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** See Annex*

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1. ABSTRACT

The actively cooled version of the JET divertor plates use a finned structure as heat exchange surface between the copper alloy base plate and the cooling water (hypervapotron). The turbulence created by the fin structure gives a remarkably good heat transfer even before the onset of boiling. The boiling heat transfer is stabilised by the colder fin structure. Finite element calculations confirm that the heat transfer can be explained by turbulent boiling heat transfer.

Power densities of up to 25MW/m^2 can be removed with a pressure drop of 4bar per meter. Beryllium tiles brazed to the CuCrZr base plate can withstand a pulsed power loading of up to 16 MW/m^2. Limiting in strength is the intermatallic layer between the braze and the Beryllium tile. The test sections, mounted rigidly against a strong back, withstood the stress caused by thermal expansion.

2. INTRODUCTION.

The JET Joint European Torus[1] in Culham U.K. operates in a pulsed mode with a pulse duration of up to 60s. The plasma is confined by magnetic fields and heated by the current in the plasma (up to 7 MA). Up to 40 MW of additional power can be supplied by the plasma heating systems. The energy confinement time is of the order of 1s. The exhausted power is absorbed in specially designed dumps. Impurities released from the dump can lead to radiative losses and to dilution of the plasma. Both effects increase with the atomic number Z of the impurity. To minimise plasma contamination, low surface temperatures of the dump plates and a dump surface material with a low atomic number, such as Beryllium or Graphite, are beneficial. Any misalignment of the dump plates will cause localised hot spots and must be avoided.

A so-called "divertor", which separates the dump area from the plasma, is at present being installed into the JET machine. The strike area between the plasma exhaust flux and the dump plates will be swept with a frequency of 4 Hz, thus reducing the peak heat flux of 60 MW/m^2 to a time average heat flux of 12 MW/m^2. In this paper we report on thermal tests of the water cooled base plates made from CuCrZr with finned internal surfaces (Vapotron)[2] and on tests of base plates with Be tiles brazed onto the exposed surface. In a previous paper [3] we have reported the results of experimental studies of the heat transfer of vapotron structures. It was found that the detailed geometric structure has little influence but the velocity of the cooling water was of major importance. The classical vapotron effect, where the steam formation in the grooves and its ejection provides

provides the driving force of the heat exchange, is only seen at low velocities. With increasing velocity, the turbulence created by the fin structure appears to dominate the heat transfer. This observation led to the development of a test section with a reduced water channel width and reduced fin height. The heat transfer characteristics of this element is covered in this report.

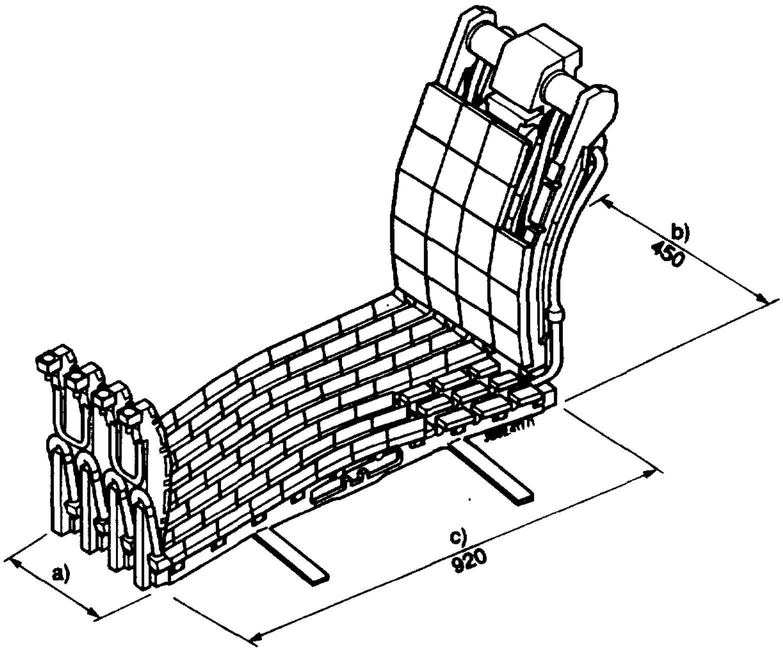


Fig. 1: Module assembly of the JET divertor. Initially all tiles are inertial (interpulse cooled). Later the bottom tiles will be actively cooled elements as descibed here.

