Comparison between Actively Cooled Divertor Dump Plates with Beryllium and CFC Armour

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Summary

Actively cooled test sections with beryllium and graphite armour all withstand power densities between 15 and 20 MW/m^2. Beryllium as structural material fails mechanically at low power densities. Monoblocks appear to be the most rigid design but frequently large variations in surface temperature are observed. All other test sections show a uniform surface temperature distribution.

1 INTRODUCTION

The design of divertor and first wall target plates is vital for the performance of a tokamak experiment. In preparation of an actively cooled divertor for JET we have tested cooled target plates with beryllium and Carbon Fibre Composite (CFC) armour. The tests have been performed in collaboration with NET and JAERI. The tests were to establish power density limits and to assess the reliability of the manufacturing process. Individual tests are partially covered in specialised papers [1 & 2]. The test rig and test procedures are identical to those used for previous tests [3].

2 TEST SECTIONS

2.1 Composite beryllium test sections

Beryllium tiles with a thickness of 1.5, 2, and 3 mm are brazed to a hypervapotron heat sink made from CuCrZr.

2.2 Directly cooled beryllium Vapotron.

This test section was supplied by ITER and consists of a 46 mm od cylinder. A spiral groove, 4 mm deep with a 3 mm pitch, is cut into the 9 mm thick wall (Fig. 2).

2.3 Carbon composite test sections.

Four different designs have been tested:

1 Monoblock design (CFC cubes brazed onto a central TZM cooling pipe as per NET divertor design [4].

2 Saddle type design: A saddle shaped CFC armour and a copper backing block of identical shape are brazed to each other and to a central cooling pipe (JAERI design [5]).

3 Flat tiles: Flat 7 mm thick CFC tiles are brazed to a copper heat sink (JAERI design).

4 Multitube: 200 x 150 x 40 mm CFC tile with 6 cooling channels made from OFHC copper (JET mark II actively cooled divertor).

The test sections are shown in Fig. 3.

Fig. 1: Test section with beryllium tiles brazed to a CuCrZr vapotron heat sink.

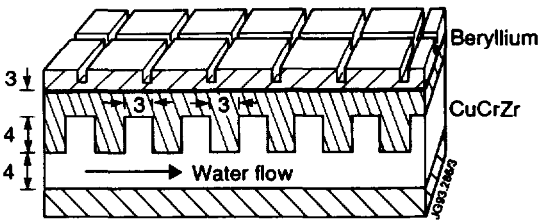
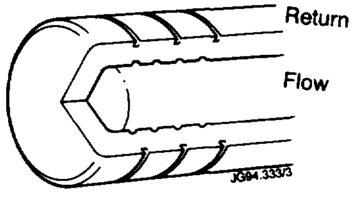


