

**Japan-US Joint Research Project PHENIX (2013–2018);  
Heat Transfer Tests, Neutron Irradiation and Post-Irradiation  
Examinations for Development of He-Cooled Tungsten Divertor**

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**Abstract.** The goal of the Japan-US joint research project PHENIX (2013–2018) is to understand the feasibility of He-cooled W divertor for DEMO applications. To achieve this goal, the project has three major objectives: (1) to understand heat transfer in a divertor module cooled with high-temperature and high-pressure He gas, (2) to establish database on thermomechanical properties of W materials after high temperature (~500, ~800 and ~1100 °C) neutron irradiation with fusion-relevant energy spectrum, and (3) to clarify tritium (T) trapping and permeation in neutron-irradiated W materials. Heat transfer tests for a He-cooled modular divertor with multi-jet (HEMJ) have been performed, and the problem of heat transfer degradation by re-laminarization was identified. The irradiation capsule with thermal neutron shielding was designed for high temperature neutron irradiation in the High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory (ORNL) with fusion-relevant transmutation. The expected damage level is 1–1.5 displacements per atom (dpa). Heat load resistance, thermal conductivity, mechanical properties and microstructures are examined in ORNL after the irradiation. Mechanical properties of W single crystal samples irradiated with neutrons in HFIR at 90– 850 °C without thermal neutron shielding were examined for comparison. Significant hardening was observed after irradiation to >1 dpa. Microstructural examinations revealed that the hardening was mainly caused by formation of irradiation-induced precipitates consisting of W, Re and Os. Comparison with new samples irradiated in the capsule with thermal neutron shielding will show the effects of irradiation temperatures and transmutation elements. Retention and permeation of hydrogen isotopes including T in neutron-irradiated samples are examined in Idaho National Laboratory, and permeation of H and D in samples damaged with surrogate irradiations (heavy ions, electrons, etc.) is measured in Sandia National Laboratories, Livermore, to study hydrogen-defect interactions in wider conditions. The measurement of D retention in the single crystal W sample after neutron irradiation to 0.1 dpa at

360 °C and subsequent plasma exposure at 400 °C showed significant trapping effects by radiation-induced defects.

## 1. Introduction

The goal of the Japan-US joint research project PHENIX (2013–2018) is to understand the feasibility of He-cooled W-armed plasma-facing component (PFC) for DEMO applications. To achieve this goal, the project has three major objectives: (1) to understand heat transfer in a divertor module cooled with high-temperature and high-pressure He gas, (2) to establish database on thermomechanical properties of W materials after high temperature (~1100 °C) neutron irradiation with fusion-relevant energy spectrum, and (3) to clarify tritium (T) trapping and permeation in neutron-irradiated W materials. Heat transfer tests for a He-cooled modular divertor with multi-jet (HEMJ) have been performed, and the problem of heat transfer degradation by re-laminarization was identified. The irradiation capsule with thermal neutron shielding was designed for high temperature neutron irradiation in the High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory (ORNL) with fusion-relevant transmutation. The measurement of D retention in the single crystal W sample after neutron irradiation in HFIR to 0.1 dpa at 360 °C and subsequent plasma exposure at 400 °C showed significant trapping effects by radiation-induced defects.

## 2. Task 1: Investigation of Overall Heat Flow Response in PFC

The heat transfer experiments have been performed at the Georgia Institute of Technology for the HEMJ test section shown in Fig. 1 (a) [1] using high-temperature and high-pressure He gas and high heat fluxes up to 6.6 MW/m<sup>2</sup>. First, the correlation of Nusselt number  $Nu$  (heat transfer coefficient) with the non-dimensional gap width  $H/D$  was established for the design under the condition that  $H/D$  was 0.4-0.9 and the temperature of He was up to 300 °C. According to the correlation, removable heat flux for divertor prototypical conditions was optimized as 9.4 MW/m<sup>2</sup> at He temperature of 700 °C. To improve the cooling performance, heat transfer tests were performed at  $H/D$  less than that of HEMJ reference design. In the case

