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Development of depleted uranium bed for tritium fuel cycle and basic absorption/desorption experiments

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ABSTRACT

For the safe and efficient operation of a storage and delivery system in a tritium plant for a fusion fuel cycle, a metal hydride bed for recovery and delivery of hydrogen isotope gas is essential. To develop a metal hydride bed for a fusion fuel cycle, and to validate the process performance of a depleted uranium hydride bed, a large scale experimental bed that considers the safe handling and uniform distribution of depleted uranium was newly designed and fabricated. To establish the activation procedure of this new bed, a number of absorption/desorption cycles necessary to reach saturated storage capacity was studied. Hydrogen desorption experiments that validate the feasibility of delivery without vacuum pumping were also investigated, and more than 95% hydrogen from $UH_{2.9}$ was successfully delivered.

1. Introduction

For the safe operation of a Storage and Delivery System (SDS) in a tritium plant for a fusion fuel cycle, a metal hydride bed for the recovery and delivery of hydrogen isotope gas is essential. The major function of the bed is to safely store tritium as a metal hydride form, rapidly absorb the emergency uptake of tritium gas, and rapidly desorb to satisfy the fueling requirement and in-situ tritium accountancy by the calorimetric measurement of tritium decaying heat.

Compared to other metal hydrides, depleted uranium (DU) has no disproportionation issue that is not easy to avoid or control with a metallic alloy hydride. Also, the decomposition pressure is flat almost all the way through complete decomposition. It has potential for high pressure delivery due to a high equilibrium pressure at a certain elevated temperature. Because of these reasons, depleted uranium is one of the strong candidates of being a tritium storage material for a fusion fuel cycle in spite of its radioactivity and limitation of handling. Also, depleted uranium is pyrophoric, even when it is not in the form of fine powder. So, fabricating the DU bed requires special care or environment.

Previous studies on uranium bed applications for tritium service or storage have shown several hydrogen unloading results both with or without pump operation [1,2]. However, the process performance validation of the DU bed for service in the large tritium plant such as ITER has to be strictly done. Also, the design development that considers the production of large numbers of DU beds is required.

The authors designed and fabricated a large scale experimental DU bed that considers the safe handling of DU. Hydrogen experiments were performed to validate the process performance. In this paper, the design features of the current experimental bed are introduced. The results of the DU bed activation and non-pump delivery experiment are presented.

2. Experimental depleted uranium bed

2.1. Design and fabrication

The current large scale experimental DU bed has two major objectives. The first objective is to establish a design and fabrication procedure that safely handles uranium. The other objective is to perform experiments on absorption/desorption, heating/cooling, and in-bed calorimetry. 1.86 kg of DU is loaded in the bed which is equal to a tritium capacity of 70 g as a form of UQ_3 (11.67 mol Q_2 gas, Q stands for hydrogen isotope).

The DU bed is basically composed of a primary vessel and outer jacket for the double confinement. The primary vessel made of 316L stainless steel contains DU hydride and is equipped with an electrical sheath heater, a hydrogen gas isotope gas in/out tubing, a sintered metal filter, thermocouples, and other components. The outer jacket made of 304 stainless steel has a conflat flange with gas ports, electrical feedthroughs, and connected gas tubing. Between the primary vessel and outer jacket, multiple layers of thermal reflectors are installed to minimize the heat loss from the primary vessel.

The major design features of the current DU bed are introduced.

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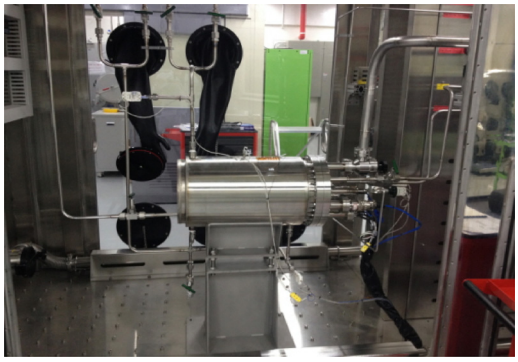

Fig. 1. NFRI (National Fusion Research Institute)'s large scale depleted uranium hydride bed for process performance validation.

Firstly, the bed was installed in a horizontal direction, as shown in Fig. 1. The authors chose this installation for effective and uniform heating of the metal hydride. The volume expansion of depleted uranium by hydriding is more than 75% [3] and the buffer volume is required to release gas from the metal hydride. Therefore, the internal primary vessel requires some portion of expansion volume. However, this extra volume in the primary vessel is unfavorable in the viewpoint of uniform and rapid heating/cooling of DU powder because of an increased thermal mass and reduced thermal contact between the DU powder and primary vessel. To compensate for this, a metal foam made of copper is installed in the primary vessel. The pulverized metal hydride is distributed into the open cells of the copper foam, and the skeleton of the foam transfers heat effectively. SRNL (Savannah River National Laboratory)'s LaNiAl alloy bed for hydrogen isotope storage also adapts the metal foam [4]. The metal foam works as a component that enhances heat transfer and is useful for mitigating powder migration in the bed. The authors already performed an experimental comparison between the metal fin and metal foam as a heat transfer enhancing component in the metal hydride bed. The metal foam was shown to be more effective for the heat transfer and absorption/desorption performance [5].

