# The JET Programme on the Development of Beryllium Clad Components for ITER

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### ABSTRACT

JET under a contract with the European Home Team and in co-operation with industry, is carrying out a programme to support development of beryllium (Be) divertor components for ITER. The basis for this programme is the existing experience on the brazing of thin (1.5 to 3mm) Be cladding to CuCrZr hypervapotrons using a silver based alloy (Incusil 'ABA), which demonstrated critical heat fluxes of up to 18 $MW/m^2$, and good low power high cycle performance. This paper reports on the mechanical strength of thick (5, 7.5 and 10mm) Be/CuCrZr braze samples showing the feasibility of brazing thick clads. Also reported are the results of testing of 10mm thick tiles brazed to a hypervapotron. These tests resulted in melting of the tile surface at power levels of $20MW/m^2$ without complete delamination of the joint. The results of these tests have allowed the European Home Team and European ITER JCT to benchmark their one and two dimensional models. Another important aspect of the JET investigations is the development of a silver free braze which is being developed in collaboration with industry and producing interesting results with shear strengths almost comparable with Incusil ('ABA') with failure occurring in the braze/CuCrZr interface.


### I. INTRODUCTION

The ITER Be divertor component concept [1] is based on a thick Be Cladding (typically 10mm), brazed to a CuCrZr heat sink, in which heat fluxes up to $5MW/m^2$ are cooled in steady state, and higher, off-normal heat fluxes are sustained inertially. The thickness of the cladding is dictated by the expected erosion rate. Critical issues are the manufacturability of components to this concept, and the experimental determination of the lifetimes under high cycle low power and low cycle high power testing. In addition, due of the high cross-section of silver for transmutation into cadmium under neutron irradiation, the ITER braze should contain no silver.

JET has now extended the silver based braze technique to 10mm Be Cladding. A number of 27mm square, 10mm thick tiles were brazed to a hypervapotron. Testing has been performed up to a maximum power flux of $20MW/m^2$ for 1.5 sec, which brings the Be surface above melting temperature. At this level, after 22 cycles, structural deformation of the Be and delamination of the joint is observed. The tile however remained attached. In addition, results of mechanical testing for two Be grades and various material thicknesses have been obtained and will be reported.

Work is under way to develop a silver free braze. Two joining techniques are being developed based mostly on Copper systems with starting temperatures not significantly exceeding those with Incusil 'ABA'. The moderate temperatures are important to retain the strength of the CuCrZr. The brazes are being qualified and compared with the silver based braze using shear testing, X-ray testing, mechanical testing of CuCrZr and finally heat load testing. Results are reported below.

JET is also contributing brazed samples of Be to CuCrZr for a neutron irradiation programme, due to start in 1995 under the auspices of the European Home Team.

### II. MECHANICAL STRENGTH OF THICK Be BRAZE SAMPLES

Mechanical testing of thick (5, 7.5 and 10mm) BeS65C induction brazed to 6 mm CuCrZr with Incusil 'ABA' alloy using the previously reported optimum braze cycle [2],[3] has been performed.

Fig. 1 shows the average shear strength of the braze samples for each thickness at as a function of temperature up to 400°C. The effect of the residual stresses due to braze cool down can be clearly seen.

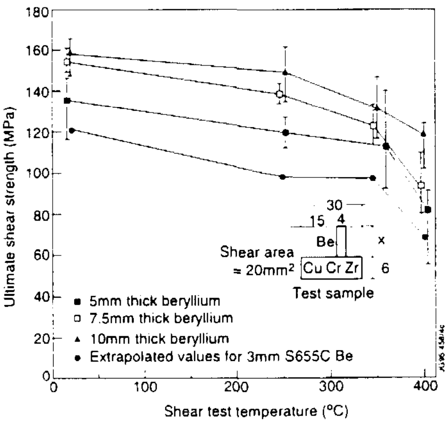


Fig. 1 Shear strength of 5, 7.5 and 10mm thick BeS65C brazed to CuCrZr

Fig. 2 shows the shear strength comparison of brazed 3mm BeS200FH and extrapolated values for 3mm BeS65C. Also plotted is the yield strength in shear of BeS200FH. Note that the yield strength of the solid BeS200FH follows closely the ultimate shear strength of the brazed BeS200FH samples.

