BERYLLIUM INTERACTION WITH STEAM OR AIR IN ITER UNDER ACCIDENT CONDITIONS

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Abstract

The combined use of beryllium as plasma facing material and water as coolant in ITER (International Thermonuclear Experimental Reactor) poses the potential risk of significant hydrogen production under accident conditions. In this paper we describe on-going R&D at several different institutions worldwide to understand the beryllium/steam and beryllium/air interactions for the ITER design. Our understanding of beryllium chemical reactivity has progressed significantly during the ITER EDA (Engineering Design Activity), allowing us to more accurately assess ITER postulated accidents. We include a brief description of how these data were used in our modeling activities for the safety analysis of ITER.

1. INTRODUCTION

The combined use of beryllium as plasma facing material and water as coolant in ITER poses the potential risk of significant hydrogen production under accident conditions. Beryllium reacts exothermically with both air and steam.

Relevant short time-scale events are in-vessel Loss of Flow Accidents or ex-vessel Loss of Coolant Accidents (LOCA) with ongoing plasma burn where the reduced cooling can hinder thermal relaxation of the overheated PFC (plasma facing component). (An in-vessel LOCA will stop the plasma burn immediately, precluding high temperatures and significant hydrogen production.) If the fusion power shutdown system fails, impurity influx from the hot FW (first wall) will eventually cause passive plasma shutdown once the FW reaches about 1150°C [1]. Hydrogen production during these types of scenarios can be several kg.

For longer-term accidents, the concern is the ability of the ITER design to remove the decay heat in the FW/shield and still remain below the 450-500°C temperature limit [2]. This limit is based on data from chemical reactivity experiments, and is the temperature above which hydrogen production can be important in longer (weeks) accidents. These types of events are analyzed to show the ultimate safety margins of ITER [3]. On-going chemical reactivity experiments enable us to assess this temperature limit, ensure that it is appropriate, and reduce hydrogen risk to tolerable levels.

The beryllium reaction rate with air or steam is a strong function of temperature and the physical form and microstructure of the beryllium. On-going ITER safety R&D is being performed at several different institutions worldwide to understand the beryllium/steam and beryllium/air interactions for the ITER design. These data are used in modeling accident sequences to determine the magnitude of the chemical reactivity problems for the ITER design.

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In this paper we describe chemical reactivity R&D performed under the auspices of ITER in the United States (Section 2), Russia (Section 3), and Kazakstan (Section 4), and briefly describe the modeling work that makes use of the data from these activities (Section 5).

2. CHEMICAL REACTIVITY R&D IN THE UNITED STATES

In the Steam Reactivity Measurement System (SRMS) [4], developed during the EDA at the INEEL, various forms of beryllium have been tested, including fully dense (irradiated and non-irradiated), plasma-sprayed, and porous [see, for example, 5,6]. In each test series, hydrogen production was measured by weight gain as well as with a mass spectrometer to provide time dependent kinetic information about the reaction rate and to increase confidence in the data. In experimental design, emphasis was placed on increasing detection sensitivity so that chemical reactivity could be measured at temperatures as low as 350°C.

In addition, the INEEL measured the effective surface area of various forms of beryllium using BET, a gas adsorption method, providing unique insights into the effect of surface area on the chemical reactivity of the beryllium [7]. Differences in the chemical reactivity between the various types of beryllium can be explained by the surface area available to react with the steam.

