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HIGH-FLUX DEUTERIUM PLASMA EXPOSURE TESTS OF ACTIVELY-COOLED DIVERTOR PLATE UNITS IN PISCES-B

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An actively-cooled divertor plate mock-up with three kinds of carbon-based armor tiles (IG430U, MFC-1, and CX2002U) designed and fabricated by JAERI was bombarded with steady-state and high-flux deuterium plasmas produced in UCLA PISCES-B. The plasma densities, electron temperatures, and ion fluxes were measured from 1 to $3\text{x}10^{19}$ m^{-3}, from 4 to 12 eV, and from 1.2 to $2.1\text{x}10^{23}$ ions/m^2s, respectively. The total ion fluence was of the order of 10^{26} ions/m^2. Interesting surface morphologies have been observed for the plasma-bombarded surfaces, having relatively large agglomerated carbon particles with diameters up to 100 micrometer.

The plasma heat flux was measured with a calorimeter embedded in a graphite (IG430U) to range from 1.1 to 4.4 MW/m^2, which is in good agreement with the calculated value with a simple sheath theory.

Keywords : High Flux Deuterium Plasma, Plasma Erosion, Actively-Cooled Divertor Plate, Carbon Based Materials, Carbon Ball, PISCES-B

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PISCES－Bにおける強制冷却型ダイバータ板ユニットの高粒子束重水素プラズマ照射試験

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（1993年8月24日受理）

米国カリフォルニア大学ロサンジェルス校プラズマ核融合研究所の低エネルギー高密度プラズマ照射装置において，原研にて製作した3種類の炭素系材料（IG－430U，MFC－1，CX－2002Uをアーマタイルとする強制冷却型ダイバータ板モデルへの定常高粒子束重水素プラズマ照射実験を世界で初めて行った。プラズマ密度は1～3x$10^{19}$$m^{-3}$，電子温度は4～12eV，イオン束は1.2～2.1x10^{23}ions・m^{-2}・s^{-1}であり，総イオンフルエンスは10^{26}ions・m^{-2}のオーダーであった。照射終了後，プラズマ照射面をSEM観察したところ，直径10～数10μmの団子状炭素の集団が形成されていた。また，黒鉛中に埋め込まれたカロリメータを用いて，プラズマ照射による熱流束を測定した結果，プラズマパラメータの変化に応じて1.1～4.4MW・m^{-2}の値が得られた。測定結果は，単純なプラズマシース理論を用いて計算された値と良く一致した。

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1. INTRODUCTION

In the Conceptual Design Activities of ITER, it was shown that plasma erosion during the normal operation as well as disruption erosion is the key factor for determining the life-time of divertor plate [1]. The net erosion rate of the armor materials at high particle fluxes relevant to the ITER divertor plasma condition (4×10^{23} ions/m^2.s) has been evaluated only by simulation codes such as REDEP [2], and no experimental data are available at present.

Since the divertor plate of the ITER should be robust against steady-state and heat fluxes of 15 to 30 MW/m^2, the divertor plate of the ITER is currently designed to be cooled by forced water flow in the heat sink [1]. From this point of view, in many laboratories small mock-ups of water cooled divertor plate have been designed, fabricated, and tested using an electron beam or an ion beam irradiation systems for ITER. Recently, JAERI has developed a small mock-up of divertor plate, which is proven to survive 1000 cycles of repeated heat load of 20MW/m^2 for 30 seconds [3], using a carbon-fiber-reinforced carbon (CFC) as the armor tile. However, in this thermal cycling test, the mock-up was irradiated by electron beams. Thus, this test can not provide information about the surface erosion of the divertor mock-up against steady-state high particle flux plasma bombardment. In addition to the electron beams, hydrogen ion beams are being used at JAERI to test the divertor plate mock-up against thermal cycling [4]. In this case, however, energies of the ions are too high and ion fluxes are too low to simulate the plasma erosion.

At present, there are no linear plasma devices and tokamaks, which have capabilities of producing heat fluxes ranging from 15 to 30 MW/m^2 at ITER relevant ion fluxes, at the steady state by plasma bombardment. But, only in UCLA PISCES-B [5], ion fluxes relevant to the ITER condition are available at the steady state.

Based on the Agreement on Japan-US Fusion Cooperation Program, the actively-cooled divertor units, which were designed by JAERI, were irradiated by high-flux deuterium plasmas produced in the PISCES-B at UCLA IPFR, and then the heat flux due to plasma incidence was measured by means of two thermocouples embedded in one of the elements. There are theoretical expressions to evaluate the heat flux due to plasma bombardment, but only a few experiments to verify the theoretical expressions can be found in the literature. A comparison between the measurement and the theoretical expression of heat flux with respect to plasma bombardment is made in this study.

2. EXPERIMENTAL

A schematic diagram of the actively-cooled divertor plate mock-up, used in the present study, is shown in Fig. 1. The mock-up is composed of three different types of divertor plate segments and one calorimeter segment.

The divertor plate segments No.1, 2, and 3 are designated as 1, 2 , and 3 in Fig. 1. Materials of the armor tiles,heat sinks and pipes of the three different segments are summarized in Table-1. IG430U (Toyo Tanso Co.) is an isotropic graphite with the thermal conductivity, λ, of 150 W/mK at 300 K, MFC-1 (Mitsubishi Kasei Co.) is a unidirectional CFC (carbon-fiber-reinforced carbon composite) with λ = 550 W/mK, and CX2002U (Toyo Tanso Co.) is a two-directional CFC with λ = 380 W/mK. The three armor tiles are all brazed to molybdenum heat sinks. One thermocouple is attached on the side of each divertor plate segment for monitoring the temperature. The calorimeter is made of IG430U because of welknown material, directly brazed to the OFHC copper pipe, and has two thermocouples embedded at different positions along the central axis.

The stainless steel (SS) and the OFHC copper pipes and the SS water manifold were protected with boron-nitride (BN) covers from damages due to arcings between the metallic surfaces and the surrounding plasma.

The sample holder connected with the mock-up is shown in Fig. 2. The sample holder has a vacuum bellow, a gear mechanism for inserting the mock-up, an electric insulator, a multi-pin connector for thermocouples, and vacuum connection flanges. Between the mock-up and the multi-pin connector, cables for the five thermocouples were fixed behind the cooling pipes by thin molybdenum wires. The sample assembly was inserted through the top flange of the main experimental chamber of PISCES-B as shown in Fig. 3. The mock-up was electrically insulated from the vacuum chamber. Surface temperature was monitored with an infrared camera and an optical pyrometer during the experiment.