3. Divertor Dump Plates

The divertor dump is made up from 48 modules to form a complete toroidal ring. The bottom section is the actual dump and will, in a second operation phase, consist of 8 individual 900 mm long actively cooled dump plates per module (Fig. 1). The tiles at the sides and initially at the bottom are made from solid beryllium with inter pulse cooling[4]. The actively cooled dump plates are rigidly connected to a strong back to prevent movement and distortion due to thermal expansion. The cross section of each dump plate increases along the length from 27 x 19 mm to 36 x 19 mm (toroidal dump). The water flow rate is 0.5l/s per actively cooled element. The heat transfer between the dump plate and the water is via a finned surface. The height of the water channel defines the ratio between flow rate and velocity and can be adjusted to the specific requirements to optimise the water circuit. (Fig. 2) The water channel in the JET divertor plates is tapered to maintain a constant flow velocity of 7m/s.

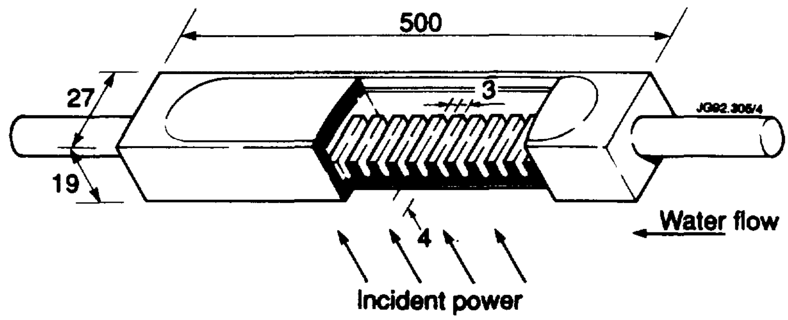


Fig. 2: Vapotron schematic. The heat transfer into the water is through a finned surface. The water channel width can be designed to match the flow requirements.

4. Test Facility

All the tests in this report have been performed in the JET Neutral Beam Test Bed, a 10MW, 160 kV beam line set up initially to commission the JET neutral beam injectors