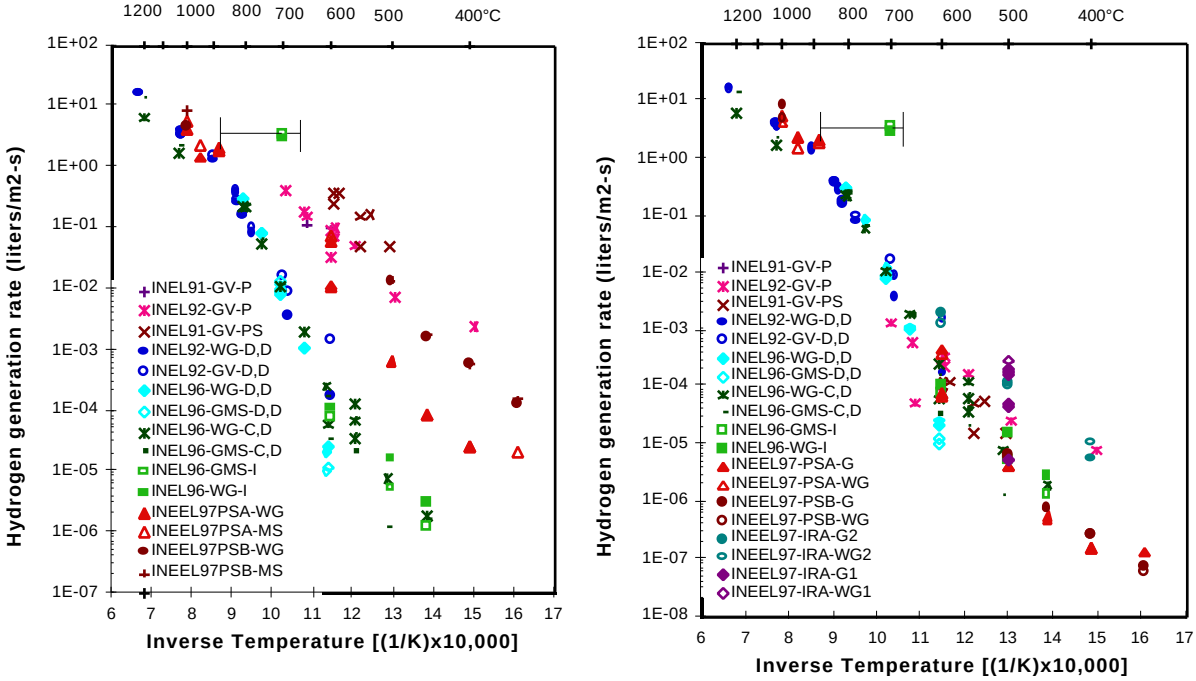

FIG 1. Chemical reactivity of various forms of Be plotted with respect to geometric surface area (left) and BET surface area (right). Methods to determine hydrogen produced were gas collection (GV), weight gain (WG), mass spectrometer (GMS, G1, G2). Forms of beryllium shown are porous - 88% dense (P), plasma-sprayed (PS, PSA, PSB), fully-dense discs (D), fully-dense cylinders (C), and irradiated fully dense (I, IRA).

Specimens with significant surface-connected porosity provide more surface area for reaction with steam. Figure 1 shows that there is less spread in the chemical reactivity data of beryllium for a number of different forms when plotted with respect to BET surface area rather than with respect to the geometrical surface area of the specimen. Data from fully-dense (both irradiated an non-irradiated), plasma sprayed, and porous beryllium are included on this graph. When data are plotted with respect to geometric surface area, there is significantly more spread in the data as evidenced by Fig. 1.

3. CHEMICAL REACTIVITY R&D IN RUSSIA

Chemical reactivity tests at VNIINM focussed on beryllium interaction with air [8], and included some experiments in steam. Reaction rates are calculated from weight gain measurements. Fully-dense, cm-size samples were tested in air over the temperature range 800-1100°C, under steady-state conditions as well as with thermal cycling. At 800°C, the chemical interaction of the fully dense beryllium was not significant, however at 900°C, the interaction was much stronger. Thermal cycling of the beryllium samples resulted in enhanced interaction with air, probably due to cracking in the oxide film during thermal cycling allowing the air access to unreacted metal.

Beryllium powders ranging in size from 20-30 μm were exposed to air at temperatures of 500-1000°C for 5 hours [8] to simulate the chemical reaction of tokamak dust. The depth of the beryllium powder was also varied. The fraction of beryllium that reacted was larger for smaller diameter powders due to the increased surface area. Additionally the fraction reacted decreased with increasing powder depth, probably due to reduced steam access as the powder depth increased. This was supported by a change in the oxide layer through the thickness; the oxide was less permeable as depth increased. At 900°C, the reaction rate showed little dependence on the initial powder size, and a weak dependence on the thickness of the fill layer. At this temperature, 94-97% of the powder reacted according to weight gain measurements. Some initial oxidation of the beryllium was probably present, which could account for this estimate indicating less than 100% reaction.