3. EXPERIMENTS AND RESULTS

The mock-up was irradiated many times mainly with deuterium plasma produced in PISCES-B. For conditioning operation of PISCES-B, argon or hydrogen plasma was sometimes used. The plasma can be considered almost uniform within a circular area of 4 to 5 cm in

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The mock-up was irradiated many times mainly with deuterium plasma produced in PISCES-B. For conditioning operation of PISCES-B, argon or hydrogen plasma was sometimes used. The plasma can be considered almost uniform within a circular area of 4 to 5 cm in diameter, even at high ion flux operation mode of PISCES-B [5].

During the shot, the density and the electron temperature of plasma in front of the mock-up were measured with the fast scanning double probe system. Plotted in Figure 4 are the plasma densities and electron temperatures in this experimental region. Dotted lines in the figure represent the constant ion flux level. Ion fluxes for almost all the shots were more than $1\text{x}10^{23}$ ions/m^2s. In the shot of No. 33, the highest ion flux of $2.9\text{x}10^{23}$ ions/m^2s was obtained, which is close to the ion flux on the ITER divertor plate ($4\text{x}10^{23}$ ions/m^2s).

3.1 Integrity Test under Steady State Plasma Bombardment

The divertor plate mock-up with the three kinds of carbon-based armor tiles, as shown in Fig. 1, was bombarded many times by long pulse deuterium plasma. The pulse duration varied from 30 to 200 seconds. The thermal equilibrium of the mock-up was attained within 5 s as shown in Fig. 7. The water flow rate in the cooling pipe was measured with a water flowmeter to be 1.0 to 4.3 l/min.

The plasma densities and electron temperatures in this test are shown in Fig.4 as data points from No. 1 to No. 19; the plasma density ranged from 1 to $3\text{x}10^{19}$ /m^3, the electron temperature from 4 to 12 eV, and the ion flux from 1.2 to $2.1\text{x}10^{23}$ ions/m^2s. The accumulated irradiation time was about 40 minutes, and the total ion fluence was of the order of 10^{26} ions/m^2.

When the mock-up was electrically floating, the floating potential during the plasma irradiation was from -25 to -40V with respect to the vacuum chamber .

The absorbed heat flux was estimated by the theoretical expression using the measured plasma parameters, which will be explained in Section 3.2. The estimated heat fluxes ranged from 1.1 to 2.2 MW/m^2.

The surface temperatures of divertor plate segments No.1 (IG4309U), No.2 (MFC-1), No.3 (CX2002U), and calorimeter (IG430U) measured with the infrared camera and the optical pyrometer were reached to, for example, 670, 510, 300, and 630 °C, respectively, under the conditions where the plasma density = $2.9\text{x}10^{19}$ /m^3, the electron temperature = 4.0 eV, the floating potential of the mock-up = -33 V, the estimated heat flux = 1.5 MW/m^2, and the water flow rate = 4.3 l/min, in case of shot No. 8.

After plasma exposure, surface modifications were observed both on the front and side surfaces of each segment. At a glance, no damage was found at the brazing region. The surface of the armor tile was analyzed with a scanning electron microscope (SEM). Figures 5 (a), (b), and (c) show the SEM micrographs of front surfaces of the armor tiles No. 1 (IG430U), No. 2 (MFC-1), and No. 3 (CX2002U), respectively. As can be seen in these micrographs, "carbon balls" of 10 to a few tens of micrometer in diameter were formed. These carbon balls were loosely attached on the surface so that a part of them were removed away when the mock-up was sawn off the pipes. In Fig. 5 (b), a crater-like damage due to arcing between the mock-up and the plasma can be found.

Impurity elements deposited on the surface of the four armor tiles were analyzed with Auger electron spectroscopy (AES) and secondary ion mass spectroscopy (SIMS). First, each of plasma-exposed armor tiles was sliced at a position 2 mm from the surface. Second, the slice was analyzed by AES and SIMS at different positions on the surface. Third, the surface was sputtered by Ar^+ ions of 1.3 to 2.3 mA at an energy of 3 keV for durations of 2 to 4 hours. In every time interval of 15 minutes, the surface was analyzed by AES and SIMS in turn.

By this process, impurities of boron, sulphur, oxygen, and chromium were detected by AES , and lithium, chromium, iron, nickel, copper, and lanthanum by SIMS, from all the four exposed surfaces. AES peaks of boron, sulphur, and oxygen decreased as the sputtering proceeds. Impurities of chromium, iron, nickel, copper, and molybdenum existed only near the surface, while lanthanum slightly increased as the sputtering goes ahead. Total impurities amounts to be roughly a few percents.

The origin of boron seems to be the LaB6 cathode in the plasma generator of PISCES-B and the BN covers protecting metallic surfaces. Chromium, iron, and nickel are the elements composing stainless steel, and thus seems to be originated from the stainless steel pipe exposed to the plasma. The origin of copper is the copper pipe. Molybdenum is clearly coming from the thin molybdenum wires, a part of which were melted during the arcings, and lanthanum from the LaB6 cathode. Considering the sensitivity of SIMS for each element, the amount of molybdenum impurity is much larger than that of boron. Based on this analysis, there is a possibility that these metal impurities would be nuclei of carbon balls if the any kinds of nuclei were necessary to form the carbon balls.

At present, the reason why and the condition where the "carbon balls" were formed is not clear. The formation of "carbon balls" has never been observed in any tokamaks with carbon-based materials as the first wall or the divertor armor tiles. For example, in case of the JT-60U at JAERI, a layered structure and a column-like structure were found in the redeposition region of damaged divertor tile of graphite, after one and half year operation [6,7]. On the contrary, in a process of SiC coating on pyrolytic graphite using RF discharge sputtering device, the structure of deposited SiC becomes ball-like at room temperature(25 °C), and becomes pimple-like and smoother as the temperature goes up to 300, 600, and 1000 °C [8]. In the plasma erosion experiments of various carbon-based materials conducted so far at relatively low fluxes in PISCES-B [9~12], formation of the "carbon balls" was not found.

3.2 Measurement of Plasma Heat Flux

The principle of the measurement is shown in Fig.6. The heat flux q passing through a position in a solid material, at the steady state, can be expressed by,

$$q = \lambda \, dT/dx \qquad (1)$$

where T is the temperature of the material at the position x, and λ is the thermal conductivity of the material. The temperature gradient at one position can be approximated by temperature difference $T_1 - T_2$ at two different positions, divided by the distance d of the two positions. Since the thermal conductivity is a function of temperature in general, we use the averaged value of thermal conductivity at the two temperatures, T_1 and T_2., because of relatively low temperature gradient. Thus, the measured heat flux was evaluated using the following expression,

$$q = (\lambda(T_1)+\lambda(T_2))/2 \;\; x \;\; (T_1 - T_2)/d, \qquad (2)$$

The temperatures T_1 and T_2 were measured with the two thermocouples embedded in the calorimeter. Figure 7 shows a typical example of the temperature evolution under plasma bombardment. As can be seen in the figure, the measured temperatures attained the equilibrium state within about 5 seconds. The difference of the two temperature rises measured in IG430U during the plasma irradiation, was about 140 K, and the heat flux absorbed in the armor tile was evaluated to be 4.4 M W/m^2 in this case, from Eq. (2).