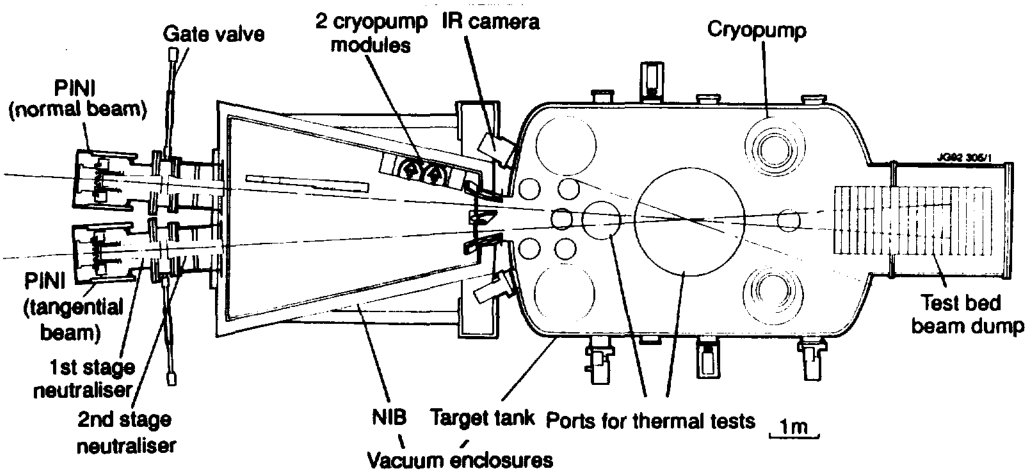


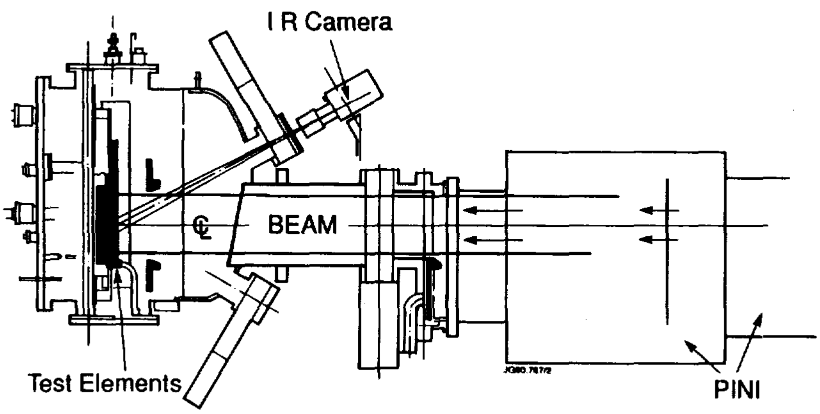
Fig. 3 : Schematic of the main beam line of 12m length. Tests are carried out in the Target Tank, 7 - 8 m from the beam source.

(Fig. 3). The main parameters of the Test Bed are shown in Table 1. Heat transfer tests are carried out in the Target Tank. Samples with Beryllium are tested in a second smaller beam line, the so called Beryllium test rig (Fig. 4), to avoid contamination of the main beam line with toxic Beryllium dust.

Table 1:	TB specification
heat source	ion beam
pulse duration	20s
max. power	2 x 4 MW
max. power density	100MW/m^2 per beam
duty cycle	1 : 30
volume	90m^3
access ports	up to 1500 mm i.d.
vacuum pumping speed	10^6 l/s for Hydrogen
Cooling loop capacity available for tests:	
water flow rate and pressure head	20 l/s (8 bar) & 100 l/s (4.5bar)
return water pressure	2 bar

4.1. Tests with Beryllium

The Beryllium test rig is a small beam line with a volume of approximately 1 m^3. The whole tank is operated at the pressure required in the plasma source to produce an arc (0.2 - 0.3 Pascal). This reduces the requirement for vacuum pumping speed considerably to less than 1000l/s. The ion source used is a standard JET source with a reduced extraction area. Power supplies, control & data acquisition, and the cooling loop of the main test Bed are shared with the main beam line.



Side view on Test Beam Line

Fig. 4: Side view of the beam line for tests with Beryllium components. The distance between beam source and target is 2m, the volume of the beam line is 1 m^3.

4.2. Instrumentation

4.2.1. Surface temperature

The surface temperature of the test panel is measured with an AGA IR camera[5]. Before and after a test the camera is calibrated against the CrAl thermocouples in the panels. This is done by heating the uncooled panel with the ion beam. The output of the IR camera is then calibrated against the thermocouple temperature. This procedure guarantees, that the panel is in thermal equilibrium.

4.2.2. Panel temperature

Bare wire CrAl thermocouples are percussion welded into 1.7 mm holes. The hot junction is normally 2mm below the exposed surface. The thermocouple output is sampled with a rate of app. 40 Hz. Assuming one dimensional heat conduction, we can calculate the surface temperature and the temperature of the water-wall interfaces from the TC temperature.

4.2.3. Water flow calorimetry

Water flow is measured using Taylor turbine flowmeters[6] installed in the return line of each water channel. The water exit temperature is measured by sheathed CrAl thermocouples sampled at a rate of 6 Hz. The signal level before the pulse is used as a base line.

4.2.4. Beam profile

The horizontal and the vertical beam profiles are measured using drive-in inertial calorimeters. The vertical profile is additionally measured using a calorimeter strip installed behind the gap between the test sections.

