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High heat loading tests and temperature measurements in Hot Cells

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Abstract

Since 1996 heat loading tests on radioactive materials were performed with an electron beam facility installed in a hot cell called 'JUDITH' (JUelich DIvertor Test facility in Hot cells) . The objectives of these tests are the development of first wall materials for a fusion reactor. The candidate materials CFC, beryllium and tungsten had been irradiated in the HFR-Petten to obtain a realistic materials structure change due to the neutron dose rate. In principle two kinds of heat loading tests were performed.

- The simulation of plasma disruption in a fusion reactor, that means a very short and intensive electron beam pulse on the material surface.
- Long time pulses with moderate beam energy (cycle mode) to simulate the normal operation of a fusion reactor with actively cooled modules.

The most important information of these tests concerns the damage of the specimens due to erosion and cracking caused by high temperature loading. The surface temperature (up to 3500°C) is measured by a special pyrometer and infrared camera system, which is located in the vacuum chamber of the electronbeam facility. Specimen, pyrometer and infrared system must be positioned by remote handling as well as changing contaminated windows of the vacuum chamber.

1. Introduction

Carbon materials, tungsten and beryllium are candidates for plasma facing materials in the next generation of thermonuclear fusion devices. Extensive neutron irradiation experiments with samples and modules, prepared for actively cooling, have been carried out to analyze the degradation of the physical properties. Due to the lack of powerful 14 MeV neutron sources, irradiation tests are performed in the high flux material test reactor HFR Petten The thermo-mechanical properties of these materials and components (irradiated and unirradiated) are investigated by heat loading tests with the electron beam facility "JUDITH". (JUelich Divertor Test facility in Hot cells) (Fig.1). In these tests special specimen geometries, so small as possible, have been used, because the space in the irradiation rig is limited. This miniaturization process has to be limited to geometries of test specimens and modules where the test conditions are still representative for components in a fusion reactor.

2. Experimental set-up

The electron beam facility "JUDITH" consists of a 60 kW electron beam gun, a vacuum chamber measuring 800 x 600 x 900 mm with a large scaled pumping system and a number of diagnostic devices.

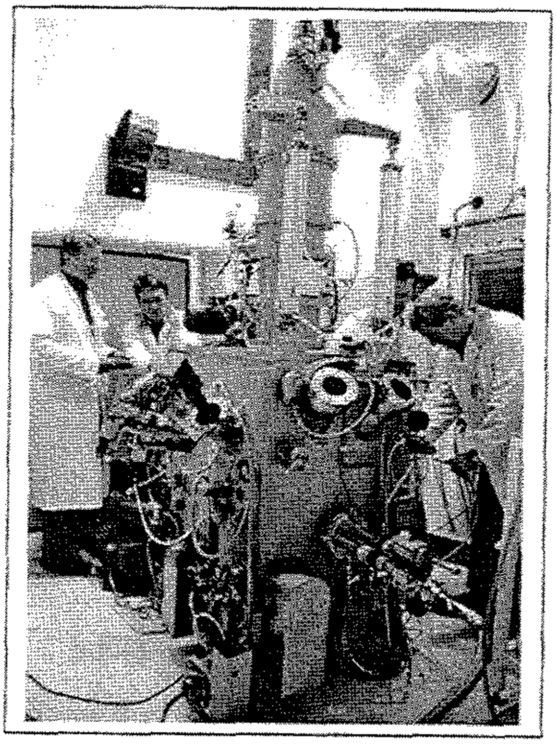

Fig.1 Electron beam facility "JUDITH"

The focused electron beam has a diameter of 1 mm approx. and can be swept in two directions at frequencies up to 100 kHz. The technical data for the machine are listed as follows:

total power: 60 kW
acceleration voltage: <150 kV
power density: < 15 GW/m^2
max. loaded area: 100 x 100 mm^2
scanning frequency: < 100 kHz
pulse duration: 1 ms...continuous
beam rise time: 130 µs (short pulses)
cooling loop: water,p <40 bar,f < 1 l/s