By the consideration of materials data, it is clear that the ~26% increase in the ultimate shear strength of the brazed samples when changing from BeS65C to BeS200FH (120MPa to 163MPa at room temperature) is very similar to the difference (~30%) in yield stress of the two grades of

Be. The tensile yield strength of BeS200FH is 360MPa compared to 251MPa for BeS65C. It can be inferred from this that the high stiffness of the Be holds the joint intact until the yield stress of the Be adjacent to the braze is reached which then results in failure of the joint.

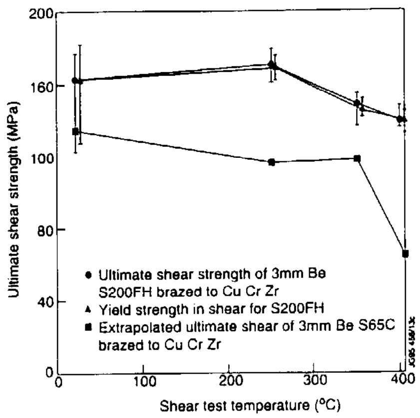


Fig. 2 Comparison of shear strength of brazed 3mm BeS200FH, 3mm BeS65C and yield strength of BeS200FH

This failure mechanism could be alleviated by the inclusion of a compliant layer, improved edge geometry and castellation design.

### III. 10mm Be Clad Hypervapotron High Heat Flux Tests

A hypervapotron [10] was clad with 10mm thick, 27mm Square uncastellated BeS65C tiles. They were brazed using Incusil 'ABA' and the standard braze cycle [2], [3]. The hypervapotron was installed in the JET Neutral Beam Be test facility and subjected to high power beam pulses derived from a JET Positive Ion Neutral Injector (PINI). Detailed results and discussions can be found in [4]. Fig. 3 shows the test set-up, with the diagnostics used. These were:-.

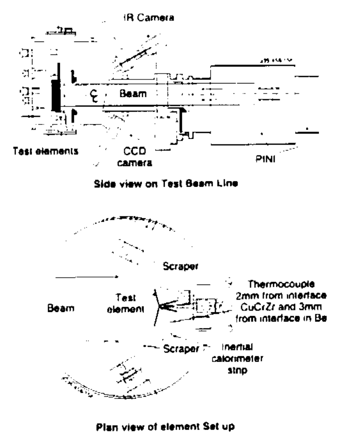


Fig. 3 Schematic of High Heat flux test set-up

- IR imaging system with either in frame repetition rate of 30 Hz or in line mode repetition rate of 2.5 KHz.
- Water calorimetry
- OFHC copper inertial calorimeter measuring average applied power
- CCD camera
- Thermocouples 2mm from the interface in the CuCrZr and the Be.

The test was divided into three stages.

1. 100 pulses of low power density (5-6MW/m$^2$) to confirm the integrity of the braze and predicted surface temperatures.

2. Several pulses of high power density (15 to 20MW/m$^2$) to establish surface melting temperature on the Be but not actually producing melting.

3. 22 pulses of 4.5MW/m$^2$ to equilibrium followed by 20MW/m$^2$ with gradually increasing duration to develop surface melting followed by several seconds of 7.5MW/m$^2$ to mimic the effect of vapour shielding.

The PINI output cannot be stepped as described in the 3rd stage so the results were achieved by setting the PINI parameters that yield a power density of 20MW/m$^2$ and then modulating this beam to give the required average power density. Fig. 4 shows a typical modulated pulse. Fig. 5 shows the exposure statistics for the whole test.