The heat flux absorbed by a solid material can be expressed analytically in terms of plasma parameters and various quantities associated with surface phenomena, atomic and molecular processes, etc.

The heat flux q_p induced by the plasma particle incidence on the surface can be expressed by refs. 13 and 14,

$$\begin{aligned} q_p = {} & (1/4)n_e v_e 2T_e \exp[-e(V_p - V_t)/T_e] \\ & + (j_{is}/e)[e(V_p - V_t) + 2T_i](1 - R_e), \end{aligned} \qquad (3)$$

where n_e is the electron density (m^{-3}), v_e the electron thermal velocity (m/s), T_e and T_i are the electron and the ion temperatures (eV), V_p the space potential of the plasma (V), V_t the potential of the target (V), j_{is} the ion saturation current density (A/m^2), and R_e the energy reflection coefficient of the ions impinging on the surface. The first term on the right hand side of Eq. (3) is the contribution from the plasma electron impact, and the second term is that from the plasma ion impact, taking the energy reflection of ions into account.

The heat flux q_{rec} induced by the recombination of plasma ions with electrons at the surface is expressed as,

$$q_{rec} = (j_{is}/e)(V_i + V_{dis} - W), \qquad (4)$$

where V_i and V_{dis} are the ionization and the dissociation energies of deuterium gas (eV), and W the work function of the material surface (eV).

The heat flux induced by the neutral particle collisions with the surface and that due to the radiation can be neglected compared with the heat fluxes q_p and q_{rec}, based on a rough estimation. Thus, the total heat flux is written by,

$$q_{tot} = q_p + q_{rec}\ , \qquad (5)$$

In weakly ionized deuterium gases, there seems to be many Frank-Condon particles. Hence we assume $T_i = 2\ eV$. In addition, we have to assume $V_p \sim 0$ (ground potential), since the space potential of the plasma could not be measured by the double probe method. It was confirmed that this assumption is not far from the real condition in our case, making use of the relation expressed by,

$$V_p \sim V_f + 3(T_e/e), \qquad (6)$$

where V_f is the floating potential of the plasma and was measured in this experiment.

As the values of the electron density, the electron temperature, and the ion saturation current density in Eqs. (3) and (4), we used those measured by the double probe method. The floating potential of the mock-up with respect to earth potential was also measured with an electronic voltage meter. And as the constants in Eqs. (3) and (4), we substitute the following values; $R_e \sim 0.1$ [15] and $W = 4.4\ eV$ for carbon, and $V_i = 13.6\ eV$ and $V_{dis} = 2.2\ eV$ (per atomic ion) for deuterium.

Figure 8 shows the relation between the measured heat flux and the calculated heat flux. Although the deviation of the calculated values from the measured is large at relatively high heat flux region, the agreement is generally good.

4. CONCLUSION

The actively-cooled divertor plate mock-up with three different carbon-based armor tiles (IG430U, MFC-1, and CX2002U) was bombarded with the ITER relevant steady-state and high-flux deuterium plasmas produced in UCLA PISCES-B. The plasma densities, electron temperatures, and ion fluxes in this test were from 1 to 3×10^{19} /m^3, from 4 to 12 eV, and from 1.2 to 2.1×10^{23} ions/m^{2}s, respectively. The total ion fluence was of the order of 10^{26} ions/m^2. After plasma exposure, surface modifications were observed both on the front and side surfaces of the armor tiles. No damage was found at the brazing region. The clusters of "carbon balls" of 10 to a few tens of micrometers in diameter were formed on all the front surfaces of the armor tiles. To clarify the reason and the conditions for the formation of the "carbon balls", further studies are required.

The plasma heat flux absorbed by the carbon-based material was measured with the calorimeter, under the condition that the mock-up was at floating potential. The highest heat flux measured was 4.4 MW/m^2. The measured heat fluxes were generally in good agreement with the heat fluxes calculated using theoretical expression and the measured plasma parameters, on the assumption that the plasma potential is equal to the potential of the surrounding vacuum chamber.

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Table 1 Materials of three different divertor plate units.

