High Temperature Test Apparatus to Study Plate-out of Fission Products on VHTR Components

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1. Introduction

Plate-out of fission products (FP) is an important phenomenon during the transport process of FP under normal operating as well as accidental conditions [1]. Metallic FP, such as silver (Ag), cesium (Cs), and strontium (Sr), can be released from fuel particles for the case of TRISO fueled reactors. These products may subsequently diffuse from the fuel, become plate-out in carbon materials, and become stored either within carbon components of the reactor or in the carbon dust in the primary loop components of very high temperature reactor (VHTR) as shown in Fig. 1. This dust is highly mobile and potentially reaches the coolant circuit, leading to the introduction of radioactive impurities into many components of the reactor. It is therefore important to be able to quantify the plate-out FP on primary components.

Although FP interactions with primary components have been a subject of study for more than four decades, prediction of FP interactions with alloy surfaces is empirical and still incomplete. It is usual to test the interaction of a specific FP on a specific material at different temperatures to generate data on interaction kinetics as a function of temperature. Each material and each FP and each of its compound forms has different kinetics and so, potentially, a very large number of experiments is necessary. It should be understood that the empirical knowledge of FP–alloy interactions makes no distinction between the different adsorption/ absorption/reaction mechanisms.

2. FP interactions with components wall

2.1. Interactions with alloy structures

The interaction process is not the same for each FP: there is the initial heterogeneous interaction occurring at the alloy surface which is generally highly temperature dependent and reversible (Fig. 2). This first step is governed by mass-transfer mechanisms and vapour-pressure driven or governed by adsorptivity. The adsorption or condensation is followed, depending on the FP, by absorption into the bulk or diffusion and chemical reaction in the bulk. This subsequent interaction may be only partially reversible [2]. It is known, for example, that Cs interaction with alloys is stronger and less reversible the higher the temperature at which it occurs. In particular, a significant fraction of the Cs diffusing in steel alloys to form a silicate that is very stable and immobile below about 1000 ℃. In addition, silver has a significant solubility in nickel so it might be expected that Ag (110m) would accumulate in the IHX and/or the gas turbine; the expectation that the turbine will constitute a preferential site for Cs and Ag plate-out is well established [1].

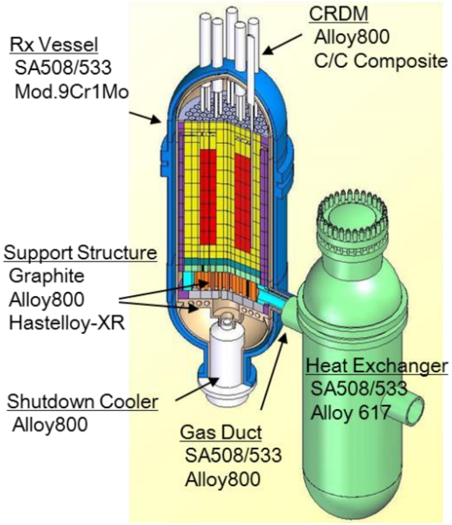

Fig. 1. Material candidates for VHTR primary components

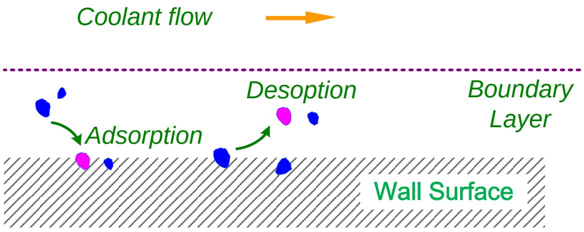

Fig. 2. Conceptual layout of FP interactions on the wall

2.2. Sorption model

The adsorption (plate-out) is the accumulation of atoms or molecules onto the adsorbent's surface by either chemical or physical attraction (Fig. 2), while the absorption indicates a process that the substance being collected diffuses or penetrates into the other substance. For the adsorption, molecules are adsorbed just on the surface, but the molecules undergoing absorption are taken up by the volume, not by the surface.

This study mainly concerns about the process of adsorption. The experimental forms of sorption isotherms are used in order to evaluate the boundary layer concentration with ideal gas law, and it plays a major role in predicting the FP behavior near the surface of components within a gas-cooled system. In general, the boundary layer concentration can be correlated with the surface concentration. It is usually expressed as a non-linear form, but specific types of correlations based on experimental observations are available for typical species and specific surface materials at a certain condition.