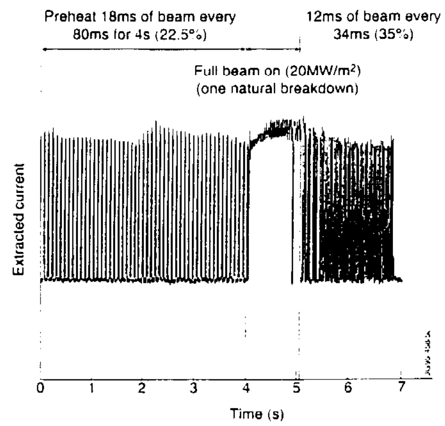


Fig. 4 Typical modulated pulse details

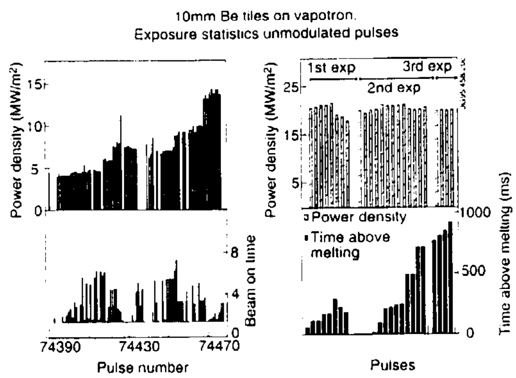


Fig. 5 Test exposure statistics

During the test, comparisons of calculated and measured surface temperatures showed that the IR camera gave erroneous measurements above temperatures of 1000°C. This is due to an irreversible change in emissivity of the Be when it reaches temperatures above 1000°C. The variation in emissivity is from 0.3 to 0.8. Fig. 6 shows a contour plot of surface emissivity cross section with all tiles at equilibrium temperature of 470°C. (Note the definite transition line highlighting the area with changed emissivity.) After the test, the IR camera was calibrated by removing the cooling and slowly uniformly heating the hypervapotron. Comparisons of the measured temperature (thermocouples) and the emissivity then gives a emissivity correction curve.

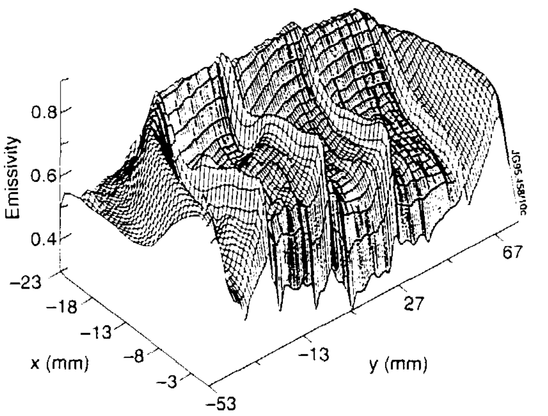


Fig. 6 Surface emissivity contour plot across tiles

The corrected surface temperatures and the measured Be I line emission are shown in Fig. 7. Also plotted, is the Be vapour pressure obtained from literature which agrees well with the measured results.

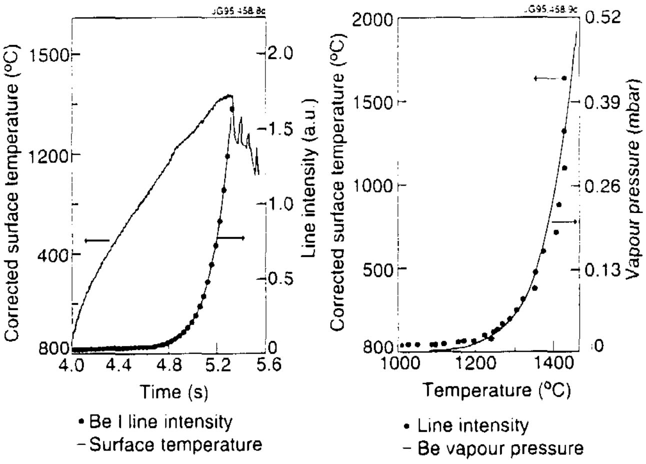


Fig. 7 Corrected surface temperatures of the Be tiles (10mm thick) clad to the hypervapotron during a pulse of $20MW/m^2$. Be I line emission and vapour pressure

On completion of the third stage, the tile which had reached the highest temperature in the test was cut in half and sectioned to examine the melt depth. Three micro graph sections were taken to enable measurement of the average melt depth which is 0.53mm. The micrograph cross sections are shown in Fig. 8.

