop of HTR-10. Two sampling experiments were conducted during the operation of HTR-10 in 2015. The concentration of the radioactive dust in the primary loop was deduced from the dust deposited on the filters, and was estimated to be 5.57(17) $\mu g/m^3_{STP}$ and 1.97(8) $\mu g/m^3_{STP}$, respectively. The nuclides present in the dust have been identified by their γ spectra. After the removal of dust from filter elements, the particle size distribution was measured with an optical microscope. In the first experiment, the average particle diameters of the radioactive dust were determined as 43.0 μm and 13.6 μm captured respectively, by the filter elements of 80 μm and 50 μm pore size. In the second experiment, the average particle diameters were 62.9 μm and 11.3 μm as captured respectively, by similar filter elements. The data show existence of large particles in the primary loop of HTR-10, generated most likely by abrasion.

1. Introduction

With the development of the high temperature gas-cooled reactors (HTGRs), the very high temperature reactor (VHTR) has been considered as a candidate for the six proposed Generation IV concept reactors by the Generation IV International Forum (GIF) (NERAC and GIF, 2002). With the use of fuel elements embedded with tristructural-isotropic (TRISO) coated particles, the inherent safety performance of the HTGRs has attracted wide attention. The high thermal efficiency and the high output temperature which can be used for hydrogen production and process heat, bring large commercial space for the future development of HTGRs (Zhang and Yu, 2002). There are, however, several safety issues that have been identified previously through operation of research reactors. These include the local high temperature in the core leading to the failure of TRISO coated particles, the release of the radioactive dust in the depressurization accident, the contamination due to the radioactive dust in the primary loop, etc. (Bäumer et al., 1990; Moormann, 2008a,b). It has been noted also that dust related problems are more important in the pebble bed type reactors than in the prismatic type reactors (Humrickhouse, 2011).

In the pebble-bed HTGRs, the dust is thought to be generated by several mechanisms, including the abrasion among fuel elements, and friction between fuel elements and other graphite structures or pipelines when the fuel elements cycled (Luo, 2004; Moormann, 2008b; Kissane, 2009). Several papers have been published regarding the behavior of dust in HTGRs, including the generation, characterization, transport, coagulation, aggregation, deposition, resuspension, etc. Humrickhouse (2011) summarized the dust safety issues in HTGRs and indicated that the dust related research was urgently needed for the development of pebble bed HTGRs on topics such as the dust distribution under normal operation, dust generation, dust-fission product interaction, etc. Cogliati et al. (2011) surveyed the available literature on graphite dust production and measurements in pebble bed reactors and concluded that there was significant uncertainty on the severity of the dust production and its consequences in pebble bed reactors. Troy et al. (2012, 2015) and Shen et al. (2016) investigated the characteristics of graphite dust particles experimentally. Simones et al. (2011), Simones and Loyalka (2015) measured the charge-size distributions of

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[*] Corresponding author at: Room 320, Energy Science Building A, Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China.
E-mail address: liu-xg@mail.tsinghua.edu.cn (X. Liu).

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graphite aerosol particles and coagulation of charged aerosols pertinent to HTGRs. Moormann (2008a,b), Kissane (2009), and Lind et al. (2010) discussed the transport of the radioactive dust which can be an important source term in pebble bed reactors. Gutti and Loyalka (2009), Boddu et al. (2011), Barth et al. (2013), and Peng et al. (2016) experimentally and/or numerically investigated the deposition behavior of dust in HTGRs. Kazuhiro et al. (1992), Stempniewicz et al. (2008), and Kissane et al. (2012) studied the resuspension behavior of dust in HTGRs.

There have been, however, very few experimental investigations regarding the radioactive dust directly in pebble bed reactors. The only available data on such dust are from Arbeitsgemeinschaft Versuchsreaktor (AVR) and Thorium Hochtemperatur Reaktor (THTR) (Bäumer et al., 1990; Moormann, 2008b; Fachinger et al., 2008). There is a need to verify conclusions from theoretical calculations and non-radioactive dust experiments against data from the radioactive dust experiments in actual reactors. Recently, several experiments related to the source terms of the 10 MW high temperature gas-cooled reactor (HTR-10) have been conducted. These include investigations of the radioactive dust, H-3, and C-14 in the primary loop, post irradiation graphite spheres from the reactor core, etc. (Xie et al., 2015a,b; Xu et al., 2017; Wang et al., 2014; Liu et al., 2017; Li et al., 2017). Previous measurements also indicated the existence of radioactive dust in the primary loop of HTR-10 (Xie et al., 2013, 2015a,b). Accordingly, an experimental sampling loop has been designed and built in the helium purification system of HTR-10.

In the present study, the radioactive dust in the primary loop of HTR-10 was investigated with use of the above sampling loop when HTR-10 was restarted in 2015. The radioactive dust has been collected with a sampling filter. The concentration of the dust in the primary loop was estimated with use of the coolant flow data. The types of solid fission and activation products which were absorbed or present in the dust were determined with a γ spectrometer (GC3018, High-purity Germanium Detectors, from CANBERRA Industries Inc.) in the radiochemistry lab in the Institute of Nuclear and New Energy Technology (INET), Tsinghua University. The counting rates of typical nuclides, including Co-60, Cs-137, I-131, etc., were measured and compared with each other. The particle size distributions of the dust from the filter elements were obtained through imaging with an optical microscope. The data reported can shed light on the behavior of fission/activation products and radioactive dust in HTGRs, and would aid in modeling and safety studies.