Unit No.	Armour Tile	Heat Sink	Pipe
1	IG430U	Mo	SS
2	MFC-1	Mo	SS
3	CX2002U	Mo	Cu

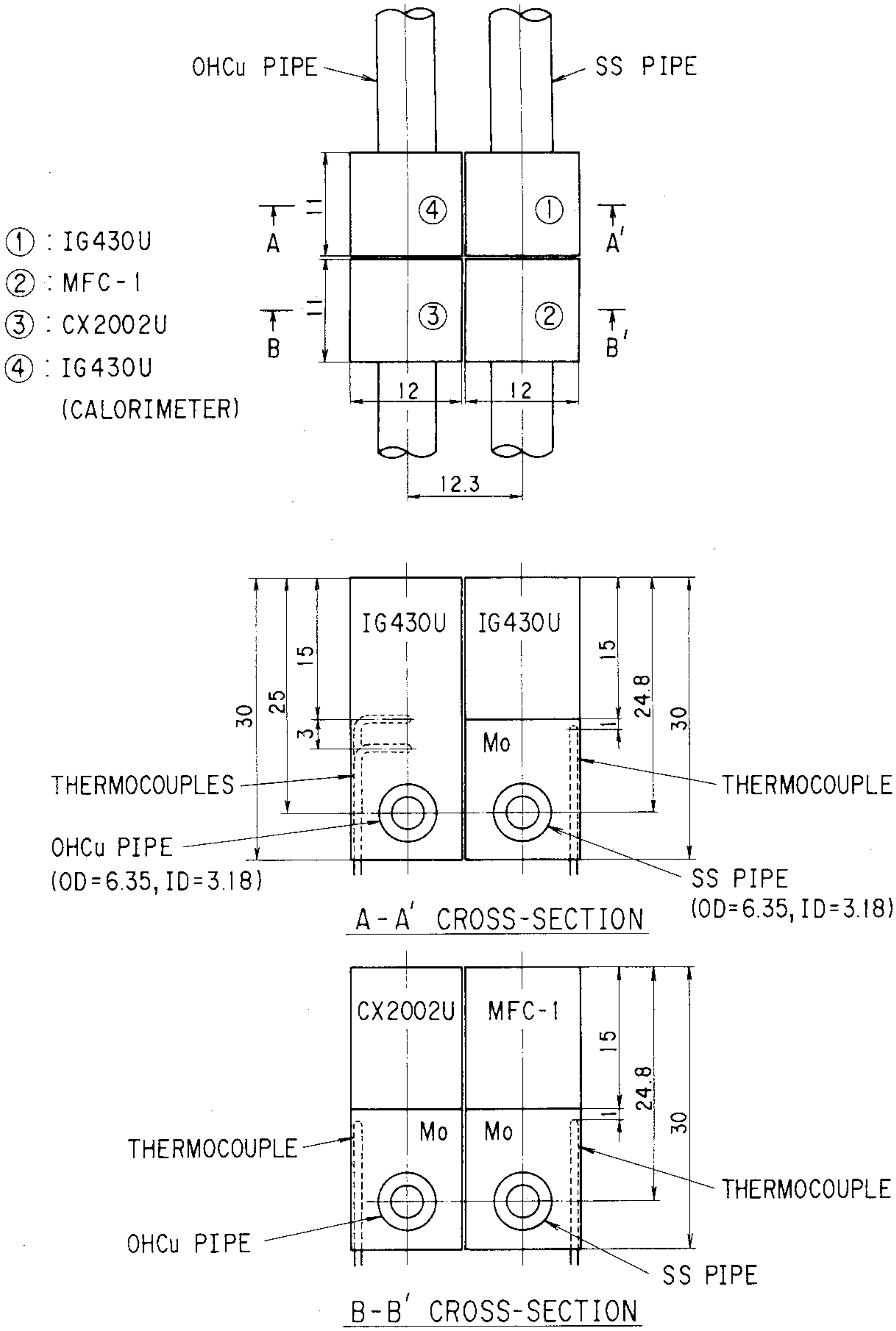


Fig. 1 A schematic diagram of the actively-cooled divertor plate mock-up with three kinds of carbon-based armour tiles (IG430U, MFC-1, and CX2002U), used in the integrity test against plasma erosion.

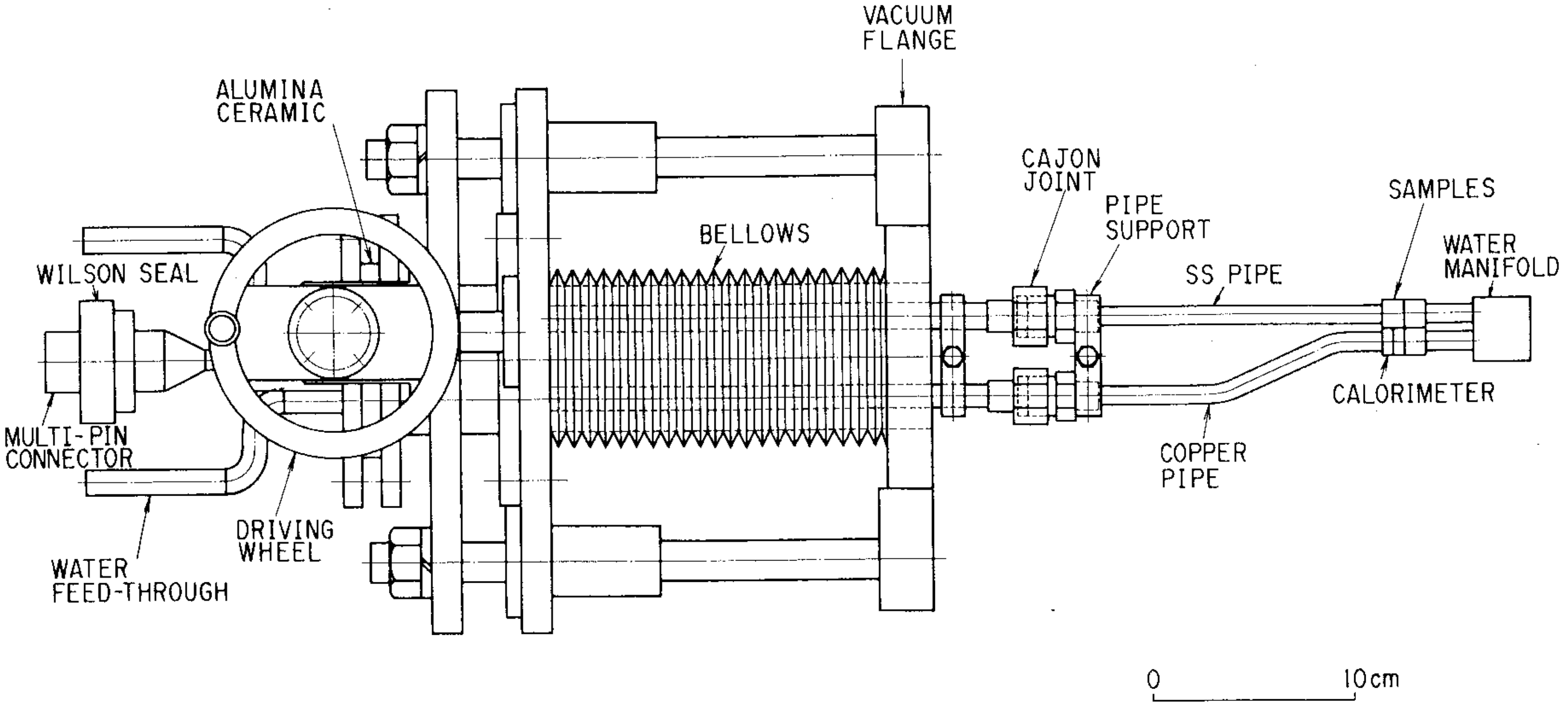


Fig. 2 A schematic diagram of sample holder, connected with the divertor plate mock-up.

