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# Development and testing of CFC-copper high heat flux elements

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In the frame of high heat flux development for plasma facing components, CEA has designed, fabricated and tested over twenty specimens, with some of them for the NET divertor application. Several CFC and copper grades have been used with flat tile or macrobloc configuration. All the mock-ups were tested in the electron beam facility EB200, for steady-state flux and fatigue up to 1000 cycles. The best four are presented here.

## 1. INTRODUCTION

The need for high heat flux elements (5-10 MW/m$^2$) is high in the fusion community. Such elements are required for divertor or limiter applications. CEA has made the choice of copper based alloys for the heat sink and CFC as plasma facing material. The choice of copper based alloys for the heat sink is justified by its high thermal conductivity. High thermal fluxes can cross the heat sink wall with a relatively low thermal gradient, and hence low stresses in the cooling wall. In some cases, the heat sink is also the structure of the component, and has therefore to withstand the loadings imposed upon it. The use of dispersion strengthened alloys such as glidcop or age-hardening alloys such as CuCrZr gives the strength that is needed for the cooling structure.

The good thermal conductivity is also the leading characteristic for the choice of CFC as plasma facing material. The high conductivity enhance the ability of the material to withstand thermal shocks, and enable the component to reach steady-state with low surface temperatures. CFC materials present also the advantage of being much tougher than other C-based materials (e.g. graphite) because of the reinforcement brought in by the fibres. As a result, the joining of tiles to the heat sink is somewhat eased due to the slow crack propagation.

The strength of the CFC gives also rise to the concept of macroblock, in which the CFC block itself bears the structural loadings. The main advantage of this concept is the low deformation under heat loading due to the low coefficient of thermal expansion (10 times less than Cu alloys). In this concept, a thin OFHC copper liner is used to insure water tightness.

Brazing is chosen as the joining technique to ensure the thermal continuity of the assembly. Depending on the case, an OFHC copper compliance layer can be used to compensate the thermal mismatch during the cooling of the assembly.

Following those guidelines, CEA designed and fabricated over twenty specimens. They were tested in the electron beam facility EB200. Finite element calculations using the Castem 2000 code were carried out to prepare the tests. The four specimens that yielded the best results are presented here.

## 2. FLAT TYPE DESIGN FOR DIVERTOR

The first design is flat type. 13 CFC tiles (A05 by Le Carbone Lorraine) were brazed on a Glidcop Al15 heat sink with a 2 mm thick compliance layer (Fig. 1) [1, 2]. A swirl was inserted in the 14 mm wide cooling channel to enhance the heat transfer in the tube. The brazing was performed by Vide et Traitement.

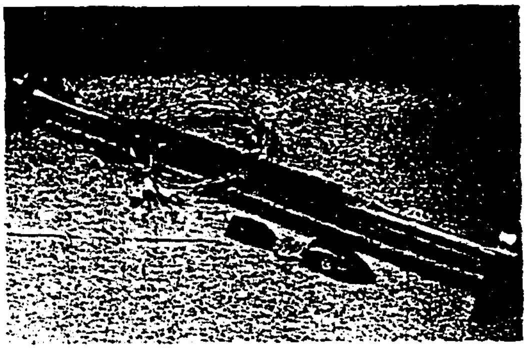

Figure 1. Flat type divertor element

Different mock-ups have sustained up to 15.3 MW/m² with surface temperature under 1900°C (Fig. 2 & 3).

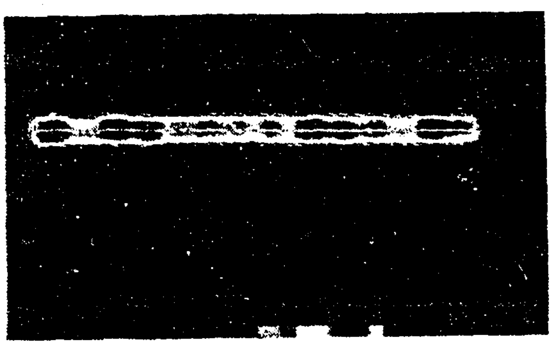

Figure 2. Surface temperature profile at 11 MW/m²

Fatigue testing was performed under 10 and 15 MW/m² heat fluxes. After 1000 cycles, no change appeared on the temperature distribution of the tiles and the test was stopped.