A well-known empirical relation of FP concentration in boundary layer for sorption isotherms proposed by GA is as follows [1];

$$B = \frac{N_A p_{B.L}}{RT} \qquad (1)$$

Where,

$$p_{\mathrm{B.L}} = \sum_{l=1}^{3} b_l S_l^{n_l}$$ for cesium,

$$p_{\mathrm{B.L}} = \frac{S_l}{a_l \cdot (K - S_l)}$$ for silver and iodine

$$a_l = a_l^0 \cdot \exp\{-Q_l/(RT)\} \quad [\mathrm{Pa}^{-1}],\ l = 1,2,3$$

$$b_l = b_l^0 \cdot \exp\{-Q_l/(RT)\} \quad [\mathrm{Pa}/(\mu\mathrm{g/cm}^2)],\ l = 1,2,3$$

Here, the constants *a*, *b*, *n* and *K* are the parameters which depend on FP species, oxidized conditions, and pipe materials. The effects of the surface roughness are considered also.

3. Experimental Apparatus

3.1. Description of experimental apparatus

The simple loop simulates the VHTR core temperature and primary loop pressure and reduced helium flow condition. The loop is composed of a helium tank, a helium heater, a metal heater, a test section, a water cooler and a filter as shown in Fig. 3. The design condition of plate-out test apparatus is as follows;

o Working Fluid	Helium
o Design Temperature	> 1000 ℃
o Design Pressure	4.0 MPa

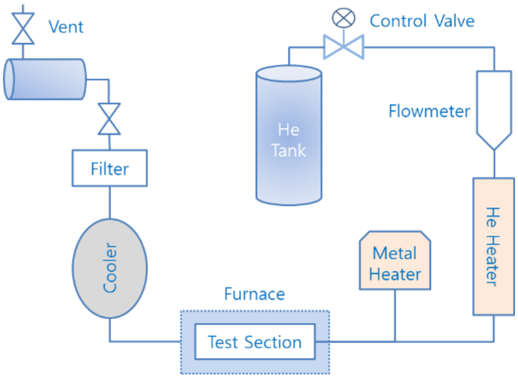

Fig. 3. Schematic diagram of plate-out test apparatus

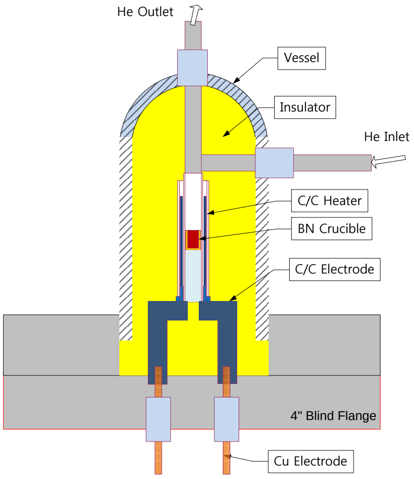

Fig. 4. Heater assembly

3.2. Heater assembly

Fig. 4 shows the layout of FP heater and its major parts. The vessel of the heater is internally insulated to protect the vessel from the high-temperature helium gas. Heater array goes through a large radiation heat loss when operating at a high temperature. A Carbon/Ceramic fiber composite (C/C) heater element is insulated by quartz tube. The FP filled in boron-nitride crucible is heated over 1000 ℃ by radiation emitted from C/C heater which could be withstand over 2000 ℃ in an oxygen free environment.

4. Discussion

Sophisticated experimental investigation for the FP behavior is very difficult due to the following reasons;

In-pile experiments,

- Long time (hundreds of days) operation are required to measure reliable level of data
- Measures global information but limited in measuring local information

Out-of-pile experiments,

- Inaccurate measurement
  - ✧ On-line measurement not possible if there is no commercial isotope supplier.
  - ✧ So many kind of factors exist that might be increasing the uncertainty of test data in the process of AAS or ICP analysis for the test coupon.
- Many kind of nuclides in fission products
- Many kind of materials in the reactor primary loop
- Surface condition of materials; oxidation of material and roughness
- Operating condition
  - ✧ Very high temperature and board temperature range in case of VHTR

- ✧ Generally, very low flowrate and pressure test conditions in the high temperature furnace or apparatus

5. Conclusion

KAERI designed a test apparatus to study the plate out phenomena on the alloy surface of VHTR primary components. The apparatus simulates the VHTR core temperature and primary loop pressure and reduced helium flow condition. The apparatus will be built in end of this year and shall be operated next year using the pure silver, a major metallic FP contaminants in VHTR primary components.

NOMENCLATURE

K = parameter in sorption isotherm [μg/cm²]
N_A = Avogadro number
p = vapour pressure [Pa]
Q = activation energy
R = gas constant
S = surface concentration [m²]
T = temperature [K]

ACKNOWLEDGEMENTS

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REFERENCES

[1] IAEA, Fuel Performance and Fission Product Behavior in Gas Cooled Reactors, IAEA-TECDOC-978, 1997.
[2] M. P. Kissane, A review of radionuclide behavior in the primary system of a very-high-temperature reactor. Nuclear Engineering and Design, Vol. 239, pp. 3076-3091, 2009.