Fig. 2: Directly cooled beryllium test section



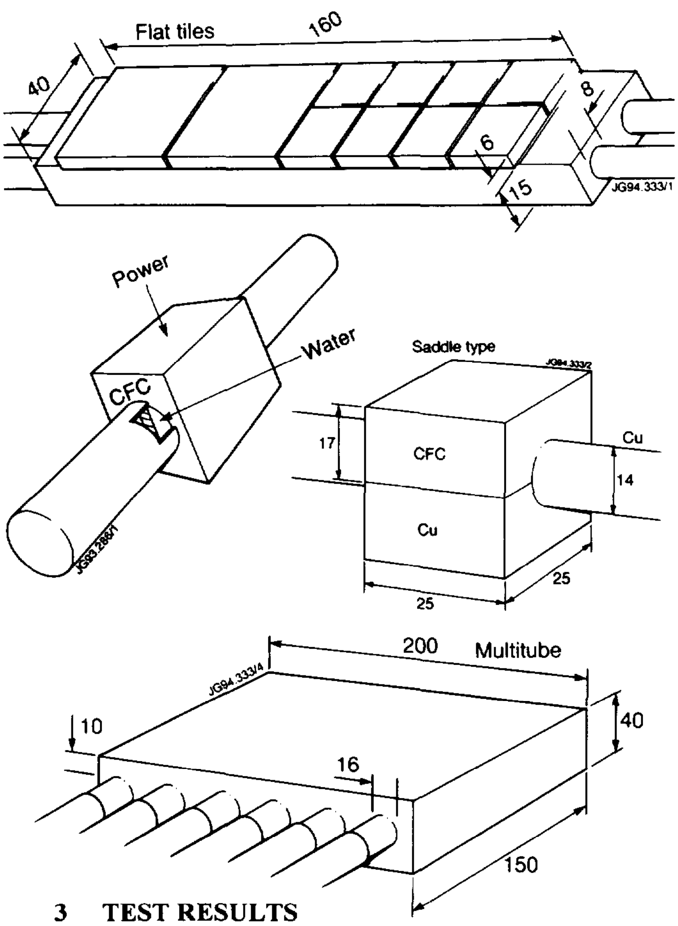


Fig. 3: Test sections with CFC armour.

3 TEST RESULTS

A comparison of the most important test results with the various test sections is compiled in Table 1.

3.1 Brazed beryllium armour tiles

The destructive limit of these tiles is between 16 and 19 MW/m^2 for tiles of 1.5 to 3 mm thickness. The uniformity of the braze is generally good. Five out of eight test sections, made by induction brazing, have been tested so far and were without fault in the exposed area. Dump plates with 2 mm thick tiles show a surface temperature of approximately 800°C at a power density of 16 MW/m^2. An endurance test on two test sections with 1000 cycles at power densities between 11 and 15 MW/m^2 has been completed successfully. Details of the test results are reported in [2 and 3].

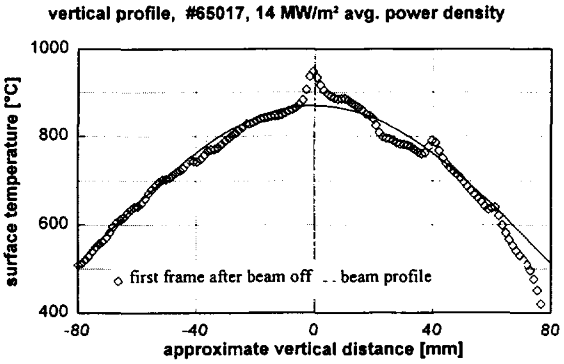
3.2 Directly cooled beryllium test section

So far we have tested one target plate where the beryllium is used as structural material. The test section failed after 34 pulses at a power density of 5.1 MW/m^2. The fault was a water leak in the exposed area. Fatigue cracks are visible on the tile surface. Approximately 1.5 mgr of beryllium was found in the water used for cooling and flushing the test section. (Water was only running from 5 seconds before a pulse to 5 s after the pulse).

3.3 Flat CFC tiles brazed to a copper heat sink.

The peak power density was limited to 19 MW/m^2 by critical heat flux in the cooling water channel. The surface temperature distribution was very uniform (Fig. 4). The temperature at the edges of two tiles is approximately 5% higher. This small non uniformity did not spread during the test. However, as we were close to critical heat flux, we did not apply a significant number of long pulses at high power density. The peak surface temperature is 570^{0} for 10 MW/m^2 (excluding the hot spots).

Fig. 4: Surface temperature profiles



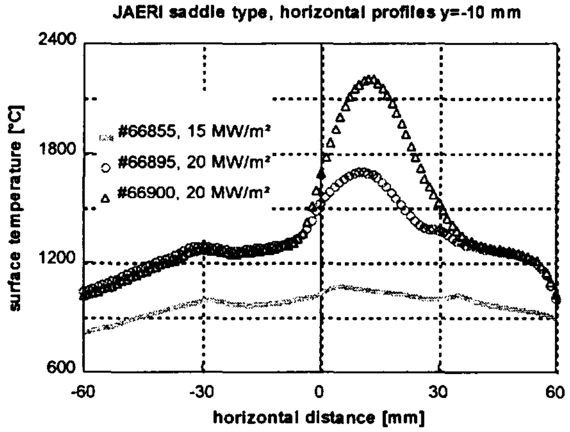
3.4 Saddle type test section.