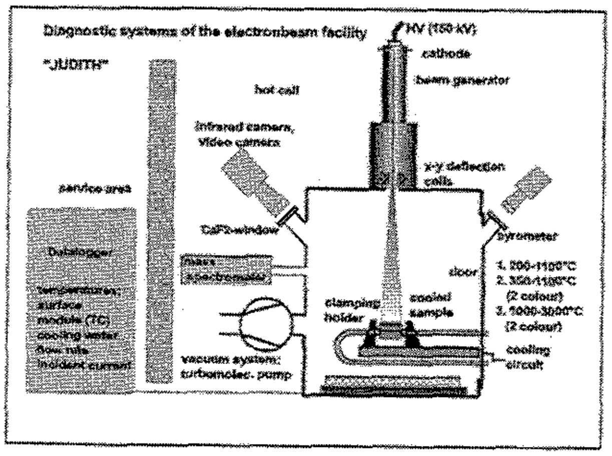

Fig.2 JUDITH electron beam facility with diagnostics

The following diagnostics have been used :

- two infrared pyrometers, covering a temperature range between 200°C and 3500°C.
- a fast pyrometer from 1200°C to 3500°C (rise time < 10µs)
- infra-red camera system (scanner) with cooled detector for temperature monitoring between room temperature and 3000°C.
- residual gas analyzer (quadrupol mass spectrometer)
- ionization chamber to measure tritium release
- video camera system
- thermo couples with datalogger system

3. Testing of divertor mock-ups

In order to save space in the irradiation rig, the mock-ups were produced with water cooling channels only, but without tube connectors .For these samples, the cooling water is supplied through a special clamping mechanism. It was achieved by special sealing adapters machined from copper in combination with O-ring sealings and springs. This provides sufficient safety against water leaks in the vacuum chamber. The mechanism is motor driven and can be operated by remote handling techniques. .A pressure cell is used to control the clamping forces. The common size of these mock-ups is 15x25x30 mm^3.

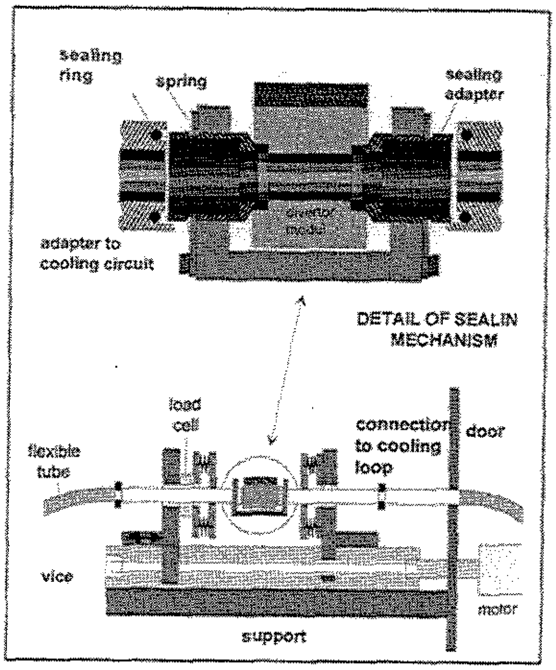

Fig.3 Clamping mechanism for actively cooled mock-ups.

Several types of mock-ups have been tested. Composite specimens with brazed joints between a flat tile and the heat sink material or monobloc types with cooling tube. To simulate the loading conditions for the most critical part of the specimens, i.e. for the braze interface, electron beam pulses of several seconds duration and absorbed power densities up to 20 MW/cm^2 have been applied. Under these conditions thermal gradients can be achieved which are relevant for the quasi stationary heat flux on an actively cooled divertor component. To remove the heat, it was necessary to install a powerful cooling circuit. Fig.3 shows the installation. A flowrate of 1 l/s with a pressure of 4 Mpa can be achieved. The heat exchanger can be loaded with 80 kW.