4. CHEMICAL REACTIVITY R&D IN KAZAKSTAN

At the IAE NNC RK, a facility was constructed to measure the chemical reactivity of heated specimens consisting of a layer of beryllium, copper, and steel (fabricated at Ulba Metallurgical Plant, Ust Kamenogorsk, Kazakstan) to simulate the ITER first wall/blanket/shield structure. The beryllium emissivity, needed for modeling accidents, is measured in this facility as a function of surface temperature and degree of oxidation as well as the chemical reactivity of the beryllium [9]. Test plans include both fully dense and porous (86.5% theoretical density) beryllium. These tasks are important to validating codes used in ITER safety analyses.

Figure 2 shows measured emissivity as a function of temperature after oxidation for two different samples (both fully dense, heated to about 700°C and exposed to steam; the inner wall temperature of the vacuum chamber was about 190°C to preclude oxidation of the wall material) as well as the curve fit to the data. After oxidation, the samples were placed in the vacuum chamber under less than 1 torr pressure. The temperature was increased step-wise, and the emissivity measured as the sample was held steady at various temperatures. Additional emissivity tests are planned, as well as tests to measure chemical reactivity as a function of various temperature gradients through the structure to simulate thermal conditions in the ITER blanket under accident conditions.

5. MODELING EFFORTS

Sophisticated thermal hydraulic computer codes (e.g., MELCOR, INTRA, and CHEMCON) are used to predict the thermal response of the ITER first wall under accident conditions. The codes use the reaction rates determined from the R&D described in this paper and apply appropriate safety factors to account for experimental uncertainties and lack of a complete database. These codes determine the ability of the ITER design to remove the chemical energy generated by the Be-steam or Be-air reactions by convection, conduction and radiation to cooler parts of the machine. These analytic tools have been used to optimize the design from a chemical energy removal standpoint and thus prevent Be-steam and Be-air interactions from posing a serious safety risk in ITER. Future efforts will focus on verification and validation of the models in these computer codes using the results of the experiments being performed at KNNC as part of the overall regulatory approval process.

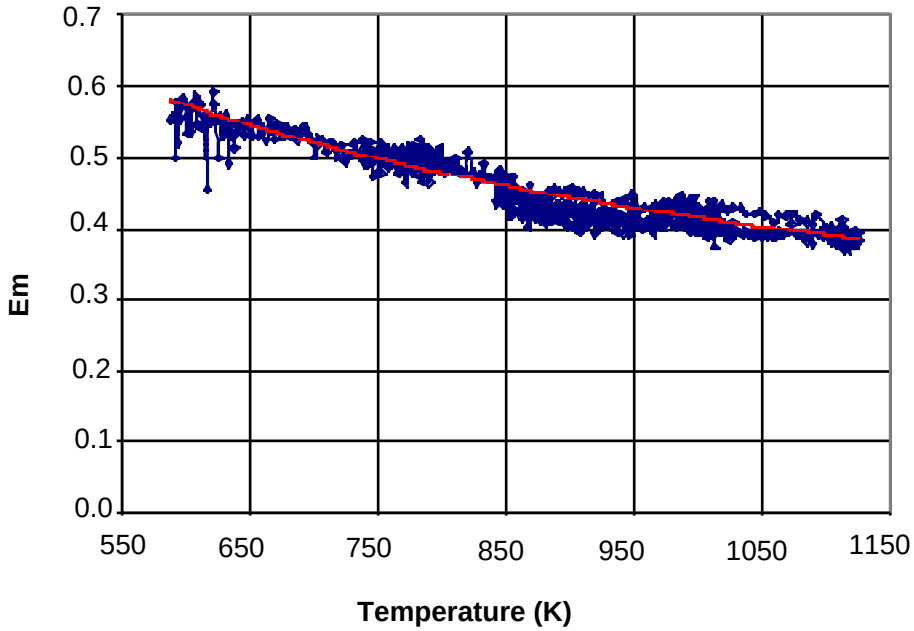

FIG 2. Emissivity of dense beryllium as a function of temperature following oxidation in steam.

6. CONCLUSIONS

A coordinated, international program, including experiments in the United States, Russia, and Kazakstan, is providing necessary data for assessing the impact of beryllium chemical reactivity on the safety of ITER. Additional experiments are planned to add to the database, including experiments to provide verification and validation of models used in thermal hydraulic computer codes.

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