Secondly, the safe handling of DU during fabrication was considered. Due to the pyrophoric characteristics of DU, handling DU in the form of a small particle or even as a wire requires an inert gas condition such as the glove box, which increases the cost and time for fabrication. With a focus on these risks, multiple DU rods were prepared by the injection molding method and inserted in the holes at the copper metal foam (Fig. 2(b)). This procedure can be done in the atmosphere without the risk of fire. The holes at the copper foam were distributed by considering the uniform distribution of DU powder in the cells of the metal foam. Also, DU has eutectic with the iron of the stainless steel at a temperature around 630 °C. As a result, a eutectic barrier was needed inside the primary vessel. The copper shell and cover were attached in the primary vessel's inner surface.

Electrical sheath heaters and cooling channels were vacuum brazed in the grooving of the primary vessel's outer surface for better heating

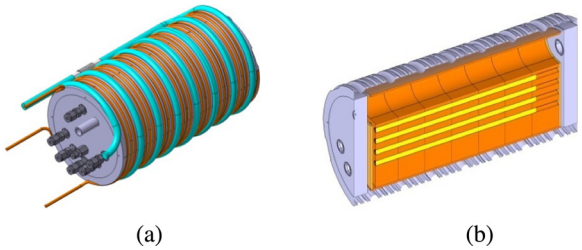

Fig. 2. Major design features of current DU bed (a) Primary vessel brazed with electrical heaters and cooling channels (b) DU rods(yellow) loaded into holes in copper foam(orange).

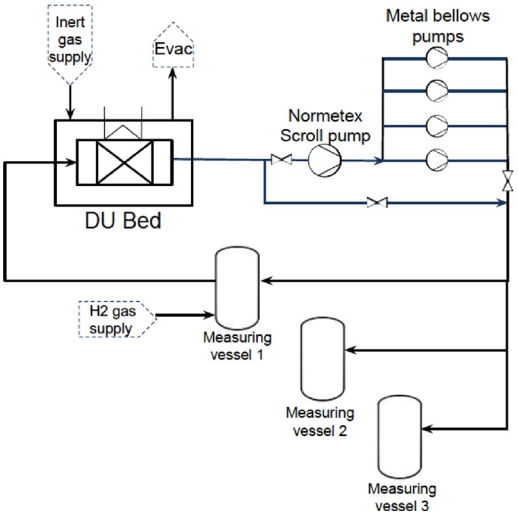

Fig. 3. Simplified process flow diagram of DU SDS process verification system for DU bed experiments.

efficiency (Fig. 2(a)). The cartridge heaters were inserted in the metal foam to simulate tritium decay heat. The components for the in-bed calorimetry by calorimetric measuring were also installed.

2.2. Experimental setup

The current DU bed was installed in the NFRI's DU SDS process verification system (DU-SPOVE). DU SPOVE is a 10-m length glove box system equipped with multiple measuring vessels, the Normetex scroll pump, metal bellows pumps, and evacuation system with a turbo molecular pump. By using hydrogen and deuterium gas, DU-SPOVE performed various process verification experiments related to the storage and delivery system operation of the tritium plant (Fig. 3). It was located in the regulated and limited space for handling depleted uranium.

3. Hydrogen experiments

3.1. Activation of depleted uranium

To activate depleted uranium by pulverization, an activation procedure composed of vacuum annealing and 5 cycles of hydrogen absorption/desorption was performed. DU was heated up to 450 °C for more than 4 h under a turbo molecular pump evacuation of the primary vessel and outer jacket. The first absorption started at an initial DU temperature of 225 °C and the initial pressure of H_2 gas was 150 kPa in the 200 L measuring vessel. From the second to fifth absorption, the initial temperature of DU was room temperature and the initial pressure of H_2 gas was also 150 kPa. The desorption process was done at the heating temperature of 300–450 °C with a vacuum pump (Normetex scroll pump + metal bellows pumps) evacuation.

Fig. 4 and Table 1 show DU being easily activated by a few cycles of absorption/desorption. Depleted uranium at the first absorption took more than 8 h to be saturated. However, from the second absorption, it took less than 1 h. The hydrogen absorption curve shows most of the DU was pulverized after the third cycle. These results agree well with the authors' previous study [6]. When the hydrogen absorption started, the depleted uranium temperature rose rapidly. The maximum temperature between 230 and 260 °C was reached in less than 5 min for the 2nd–5th absorption with the current bed (see Fig. 5). However, the slopes of the temperature decrease did not strictly increase with the number of absorption cycles. The change in the size and distribution of the DU powder near the thermocouple during absorption cycles was considered to be the cause.

The average absorption rate to reach $UH_{2.0}$, $UH_{2.7}$, and $UH_{2.8}$ are