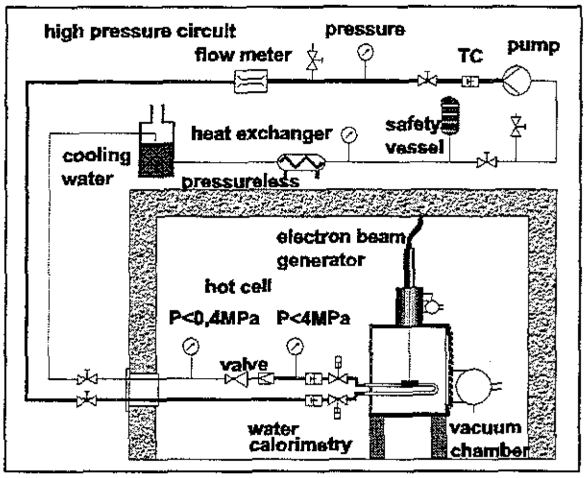

Fig. 4 Cooling system of the electron beam facility

For the assessment of heat removal efficiency of the different mock-ups it is essential to measure the surface temperature on the mock-ups. As thermocouples can measure the temperature only in a certain distance from the surface, IR-measurements (IR-scanner, pyrometer)are required

These measurements are subjected to uncertainties in emissivity. The pyrometers (one- and two-colour) and the IR-camerasystem are calibrated with a black body (in practice a grey body with e=0.9). This calibration is used to measure the surface temperature of graphites. For materials like beryllium or tungsten other calibration factors are required due to specific emissivity values. The measurement of the emissivity is performed by heating an isolated positioned sample with inserted thermocouple. The measurement must be done with the original geometry especially with clean window. The material of the window is CaF2 with a very high transmittance (t=0.9) up to a wavelength of 5µm. An additional fixed point by spraying graphite varnish on the material surface is a helpful method to get reliable results

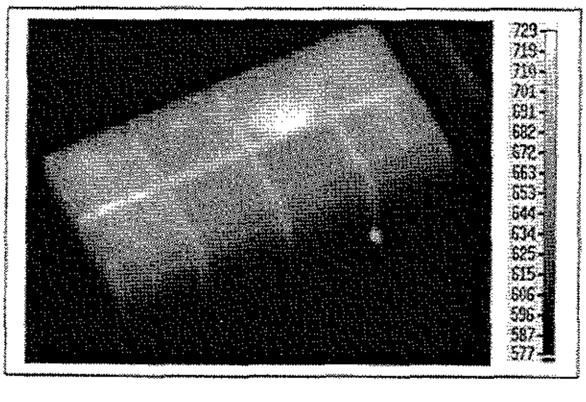

Fig.5 IR-picture of the temperature distribution of an actively cooled Be-Cu-divertor mock-up.

Fig.5 shows a typical picture during long time testing of a beryllium mock-up with castellated tile ,brazed on a copper cooling body. The surface of the tile is prepared with a graphite spot. The heat loading of 8 MW/m² and the temperature distribution are homogeneous, the visible differences of the temperature are caused by the change of emissivity. The slits of the castellation are comparable with cavity radiation and look like a black body. The calibration with an emissivity of 0.8 amounts to a surface temperature of 720°C measured on the graphite spot. The emissivity factor of 0.8 is combined by the factor of a black body (0.9) and the transmittance factor of the CaF2 window (0.9).

The two-colour pyrometers theoretically measure independently from emissivity or transmissivity, provided that there is no dependence on the wavelength of the IR-spectrum .In the case of beryllium and tungsten the IR-spectrum is diversified to that of a black body, therefore a special calibration has to be performed.

3. Thermal shock tests

In addition to normal operation so-called "plasma disruptions" occur, involving extremly high thermal loads for several milliseconds, which lead to material erosion due to evaporation and spalling at the surface of the wall material. To simulate disruption events in the electron beam facility, small specimens (10x10x5 mm³) of relevant materials are used and loaded on a small area of 5x5 mm². In few milliseconds (i.e. 5 ms) an energy density of 8 MJ/m² can be deposited.

Fig. 6 shows a photo of a thermal shock test on a sample of fine grain graphite. Blown-off particles can be identified, some of them are rotating, realized by a dotted trace.

