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Tritium permeation experiment using a tungsten armored divertor-simulating module

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Abstract

A first engineering type experiment for evaluation of tritium permeation rate through a tungsten armored divertor of a DT fusion machine was carried out using tritium plasma experimental (TPE) apparatus under the collaborative program between US-DOE and JAERI. A test module having a multi-layer structure (W:1 mm^t, Cu:5 mm^t and a cavity containing water pressurized at 2.2 MPa) was exposed to DT (D:T = 2:1) plasma. Break-through of tritium permeation into the water was observed after 4 h of plasma exposure. The amount of tritium permeated was compared with permeation rates predicted by numerical simulation codes (TMAP4 and TPERM). Feasibility of the experimental system and procedures to predict the tritium permeation behavior was examined using the simulation codes. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Estimation of the amount of tritium permeated through the plasma facing components (PFCs) is one of the important issues for DT fusion reactors including the ITER, not only for safety evaluation but also for tritium processing facility designs related to water detritiation. Extensive experimental and theoretical work has been carried out for the evaluation of tritium permeation for the plasma facing materials selected in the ITER design [1–3]. Most studies were carried out using a single material. However, real PFCs are of multi-layer structures consisting of different materials. For example, referring to the design of ITER [4], the divertor is an armor material brazed to copper heat sink, which is cooled by pressurized water flowing in a cooling channel. To date, there are few permeation data with a system simulating such conditions of a real divertor. This is due to the fact that it is not possible to measure the permeation rate of protium or deuterium into water. Although the measurement of the permeation of tritium into water is not difficult, this kind of experiment requires a large amount of tritium. The tritium plasma experimental (TPE) apparatus [5] at the tritium systems test assemblies (TSTA) at Los Alamos National Laboratory is the only apparatus of its type that can generate tritium plasma exposure conditions similar to that on the real PFCs. Demonstration of the first engineering experiment with a tungsten armored divertor simulating module was carried out using the TPE apparatus at the TSTA under the collaborative program between United States Department of Energy (US-DOE) and Japan Atomic Energy Research Institute (JAERI).

In this paper, the experimental system, procedures for the measurement of tritium permeation rate, the experimental results, and preliminary analysis using numerical simulation codes TMAP4 [6] and TPERM [7] are presented.

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2. Experimental

2.1. A divertor-simulating module

A new testing module for the tritium permeation experiment, shown in Fig. 1, was developed at the Tritium Engineering Laboratory in JAERI [8]. The assembly was designed by modifying the module used in the previous retention measurement [9]. The module has a tungsten armor tile (wrought tungsten, $30\,mm^{\varnothing} \times 1\,mm^{t}$) brazed on an oxide-free copper heat sink block (5 mm thick) by silver based wax. To simulate the conditions of a real divertor, the heat sink block contained water pressurized at 2.2 MPa in a small cavity, just behind the tungsten/copper wall.

Helium gas was chosen as the coolant of the test module and its flow rate was adjusted to maintain the module temperature at 473 K. The water supply/sampling lines, which were pressurized to 2.2 MPa during the plasma exposure, were configured as shown in Fig. 1. Some parts outside of the vacuum chamber, such as the pressure adjustment tank and 1/8″ stainless steel pipes connected to the tank, were electrically insulated. This allowed the module to be biased. The amount of total water contained in the pressurized line was about 17 cm^3 and that in the major part of the module was $\sim 3.2\,cm^3$.