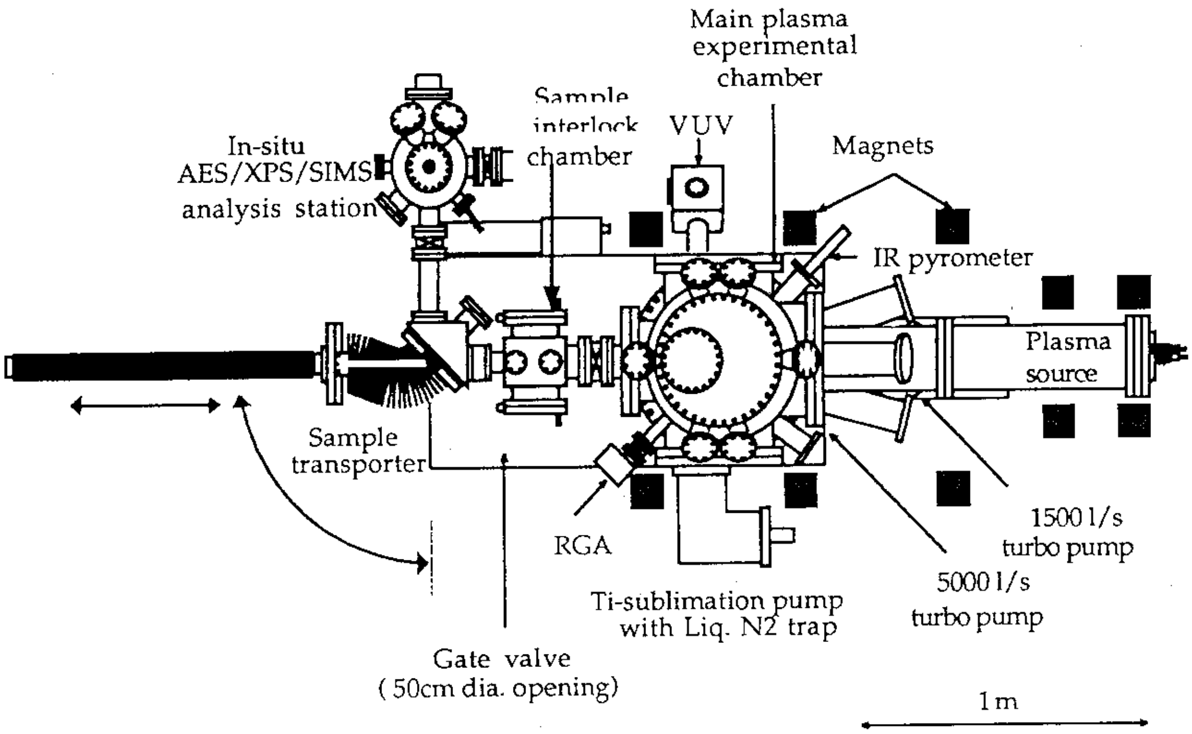


Fig. 3 Plan view of PISCES-B device.

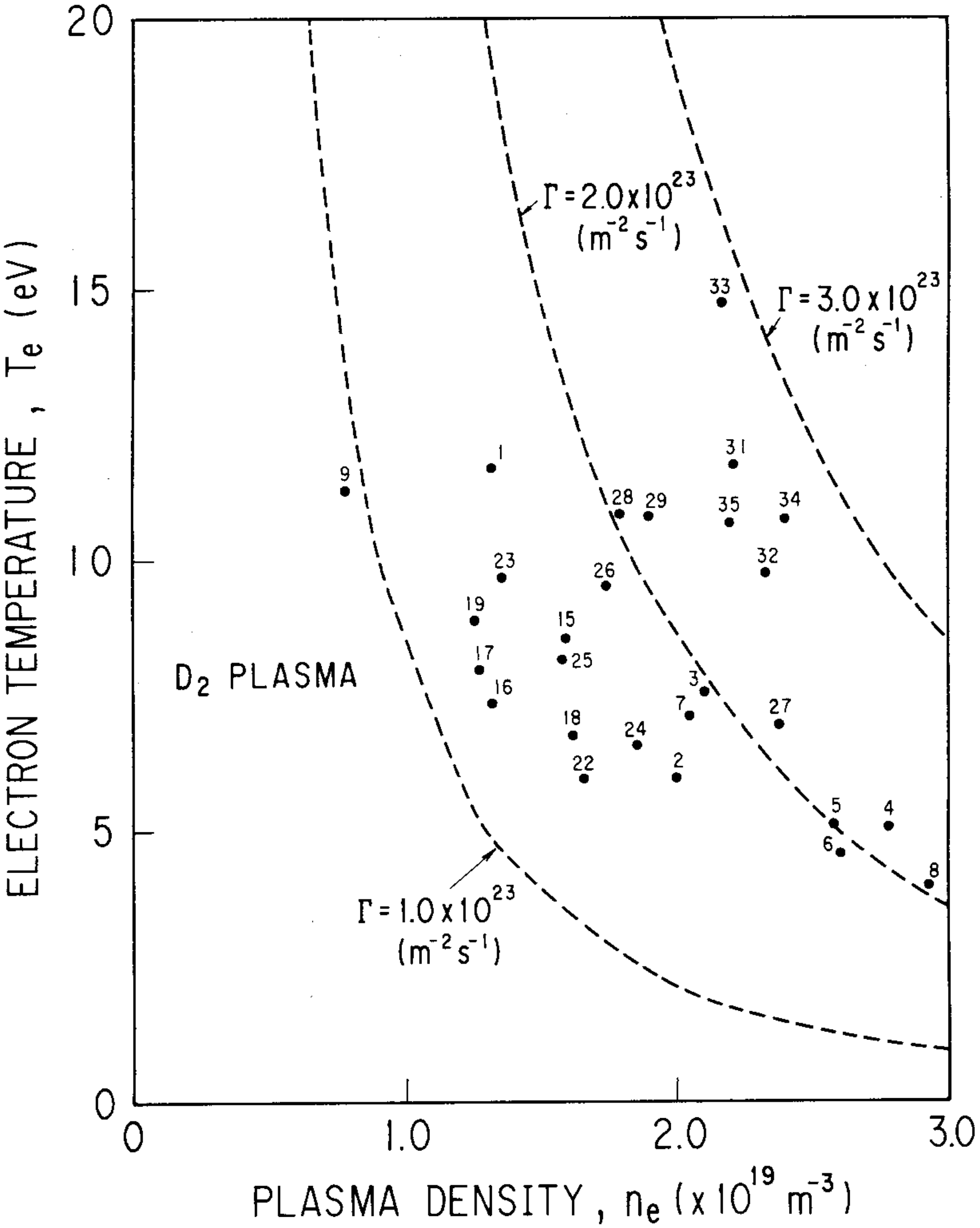