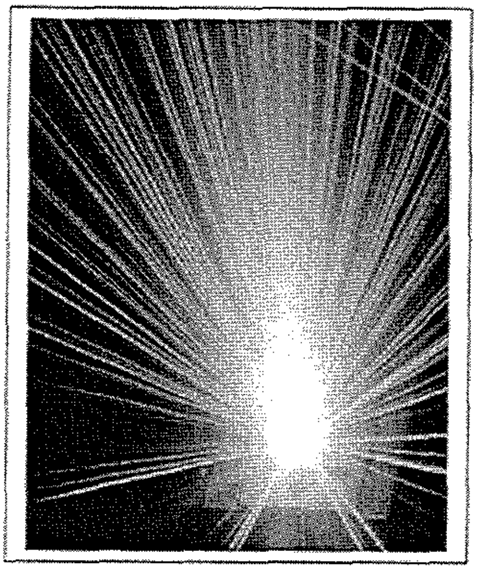

Fig.6 Thermal shock test on graphite sample

To measure the temperature during a 5 ms- shot a specially constructed pyrometer with very short response time has to be used.(Fig.7)

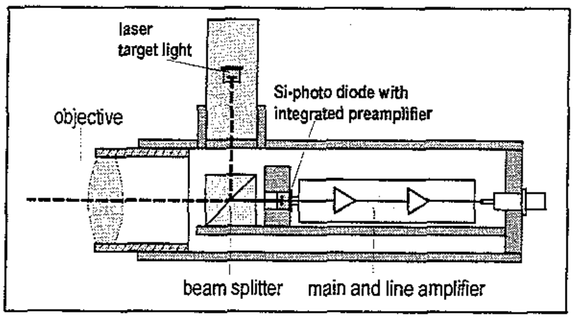

Fig. 7 Basic construction of the fast pyrometer

The fast pyrometer is based on a silicon detector with integrated amplifier. The measuring point on the target with a diameter of 3 mm in a distance of 80 cm is adjusted by a laser pointer. The response time of the diode and the connected electronics is less than 1 µs. The silicon diode is sensitive to the short wave range of the IR spectrum (0,6-1,0 µm), therefore the measuring range starts with temperatures higher than 1200°C. In this case, the window and the lens of the objective consists of special glass.
A further useful information during a thermal shock test is the amount of the net current, which flows through the sample. When the electrically isolated sample is grounded by a resistor, the course of the current can be measured by the potential difference. Fig. 8 shows the basic circuit diagram

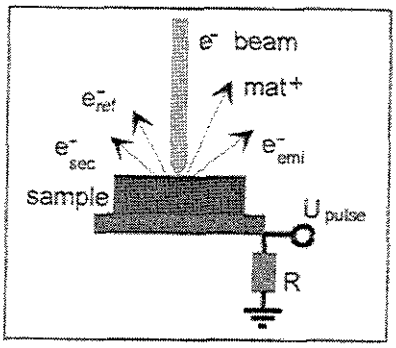

Fig. 8 Measuring of the net current flowing through the sample

The incident electron beam generates reflected electrons depending from the material. In the case. of tungsten , 50% of electrons will be reflected. When the surface becomes hotter, the emission of electrons begins and additionally reduce the net current The heat induced stress in the surface layer leads to ejected particles which influence the net current

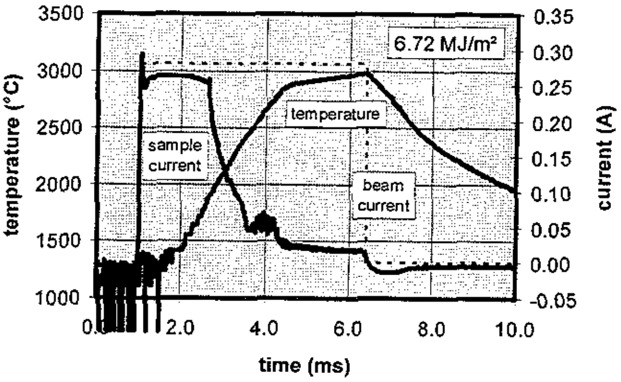

Fig. 9 Temperature and current during thermo-shock test

Fig. 9 shows the measurement of the temperature and the current during a test with a graphite sample. (like Fig.6) The dotted curve shows the amount of the incident current. About 7% of the electrons were reflected directly during the surface of the graphite was heated up to 1800°C in the first millisecond. Now the effect of electron emission became dominant and the net current has been essentially lowered. After 2.5 ms the surface temperature reached 2800°C. The beginning of sublimation caused an additional cooling effect, consequently a lower temperature gradient could be measured. The aim of the test is to find materials with a minimum of material loss. In this case a correlation between weight loss and interpretation of the current curve would be very helpful. This has to be investigate by further tests.