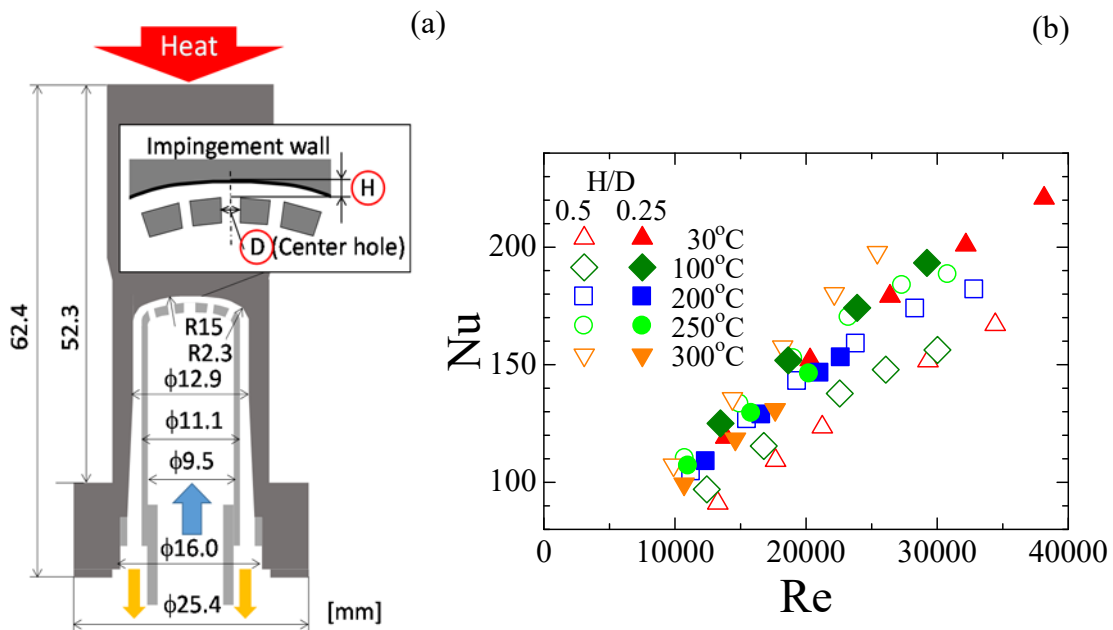


FIG. 1. (a) Cross-sectional view of HEMJ test section, and (b) effects of  $H/D$  on heat transfer performance of HEMJ [1].

of  $H/D = 0.25$ , the cooling performance increased by  $\sim 20\%$  from the value for  $H/D = 0.5$  when the jet temperature was less than  $100\text{ }^\circ\text{C}$ . By contraries, the cooling performance was degraded by max.  $15\%$  with increase in jet temperature higher than  $200\text{ }^\circ\text{C}$  in the  $H/D = 0.25$  case as shown in Fig. 1 (b). The degraded cooling performance with increasing jet temperature is attributed to the laminarization due to highly accelerated flow near cooling surface. The cooling performance degradation is possible for  $H/D = 0.5$  and more wider spacing cases, because the temperature levels of both cooling surface and coolant become much higher in an actual divertor. By changing the jet configuration, the mitigation of highly accelerated flow region is required as well as development of turbulence model to predict the laminarization.

Heat load resistance of neutron-irradiated samples are examined in ORNL. Steady-state and pulsed heat load tests are performed with the Plasma-Arc Lamp (PAL) facility [2]. To avoid dispersion of neutron-induced radionuclides during heat load tests, a vacuum-tight enclosure made of quartz glass has been constructed. A water-cooled Cu sample holder has been developed to achieve large temperature gradient in a sample. Tests for a non-irradiated W/reduced-activation steel layered material have been successfully performed.