2. Experimental setup

The HTR-10 is a helium cooled, graphite-moderated, and thermal neutron spectrum test reactor, which was designed and built by INET, Tsinghua University, China (Wu et al., 2002). It reached its criticality in December 2000, ran up to full power operation in January 2003, and was shut down in July 2007. It was restarted at the end of November 2014 (Wei et al., 2016).

During the shutdown stage of HTR-10, an experimental sampling loop in the primary system aiming to study the behavior of radioactive dust was designed. It was approved by the State Bureau of Nuclear Safety of China in June 2012. In December 2013, the experimental loop with a sampling filter was built at the entrance of the helium purification system of HTR-10, as shown in Fig. 1. The helium purification system contains two normal purification lines and one dehumidification line. Each normal line contained a dust filter, a copper oxide bed, a molecular sieve adsorber, and a low temperature adsorber. This system is very important for the reactor operation since it can purify a bypass helium from the primary coolant system and maintain the quality of the primary helium by continuously reducing the quantity of chemical impurities and removing the dust, fission products and activation products.

Parallel to the dust filter in the helium purification system, which was bulky and difficult to dismantle, an experimental system for accurately measuring the radioactive dust in the primary loop of HTR-10 was designed and built. Though details of the radioactive dust sampling loop of HTR-10 have been presented in Xie et al. (2015a,b), it is necessary to give a brief description here. As shown in Fig. 1, the main sampling loop includes two electric check valves (KBE03 AA001 and KBE03 AA002), one electric control valve (KBE03 AA003), two thermometers (KBE03 CT001 and KBE03 CT002), two pressure gauges (KBE03 CP001 and KBE03 CP003), one flowmeter (KBE03 CF001), one differential pressure transmitter (KBE03 CP002), and five manual globe valves (KBE03 AA004 ~ KBE03 AA008). Primary features for this dust sampling loop are as follows:

(1) A small and easily disassemblable sampling filter was designed, as shown in Fig. 2. It can contain as many as 8 filter elements with different pore sizes, from 1 μm, 3 μm, 5 μm, 10 μm, 20 μm, 50 μm, and 80 μm, and can separate the radioactive graphite dust according to the particle diameter.
(2) Two electric check valves (KBE03 AA001 and KBE03 AA002) can isolate the experimental system from the helium purification system effectively. The electric control valve (KBE03 AA003) before the dust filter can adjust the flow ratio between the experimental loop and the main circuit.
(3) Two thermometers (KBE03 CT001 and KBE03 CT002), two pressure gauges (KBE03 CP001 and KBE03 CP003), one flowmeter (KBE03 CF001), and one differential pressure transmitter (KBE03 CP002), can record the temperature, the absolute pressure, the flow capacity, and the pressure drop across the sampling filter, respectively.

The operation for the radioactive dust sampling loop can be divided into preparation, sampling, and shutdown phases. In the preparation phase, the electric check valves (KBE03 AA001 and KBE03 AA002) at the entrance and exit of the sampling loop are closed, and the manual globe valves in the sampling loop are open. The whole sampling loop is pumped to remove the air inside from KTT system whose function is to pump the air out to the system and to relieve the high pressure in the pipe, if necessary. The preparation phase is completed when the pressure of the system is below 100 Pa and the manual globe valve is closed. In the sampling phase, the radioactive dust sampling loop will be connected to the helium purification system by opening of the electric check valves (KBE03 AA001 and KBE03 AA002). The electric control valve (KBE03 AA003) can be adjusted to the predetermined flow capacity, and the sampling filter would collect the dust particles for several days or weeks. In the shutdown phase, the sampling loop would be separated from the main circuit by closing of the electric check valves (KBE03 AA001 and KBE03 AA002). After the pressure in the sampling loop drops to normal conditions due to opening of the manual globe valve (KBE03 AA008) and the temperature falls to the room temperature, the sampling filter can be dismantled and sent to the radiochemistry lab for further analysis.

3. Results

After a long term shutdown from 2007 to 2014, HTR-10 was restarted at the end of November 2014, and was operated in a power stage in March 2015. During June 1st, 2015, to August 6th, 2015, two sampling experiments about the radioactive dust in the primary loop were conducted. The operational thermal power of HTR-10 was about 2.9 MW compared to the rated thermal power of 10 MW. The primary helium temperature at the reactor inlet and outlet were respectively, ~185 °C and ~575 °C. The primary helium pressure was about 2.1 MPa and the flow rate was about 1.39 t/h. Note that the rated values for the primary helium temperature at the reactor inlet and outlet, primary helium pressure, and primary helium flow rate at the full power operation of HTR-10 were 250 °C, 750 °C, 3.0 MPa, and 4.32 t/h, respectively. The concentration of the radioactive dust, the types of