This design had been very successful in previous tests sustaining up to 25 MW/m^2 at long pulses and 1000 cycles at 20 MW/m^2 [5]. The test section tested at JET had a small non uniformity in the surface temperature at the left edge of several tiles, in which lack of braze in the bonding interface was found after the test. Long pulses (15s) at 20 MW/m^2 lead to a rapid growth of the non uniform area of the hottest tile and more than 50% of the surface of this tile became detached within 8 pulses. The peak surface temperature at 10 MW/m^2 is 670 °C - again excluding the non uniform areas. The surface temperature distribution at the beginning and at the end of the long destructive pulses is shown in Fig. 5.

3.5 CFC monoblock test section

A full module of the NET divertor design with six individual monoblock test sections from 3 different manufacturers was tested.

Fig. 5: Surface temperature of the saddle type test section before and during destruction.

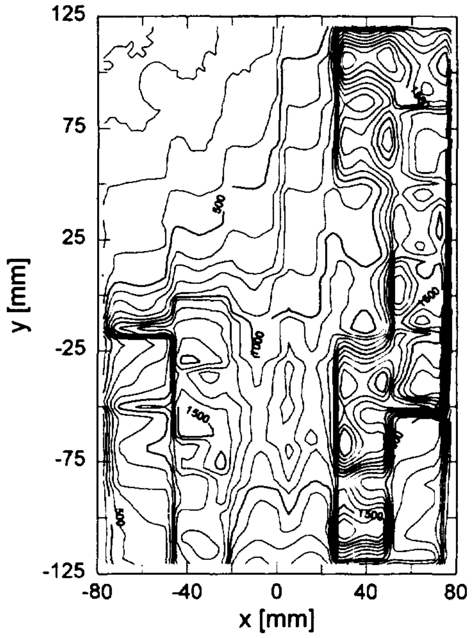


The surface temperature distribution after a 18 MW/m^2 pulse is shown in Fig. 6. The best test section shows a non uniformity of 10% in temperature over 26% of the surface, the worst has a non uniformity in excess of 50% in temperature over 63% of the surface. The peak power density was limited by the surface temperature of the hottest areas. During a total of 365 pulses we observed an increase in surface temperature of approximately 10% at constant power density on all the test sections, but non of the test sections deteriorated catastrophically.

While the module was exposed to power, the conductivity of the cooling water deteriorated significantly due to Molybdenum being dissolved. From the flow rate and the increase in water conductivity we estimate that 10 mg/s of Molybdenum is being dissolved during beam on.

Neighbouring tiles which get significantly different surface temperatures during exposure, also show a different temperature rise (Fig. 7). The initial temperature rise is defined by $\frac{dT}{dt} = \frac{2}{\sqrt{\pi}} \frac{\Phi}{\sqrt{c_p \rho k}} \sqrt{t}$ where Φ is the power density, c_p the specific heat, ρ the density, and k the thermal conductivity. As the tiles which get hotter also show a faster initial temperature rise we have to conclude that the tiles have reduced thermal properties rather than a faulty braze contact. A similar observation is made with respect to the increase in tile temperature during the test. The rise in surface temperature with exposure time is accompanied by an increase in the inertial temperature rise at the beginning of the pulse (Fig. 8) The initial temperature step in Fig. 8 is due to not fully contacted graphite on the surface and is dealt with in paper [6] in more detail.

Fig. 6: Temperature contours on the NET divertor module, taken after a 18 MW/m^2 pulse



3.6 CFC Multitube test section

The surface temperature distribution is quite uniform with two small areas with an excessive temperature of less than 10% (Fig. 9) The peak surface temperature is higher than for the other CFC designs due to an increased distance between surface and cooling channel. Two tiles have been tested so far