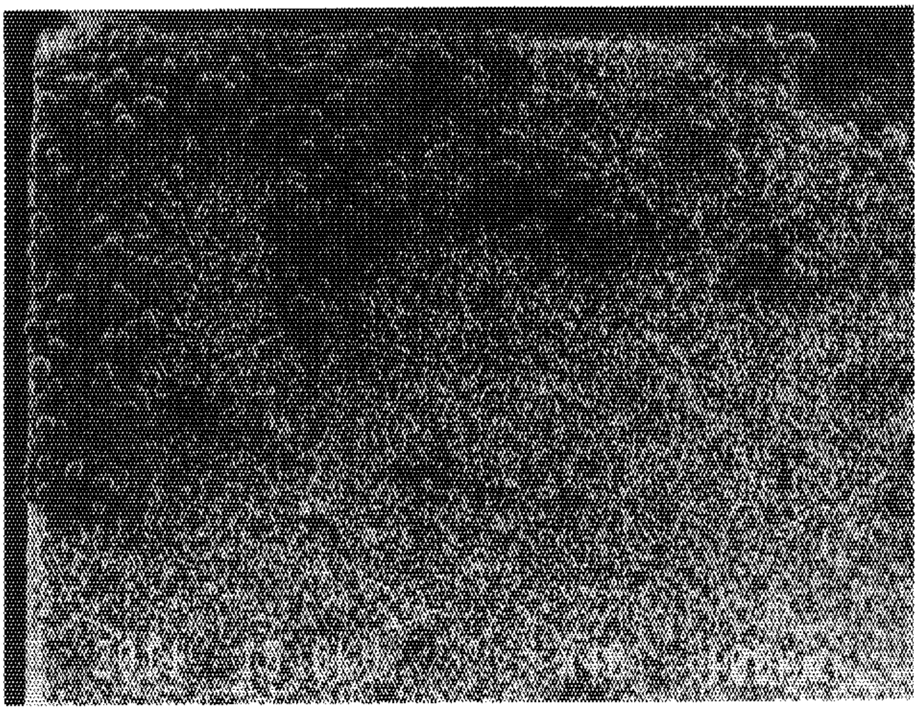
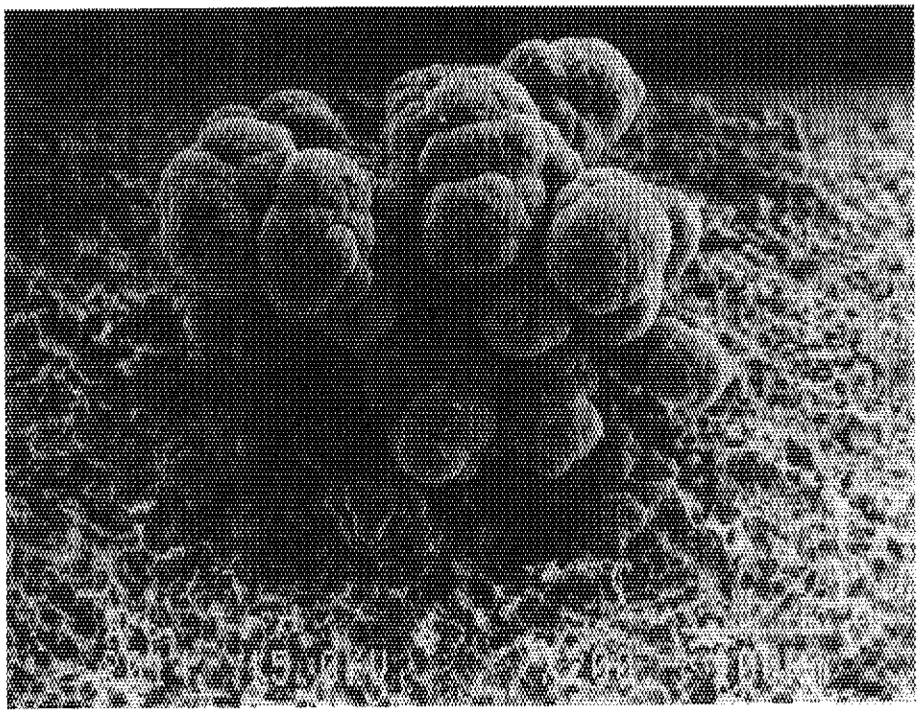