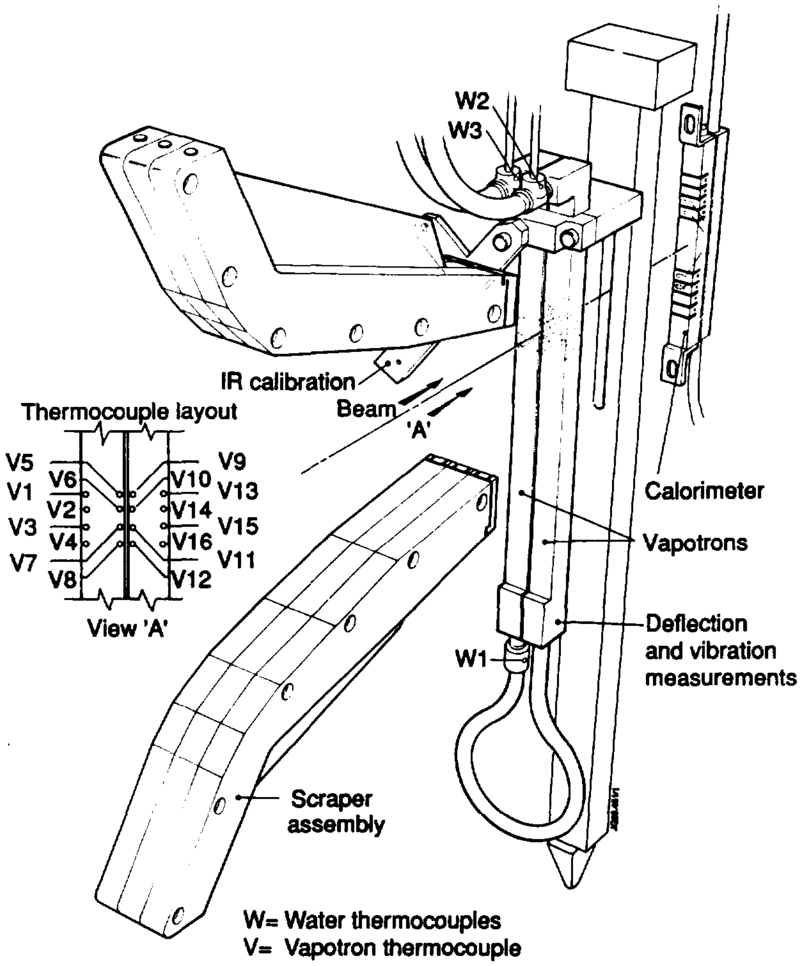


Fig. 5: Test setup in the Target Tank: two test sections are mounted side by side with a 2mm gap and a vertical calorimeter behind the gap. Thermocouples are grouped around the centre position.

source and test section is of the order of 2m and the beam profile has a larger flat top area of approximately 100 x 40 mm² (vertical x horizontal).

4.4. Test Rig and test samples

4.4.1. Large test facility

Two elements of 27mm width each are installed side by side with a nominal gap of 2mm (Fig. 5). Water flow can be either serial, (as shown in Fig. 5), or parallel. The vertical beam width is limited to 175 mm by two scrapers. The test sections were vapotrons with 500 x 27 x 19 mm³. The internal fin structure was as detailed in Table 2. Thermocouples are installed in the side walls with a distance of 2mm from the surface exposed to the beam. Alongside a vapotron test section we have also tested a swirl tube

This latter diagnostics is used for relative measurements only, because the width of the gap between the elements is not well defined.

4.3. Ion Beam

4.3.1. Parameters:

The JET Test Bed can be operated with Hydrogen, Deuterium, or Helium Beams. In Hydrogen or Deuterium, typically 60 - 80% of the power is in the full energy component (ions accelerated as H^+) and the rest in the half and third energy component (ions accelerated as H_2^+ or as H_3^+). Roughly 50% of the extracted ion beam is converted into neutral atoms due to charge-changing collisions after acceleration. The beam can be 100% amplitude modulated with a minimum off period of 30ms and a minimum on period of approximately 3 ms. This modulation has been used to simulate the sweeping of the plasma strike point over the dump plates.

4.3.2. Beam profile

The distance between the beam source and the test section is 7m in the large test facility. The beam has essentially a gaussian shape with a small (30mm) flat top in the vertical plane and with scraped edges (±75mm) in the horizontal plane. The 1/e width is of the order of 100 mm. In the Be test rig the distance between beam

Table 2: vapotron dimensions

fin height	4 mm
fin width	3mm
groove between fins	3mm
water channel height	3mm

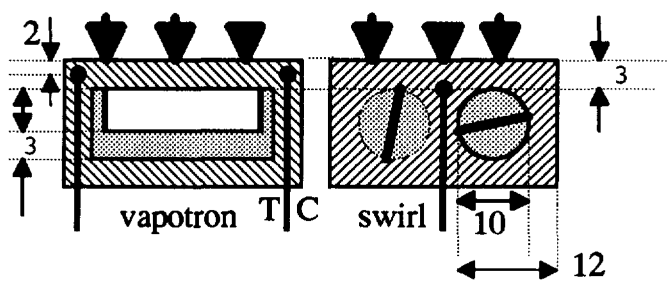


Fig. 6: Schematic of the test sections

ANNEX

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