Fig. 7: Initial temperature rise of neighbouring tiles during one pulse

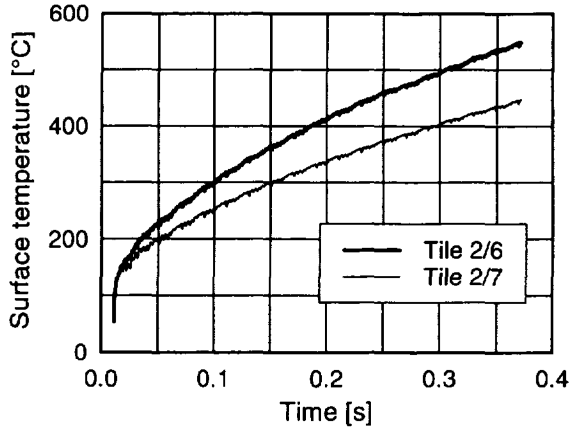


TABLE 1:	AREA		PEAK SURFACE		AREA WITH EXC.		destructive	PULSES
	TOTAL	TESTED	TEMP [10MW/m^2]		TEMPERATURE		LIMIT	total
	mm^2	mm^2	max	min	>10%	>50%	MW/m^2	
JAERI FLAT TILE	6560	6560	570	500	0%	0%	>19	211
JAERI SADDLE TYPE	2500	2500	670	580			20.5	54
NET DIVERTOR PROTOTYPE	64512	32000					>18.5	365
max			1800	1000	72.00%	63.00%		365
min			880	720	14.00%	0.00%		365
avg			1275	817	40.17%	13.33%		365
JET CFC MULTITUBE	30000	30000	1000	900	0	0	>15	21
2MM BE TILES	24300	11000	400	400			17	1000
BE VAPOTRON	13800	8800					5	34

Fig. 8: Initial temperature rise early and late in the test.

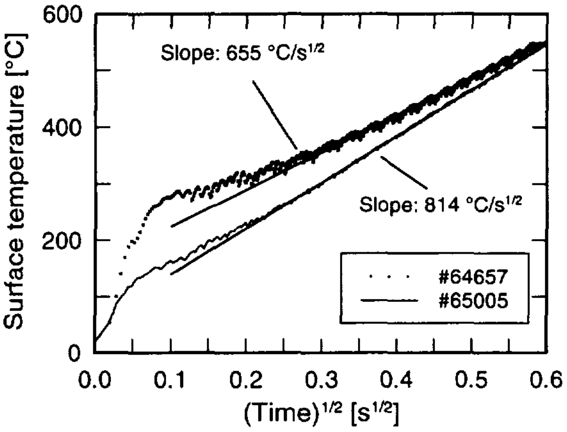
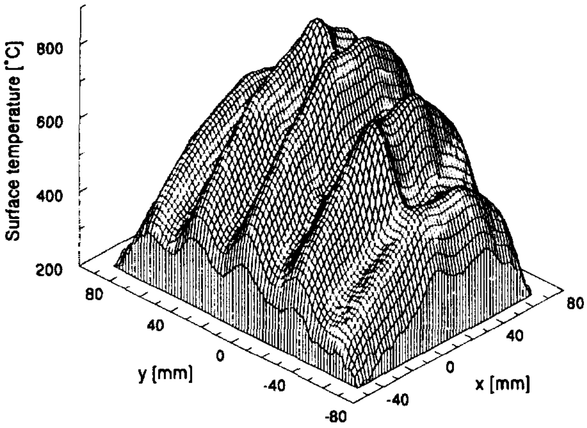


Fig. 9: Surface temperature distribution on the CFC multitube 0.6 s after a 3s pulse with 15 MW/m^2



without an attempt to determine the endurance of this design. The uniformity and performance of both tiles is similar to each other.

4 COMPARISON.

All test sections - with the exception of the directly cooled beryllium - withstand comparable power densities of 15 - 20 MW/m^2. The monoblock design appears to be the least vulnerable method in the sense that no catastrophic failures have been observed, but the large variation in surface temperature limits the peak power density which can be applied in a divertor . The lowest surface temperature is observed with the high conductivity unidirectional CFC tiles which also shows good uniformity. The drawback of this design is that a reduced thermal contact appears to spread faster than in the case of the monoblock design, although these designs have the possibility of in-situ repair.

The beryllium composite dump plates show good uniformity. The drawback of this design is that the armour plate has to be either thin (2 mm) or the power density is limited by the surface temperature. The failure with beryllium tiles is catastrophic: Local melting with droplet formation, or complete detachment of the respective tile.

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