Fig. 4 Map of the plasma densities and electron temperatures, measured in deuterium plasma shots. No.1∿19 : the integrity test, No. 22∿35 : the plasma heat flux measurement.

IG430U



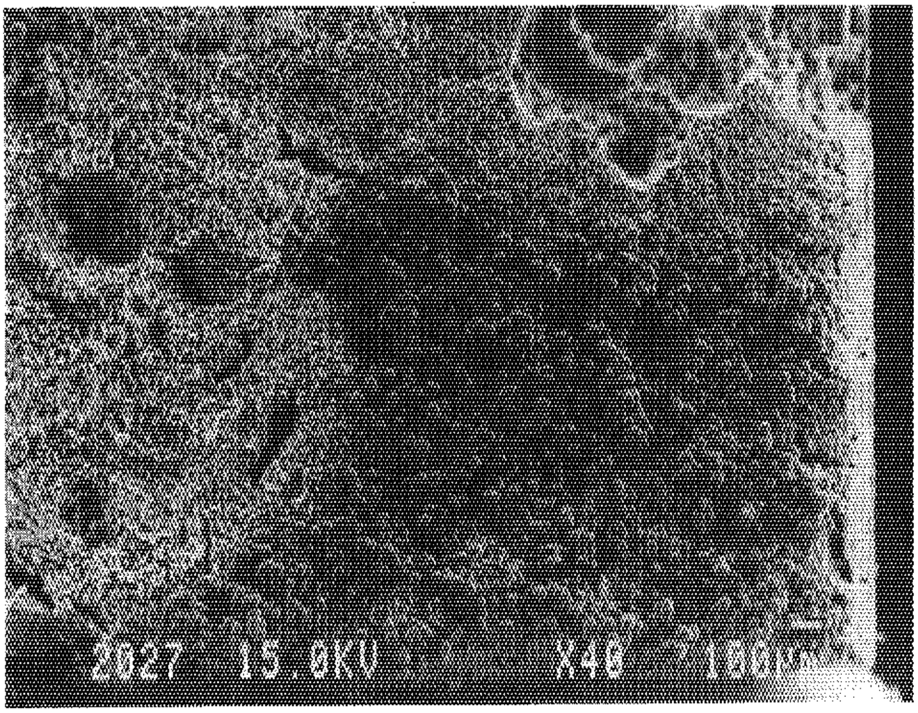
x 40



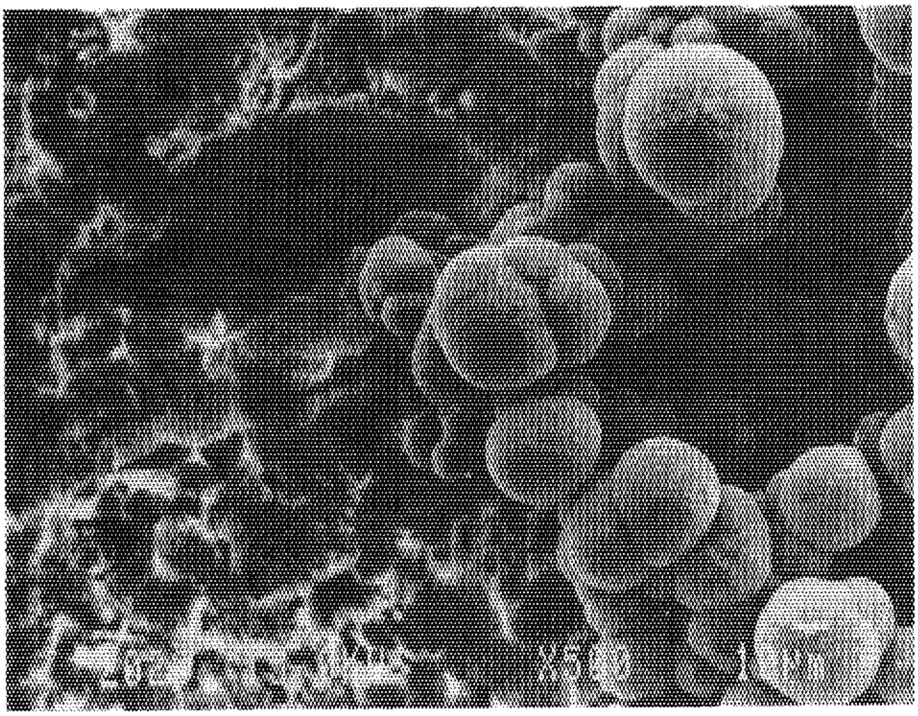
x 200

Fig. 5(a) SEM micrograph of the armour tile 1 (IG430U) after plasma exposure (x40), and magnified one (x200).

MFC-1



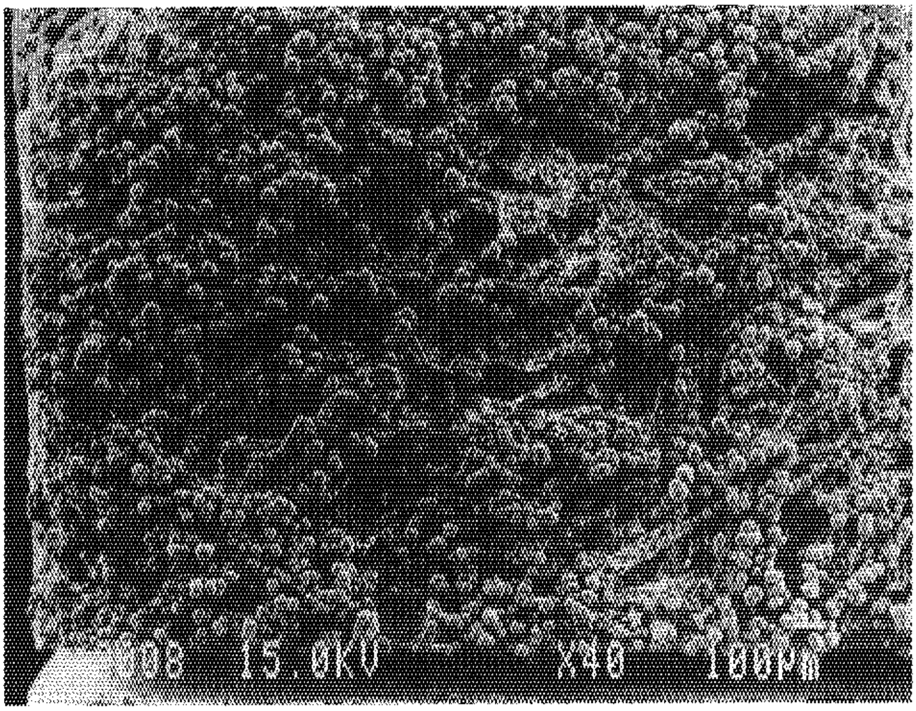
x 40



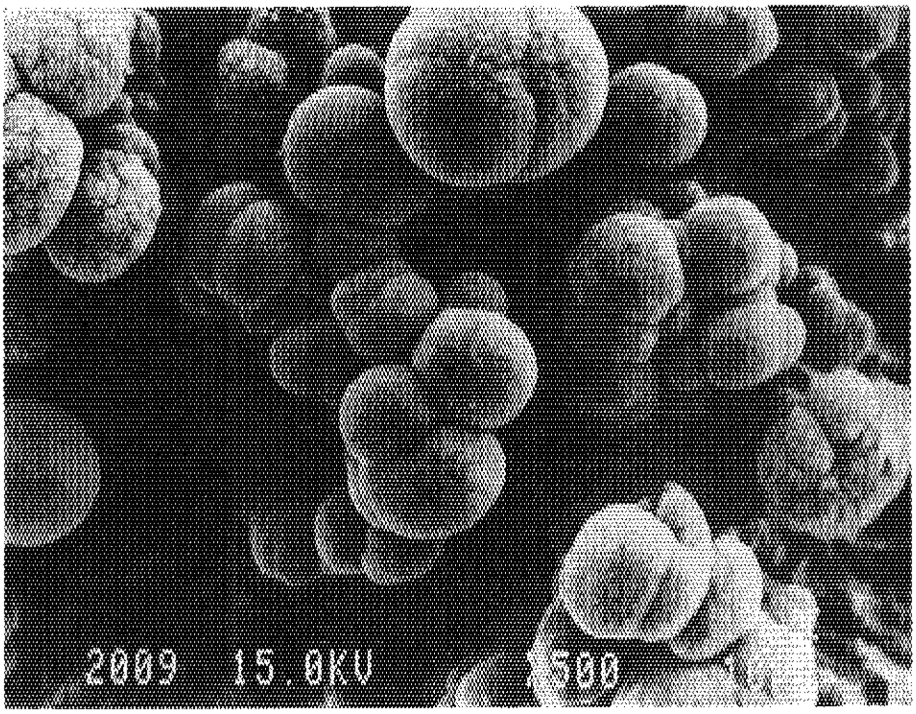
x 500

Fig. 5(b) SEM micrograph of the armour tile 2 (MFC-1) after plasma exposure (x40), and magnified one (x500).

CX2002U



x 40



x 500

Fig. 5(c) SEM micrograph of the armour tile 3(CX2002U) after plasma exposure (x40), and magnified one (x500).