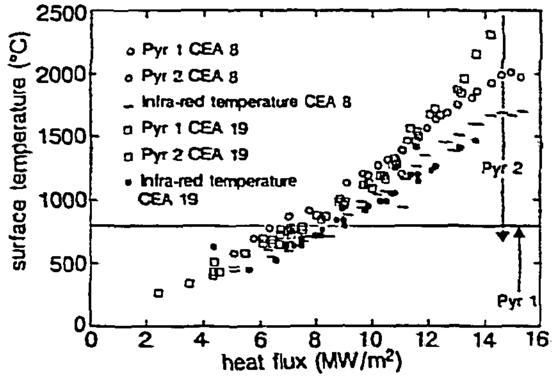


Figure 3. Comparative results of screening tests

## 3. FLAT TYPE DESIGN FOR LIMITER

The flat type geometry can also be used for the design of limiters (Fig. 4).

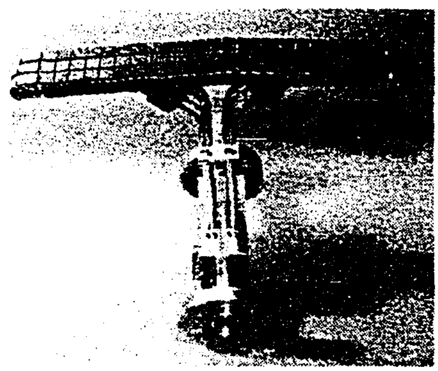

Figure 4. Pump limiter mock up

In this case, flat square tiles were brazed on three tubes with a 2 mm thick compliance layer in OFHC copper. Two rows had N112 tiles from S.E.P., the third row had A05 tiles from Le Carbone Lorraine. The mock-up sustained up to 10.1 MW/m² (Fig. 5).

1000 thermal cycles were performed with a 10 MW/m² heat flux. The cycling led however to an evolution of the thermal distribution of the mock-up's surface (Fig. 6).

Hot spots connected to deteriorating joints appeared during thermal cycling on N112 tiles.

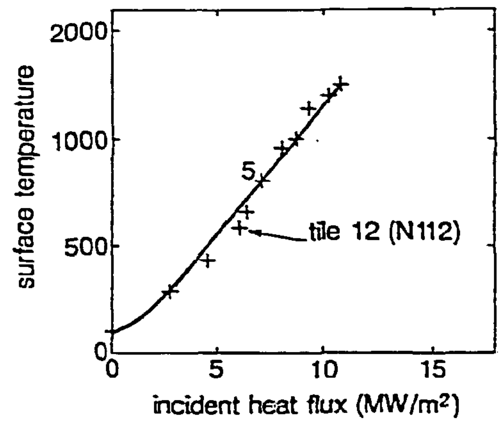


Figure 5. Surface temperature of N112 versus the incident heat flux

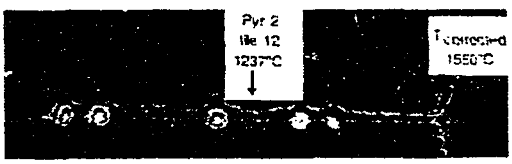

Figure 6. Surface temperature profile of one tube at 10 $MW/m^2$

## 4. MONOBLOCK FOR DIVERTOR

Monobloc designs have the major advantage of having very few singular points in comparison to flat or saddle type designs [3]. A mock-up made of four blocks of CFC (60 mm each) was realised (Fig. 7).

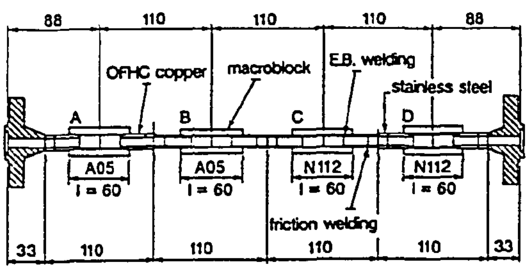


Figure 7. Divertor mock-up made of 4 blocs

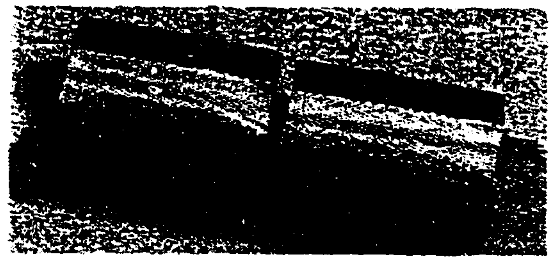

Figure 8. The ripple fin tube

The CFC blocks are brazed on copper tubes having helical ripple fins extrudes inside the water cooling channel (Fig. 8).