### 3. Task 2: Material Performance –Evaluation and Irradiation–

The samples subjected for neutron irradiation in HFIR, ORNL are pure W with different microstructures, W-Re alloys, K-doped W-Re alloys and layered materials. Fig. 2 shows microstructures of neutron-irradiated W summarized in [3] together with irradiation conditions in the PHENIX project. The main irradiation capsule of the PHENIX project is divided in three temperature zones ( $\sim 500$ ,  $\sim 800$  and  $\sim 1100\text{ }^\circ\text{C}$ ) to cover a range from ductile-brittle transition temperature to recrystallization temperature of W. High thermal neutron flux in water-cooled reactors generally results in excess formation of Re and Os via transmutation. To avoid this, the capsule is surrounded by layers of Gd serving as an absorber of thermal neutrons. The neutron irradiation has been started by setting the capsule in the large removable beryllium (RB\*) position in HIFR. The expected damage level is 1–1.5 displacements per atom (dpa). Post-irradiation examinations (PIEs) will be performed in 2017–2018 in the Low Activation Materials Development and Analysis (LAMDA) laboratory, ORNL [4]. Irradiation up to  $\sim 0.5$  dpa with smaller rabbit capsules at  $\sim 800$  and  $\sim 1100\text{ }^\circ\text{C}$  without thermal neutron shielding has already been completed. PIEs will be started in 2017.

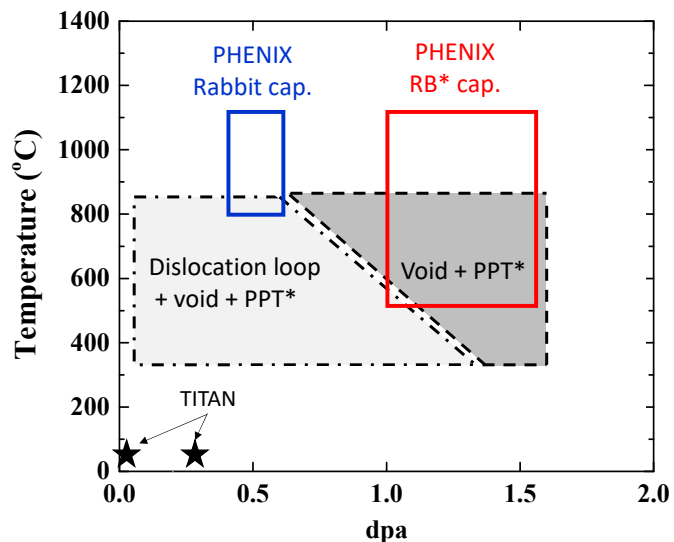


FIG. 2. Microstructures of neutron-irradiated W summarized in [3] and irradiation conditions in PHENIX project. PPT indicates precipitates which appear at high Re contents. Two black stars show irradiation conditions for W samples used for D retention measurements in [5].

Regarding to PIEs, thermal conductivity, mechanical properties and microstructures are examined in LAMDA laboratory, ORNL in addition to the heat-load resistance. Pure W single crystal samples irradiated with neutrons in HFIR at 90–850 °C without thermal neutron shielding for a previous project have been subjected to PIEs. Significant hardening was observed after irradiation to >1 dpa. Microstructural examinations using transmission electron microscopy and positron annihilation spectroscopy revealed that the hardening was mainly caused by formation of irradiation-induced precipitates consisting of W, Re and Os. Comparison with new samples irradiated in the above-mentioned capsules will show the effects of irradiation temperatures and transmutation elements

#### 4. Task 3: Tritium Behaviour and Neutron Irradiation Effect

Retention and permeation of hydrogen isotopes including T in neutron-irradiated samples are examined in Idaho National Laboratory (INL), and permeation of H and D in samples damaged with surrogate irradiations (heavy ions, electrons, etc.) is measured in Sandia National Laboratories, Livermore (SNL/CA) to study hydrogen-defect interactions in wider conditions. In the previous Japan-US joint research project TITAN [5], D retention was measured solely after low temperature (50–70 °C), low dose (0.025 and 0.3 dpa) neutron irradiation, as shown in Fig. 2. Comparison between TITAN and PHENIX results will show the effects of irradiation temperatures and damage levels.