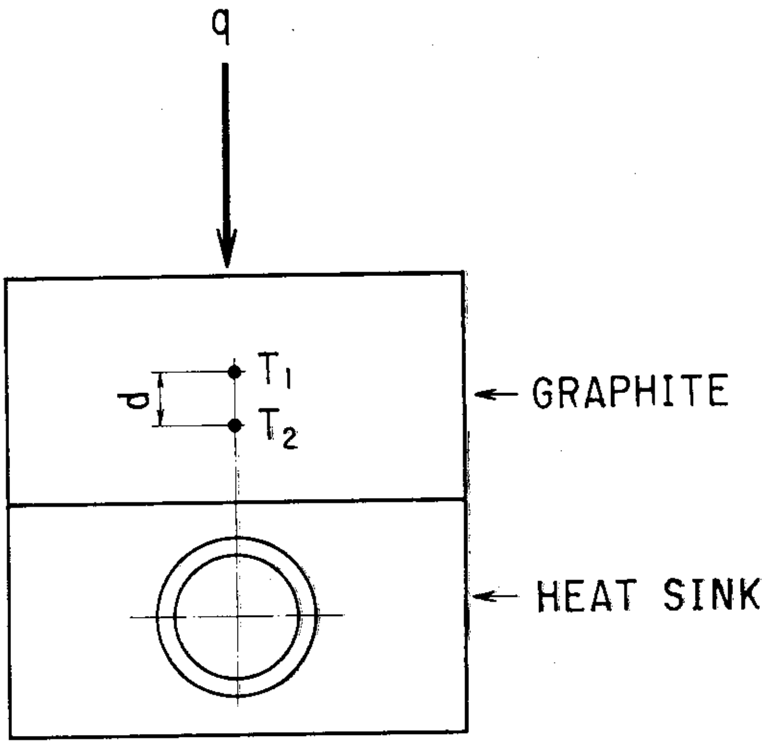


Fig. 6 Schematic indicating the principle of the measurement of plasma heat flux.

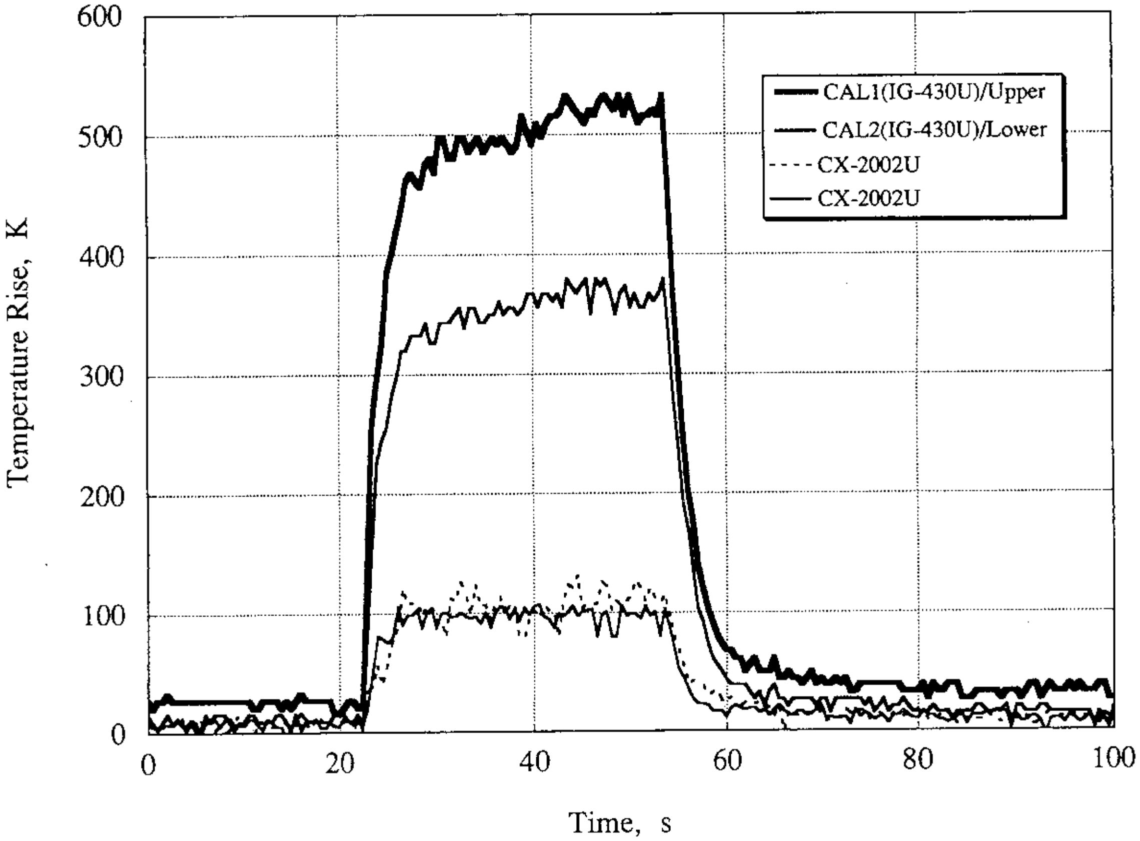


Fig. 7 An example of temperature evolution under plasma bombardment. The two curves tracing higher temperature rises, during the plasma bombardment, represent the temperatures measured in the calorimeter, and the other two represent the temperature rises of two divertor plate units measured in heat sinks.

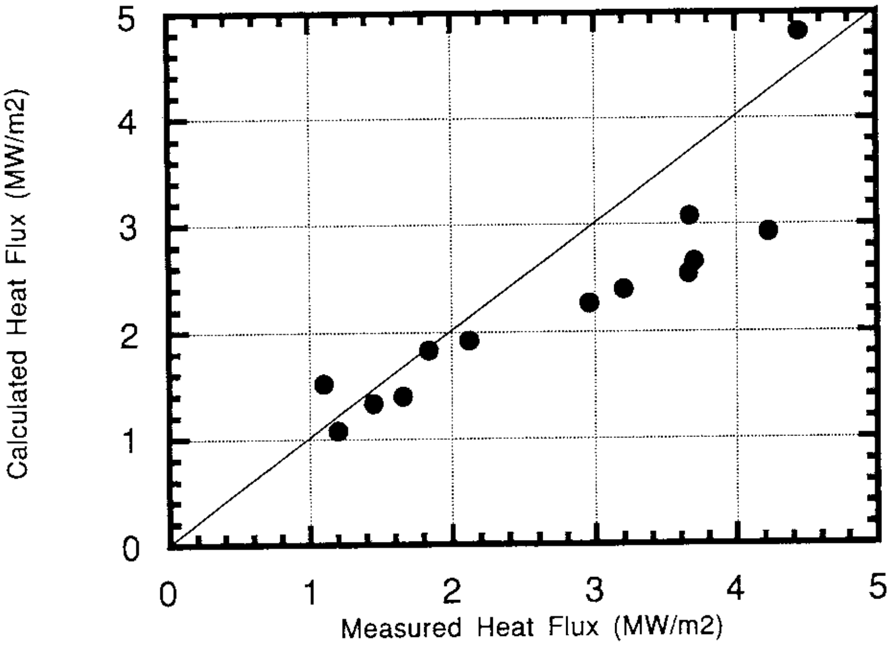


Fig. 8 Relation between the measured and the calculated plasma heat flux.