Two different diameters of Wieland ripple fin tubes are used (16 and 12.6 mm outer diameter) and brazed with Aerolor A05 (Le Carbone Lorraine) and S.E.P. CARB N112. The A05 blocks sustained an incident heat flux up to 12.5 $MW/m^2$. The surface temperature was around 2000°C. The test was stopped due to this high value of temperature corresponding to a low thermal conductivity of the CFC. The two SEP N112 blocks withstood up to 18.5 and 19 $MW/m^2$ with surface temperature of respectively 2000°C and 1900°C (Fig. 9).

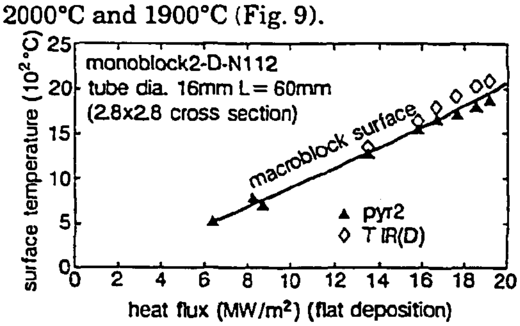


Figure 9. Surface temperature versus heat flux

During this test the maximum heat flux at the water/copper interface were 32 and 33.5 $MW/m^2$ and no indication of a near critical heat flux regime was noticed.

After these screening tests, the two N112 blocks were fatigued at 16 $MW/m^2$ on the whole surface. After 1000 cycles on each block the tests were stopped as no evolution of surface temperature (1550 to 1600°C) were visible with infrared camera.

## 5. LARGE MACROBLOCK FOR DIVERTOR

A new concept of a long SEP N112 CFC macroblock structure lined with a brazed thin copper cooling tube has been developed as a divertor target for ITER (Fig. 10).

Figure 10. Macroblock mock-up

A 20 cm long CFC macroblock with an external section of 2 cm * 3 cm was brazed with a copper liner (cylindrical 10 mm inner diameter, 11.6 mm outer diameter). The mock-up was tested with the EB200 electron beam facility. It sustained during several hours a flat heat deposition profile, onto a length of 12 cm, ranging from 5 to 14 $MW/m^2$ with respectively a maximum surface temperature ranging from 1200°C to 1800°C (Fig. 11).

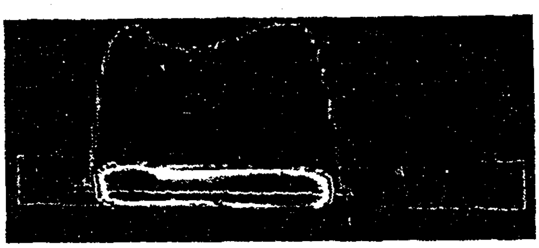

Figure 11. Flat heat flux surface temperature at 11 $MW/m^2$

The mock-up withstood 300 cycles of 30 seconds under a peaked thermal flux profile of 34.2 $MW/m^2$ (spread over 6 cm) and 30 $MW/m^2$ (spread over 12 cm). The maximal surface temperatures corresponding to those fluxes were respectively 2600°C and 1650°C. A strong erosion was noticed, but the cooling capacity of the macroblock wasn't lost.

## 6. CONCLUSION

High heat flux elements with various combinations of designs an materials were successfully realised and tested. They demonstrate the possibility of manufacturing elements which can operate steadily at a 5 $MW/m^2$ heat flux. Moreover, the operating of the mock-ups prove the feasibility of the friction and electron beam welding that were used to join the test sections to the fittings.

The macrobloc design is the most favourable concept with respect to the residual stresses. Further studies to validate the SEP CARB N11 are necessary to validate it as a plasma facing material, for only that grade would be available as industrial material.

## REFERENCES


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