2.2. Operating procedures of plasma exposure and measurement of tritium permeation

After pressurizing the water inside the cavity of the module, the DT plasma was initiated by introducing deuterium and tritium mixed gas (flow rate: 30 cm^3/min, D_2:T_2 = 2:1) into the arc ion source of the TPE apparatus. The plasma current provided the heating and raised the test module to 473 K. The module was exposed to the D/T mixed plasma (ion energy: ~ 100 eV, ion flux: 4×10^{21} $D^+, T^+/m^2$ s) for a designated period, then the plasma was terminated. After a few minutes, the temperature dropped below 373 K. The pressure on the water in the cavity was then released and the water was sampled by flushing with 100 cm^3 of deionized water into a sampling tank. This procedure flushed inside of the cavity with water of 30 times larger volume than that contained in the cavity. The tritium concentration of the collected water was measured using a liquid scintillation counter. According to the background of the liquid scintillation counter, it was expected that a couple of tens of Bq/l of tritium concentration in the collected water would be detectable when tritium permeated into the cavity. This corresponds to a permeation flux on the order of 10^9 D, T/m^2 s for several hours. For each interval between exposure periods, the above sampling procedure was repeated. Total tritium amount required to operate the D/T plasma, with a T_2 gas flow rate of 10 cm^3/min, was about 3 g.

3. Results of the experiment

In the experiment, the plasma exposure was carried out for about 6 h per day and repeated for three consecutive days. Table 1 shows the amounts of tritium measured in the water sampled in the individual intervals. Tritium permeation into the water was observed in the third batch sample, collected after 6 h of plasma exposure. Then, the tritium permeation rate gradually increased as the experiment proceeded. The permeation experiment was terminated after 3 days of operation (total 18 h of DT plasma exposure) due to the finite tritium availability for the experiment. At the completion of the experiment, the steady-state tritium permeation had not been reached.

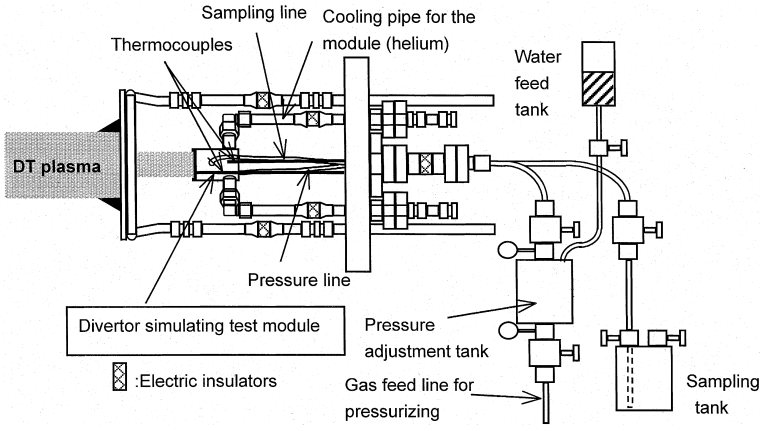

Fig. 1. A schematic drawing of the experimental system with a divertor-simulating test module.

Table 1
Amount of tritium observed in the water sampled in the individual intervals

Sample #	Period of plasma exposure (h)	Total exposure time (h)	Tritium concentration in sampled water (MBq/l)
1	2	2	0.4
2	2	4	0.37
3	2	6	0.74
4	3	9	2.48
5	3	12	9.03
6	3	15	11.06
7	3	18	12.84

4. Preliminary analysis

Prior to the actual experiment, the feasibility of performing a successful measurement with the experimental system and procedures was examined using numerical analytical codes. Two one-dimensional analytical simulation codes, TMAP4 and modified TPERM, which were developed as the tritium behavior analysis codes by Idaho National Engineering Laboratory (INEL) and JAERI respectively, were used.

4.1. Model of numerical simulation

For the analysis with the codes, the test module was modeled in a one-dimensional geometric scheme as shown in Fig. 2. In the modeling, the following assumptions were made in order to simplify the analysis.

1. The structure of the test module behind the cavity which contained pressurized water was ignored and the heat transfer path ended in the cavity.
2. At the inner surface of the cavity, where tritium permeates into the water, tritium concentration was assumed to be zero (release into the water was not rate limiting).
3. The mass flow/chemical potential of D/T was continuous at the interface of tungsten and copper. Therefore, D/T concentrations were to be given proportional to the solubilities at the interface.