The retention of D in the single crystal W sample irradiated with neutrons at 360 °C to 0.1 dpa was measured after exposure to D plasma at 400 °C to  $\sim 5 \times 10^{25}$  D/m<sup>2</sup> in the linear plasma machine called Tritium Plasma Experiment (TPE) [6] in INL. Thermal desorption spectrum of D is compared with that from W samples without neutron irradiation and samples irradiated in TITAN project to 0.025 dpa at 50–70 °C and exposed to D plasma at 200 and 500 °C. The values of D retention for all neutron irradiated samples were significantly larger than that in non-irradiated samples due to trapping effects of radiation-induced defects. Despite the higher neutron dose, neutron irradiation at 360 °C followed by plasma exposure at 400 °C (0.1 dpa) resulted in smaller D retention than neutron irradiation at 50–70 °C followed by plasma exposure at 500 °C (0.025 dpa). These observations indicate that dynamic annealing of radiation-induced defects occurred at 360 °C. In SNL/CA, D permeation through W samples damaged with 6.4 MeV Fe ions at 300 °C to 1 dpa was measured in an apparatus described elsewhere [7] to examine the effects of irradiation at a higher temperature. Obvious increase in permeation lag time was observed due

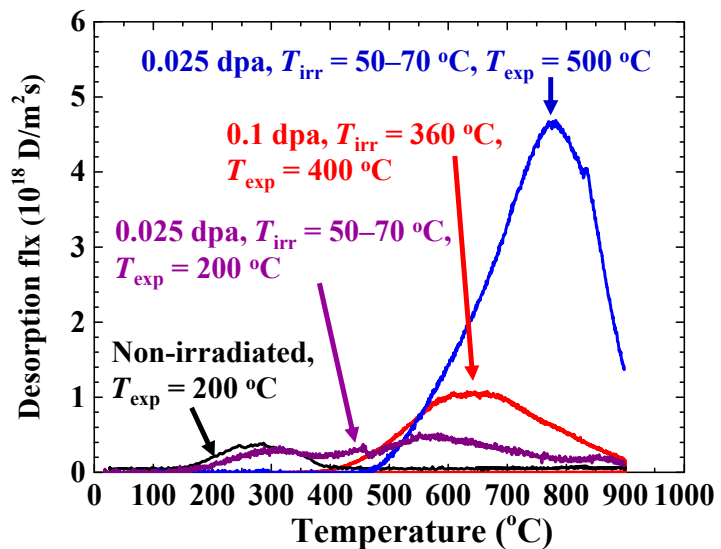


FIG. 3. Thermal desorption spectra of D from W sample without neutron irradiation and that irradiated with neutrons in HFIR to 0.025 dpa at 50–70 °C [5] and 0.1 dpa at 360 °C. D plasma exposure was performed in TPE [6] at 200, 400 and 500 °C as indicated in the figure where  $T_{irr}$  is neutron irradiation temperature and  $T_{exp}$  is plasma exposure temperature.

to D trapping at radiation-induced defects. Trapping effects were significant at temperatures as high as 900 °C.

## 5. Summary

The Japan-US joint research project PHENIX has been initiated to address key issues for thermostructural integrity and transport phenomena in helium-cooled, tungsten-armed PFC. In the first half program, the degradation in heat transfer due to laminarization was identified. The mechanical properties, microstructure and D retention in W samples irradiated with neutrons at elevated temperatures were examined. Higher dose neutron irradiation with thermal neutron shielding was started for fusion-relevant transmutation. In the second half of the project, the neutron irradiation effects on material properties, responses of PFC to steady-state and transient heat loads, and hydrogen isotope behaviour will be examined as well as the heat flow in helium-cooled PFC structures. An integrated modelling on thermomechanical performances of PFC and T transport will be performed based on the acquired results.

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