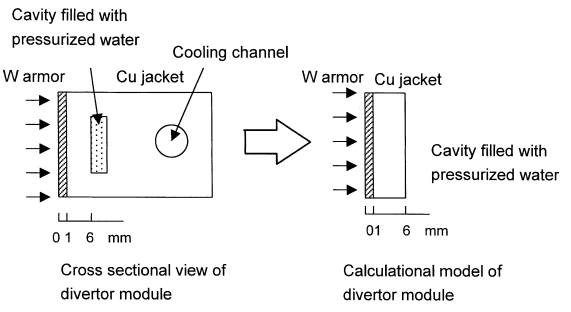

Fig. 2. Geometrical conditions of the model simulating the test module.

4.2. Effect of intermittent plasma exposure on tritium permeation

An analysis of the tritium permeation under the intermittent plasma exposure was carried out. A cycle of operation was assumed to consist of 3×10^4 s of plasma exposure and 6×10^4 s interval time. In Table 2, the values of the materials properties, such as diffusion coefficients, solubilities, thermal properties, etc., used in the analysis are listed.

Fig. 3 shows a comparison of the permeation rates under the cyclic and continuous plasma exposure for a case of no trap and a case of 0.35 eV trap energy at 473 K calculated by TPERM. The plot of permeation rates calculated for the cyclic exposure in Fig. 3 interval time between plasma exposures. The results show that the permeation rates under cyclic and continuous plasma exposure differ by only 20%. The build-up of the permeation rate for cyclic plasma exposure was slightly more rapid than that for continuous exposure. This difference can be attributed to the minor tritium diffusion during the exposure intervals.

The results of the preliminary numerical simulation of tritium permeation through the test module show that simulation of the tritium permeation behavior under the actual experimental conditions by the TMAP4 or TPERM codes is possible. They also show that it is possible to approximate the permeation rate with cyclic plasma exposure by assuming a continuous plasma exposure at constant temperature.

5. Discussion

The tritium permeation through the test module observed in this experiment is presented in Fig. 4 with some results of the numerical calculations using the analytical codes with various trap energies believed to exist in the tungsten armor tile. The time dependence of the tritium permeation rate obtained in the experiment was quite different from that predicted by the numerical simulations. The permeation may have only been in a transitional stage as the rate was smaller than that of the steady state predicted by almost three orders of magnitude. The permeation rate predicted by TMAP and TPERM with an assumed trap energy of 0.26 eV and a trap density of 0.01 agreed with the experimental data only in the first twelve hours; the discrepancy between them increased after that point. While varying other parameters may enable us to improve the fit of the calculated permeation rate to the experimental result, we chose only the trapping energy as a fitting parameter, because several values have been reported with wide

Table 2
List of materials properties used for the numerical analysis

	Constant	Value	Unit	Ref.
Materials properties				
W	Diffusivity	$4.1 \times 10^{-7} \exp(-0.39\ \mathrm{eV}/kT)$	m^2/s	[10]
	Solubility	$1.83 \times 10^{24} \exp(-1.04\ \mathrm{eV}/kT)$	$at/m^3/Pa^{1/2}$	[10]
	Recombination coefficient	$6.0 \times 10^{-20} \exp(-0.41\ \mathrm{eV}/kT)$	m^4/s	[11]
	Trap Energy	Variables	eV	
	Trap Density	0.01	–	[12]
Cu	Diffusivity	$6.6 \times 10^{-7} \exp(-0.39\ \mathrm{eV}/kT)$	m^2/s	[13]
	Solubility	$3.14 \times 10^{24} \exp(-0.572\ \mathrm{eV}/kT)$	$at/m^3/Pa^{1/2}$	[13]
	Recombination coefficient	$1.3 \times 10^{-24} \exp(-0.03\ \mathrm{eV}/kT)$	m^4/s	[14]
	Trap density	None	–	
Thermo-physical properties				
	Heat load	0.089	MW/m^2 s	
W	Thermal conductivity	1.32×10^2	W/m K	[15]
	Specific heat	1.30×10^2	J/kg K	[15]
Cu	Thermal conductivity	3.96×10^2	W/m K	[15]
	Specific heat	3.80×10^2	J/kg K	[15]
	Heat transfer coefficient	517	W/m^2 K	[15]
Plasma conditions				
	D:T ratio	2:1	–	
	Ion energy	100 eV (range 2.5×10^{-9} m)	–	

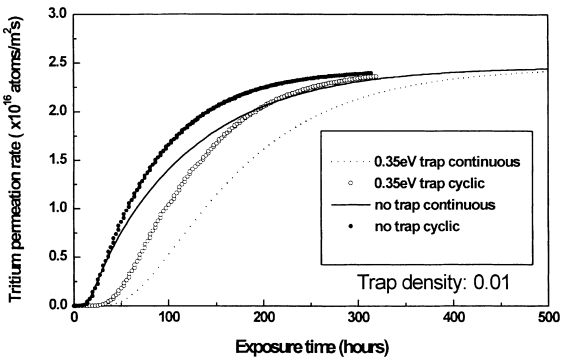

Fig. 3. Tritium permeation behavior predicted under cyclic and continuous DT plasma exposure.

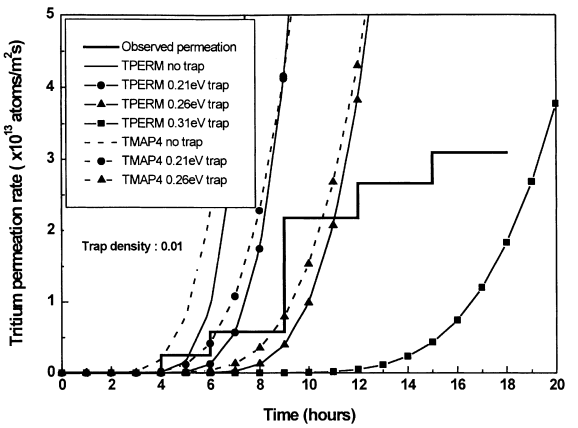

Fig. 4. Observed tritium permeation and tritium permeation rates predicted by TMAP4 and TPERM.

discrepancies [3,16]. To discuss this discrepancy between the experimental and numerical analytic results, more experimental data are needed. Engineering type experiments similar to the present experiments, and ones related to the basic physical properties, such as diffusion coefficient, solubility, recombination factor on the surface under various conditions, for individual structural materials are needed.

The permeation rates predicted by TMAP and TPERM under the assumptions of the traps agreed with each other in their tendency, but some difference in the absolute permeation rates of the transition stages existed between them. The comparison of the results obtained with the codes will be discussed elsewhere.

This first demonstration run of the permeation experiment, revealed several factors that could be changed in order to obtain results using less time and tritium. A thinner sample would shorten the period necessary to observe the steady-state permeation. However, in this case, the size of the cavity containing the pressurized water must be reduced so that the wall

will not rupture under applied pressure. Such an improvement can be easily done without any change of the major experimental systems or the experimental procedures.

Tritium distribution in the test module is another factor of interest. Knowing the tritium concentration at the interfaces, such as in the binding material layer between the armor tile and heat sink and the inner surface of the cavity filled with water (which was ignored in the numerical analysis), will aid the understanding of the results. The means to measure such a tritium distribution are now being examined.

6. Conclusion

A demonstration of the first engineering type experiment for evaluation of tritium permeation behavior through a multi-layer test module simulating a real divertor was carried out. The experimental conditions and procedures were examined to validate the feasibility of analysis for prediction of tritium permeation through the module using two independent one-dimensional numerical analysis codes TMAP4 and TPERM. As a result, it is confirmed that the permeation rate determined by measuring the collected sample water can be evaluated with the codes even with an approximation of continuous plasma exposure. For more accurate prediction of tritium permeation in fusion machine, further improvements of the experimental system and analytical codes, which is associated with acquisition of more precise data of physical properties of individual materials, are desirable.

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