Note the cracks in the melt region that propagate down into the unmelted material. Cracks are observed in areas of the tile that did not show signs of surface melting.

Ultrasonic examination of the tiles that delamination of around 50% of the braze area has occurred but the tiles have remained attached to the hypervapotron.

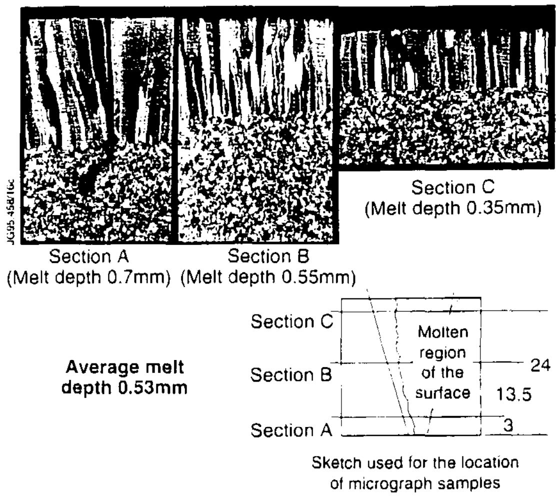


Fig. 8 Micrograph cross sections showing melt depth

## IV. ONE AND TWO DIMENSIONAL FE MODEL COMPARISONS

One major benefit of this experiment is to benchmark FE codes to predict the melt depth and evaporation rate. For this work FE modelling is being carried out by members of the European Home Team and European ITER JCT.[5] [6].

Figs. 9 and 10 show the results of modelling with various power settings compared with the measured data. The sensitivity of the melting and re-solidification in the model to the power setting is clearly seen.

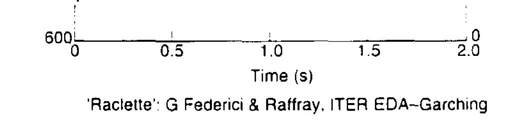


Fig. 9 One dimensional ITER 'RACLETTE' [5] model fits to measured data

## V. SILVER FREE BRAZE DEVELOPMENT

Silver has been identified as a potentially damaging element in ITER because of its transmutation to cadmium, which having a high vapour pressure at the ITER operating temperatures would lead to fears of vacuum vessel, and hence plasma, contamination. Within the European Home Team contribution to the ITER task T1, part of the development of Be brazing activity has been to investigate Silver free alternatives to the successful InCuSil 'ABA' braze. This development work, still in its early stages, has been based upon two joining methods identified by GEC-Marconi Materials Technology [8]. These methods are:-

- Vacuum Induction Brazing based upon a CuMnSnCe braze alloy

- Diffusion Soldering using copper and tin.

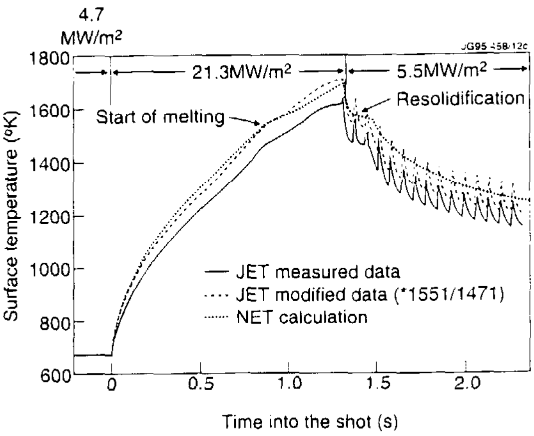


Fig. 10 Two dimensional NET model fit to measured data

In the work carried out in this development, 0.1mm thick foil of CuMnSnCe braze has been used to vacuum induction braze Be to CuCrZr under conditions similar to the InCuSil ABA braze mentioned previously.. Optical examination of the samples has shown good filling of the braze and good wetting of the Be. Scanning acoustic microscopy shows little detail in the assemblies. Metallography of the joints, Fig. 11 has revealed that the joints are well filled with no evidence of porosity associated with the evolution of gas during the brazing operation. The metallography also indicates the formation of an intermetallic layer between the Be and the braze similar to that seen for the Incusil 'ABA'. However, there does appear to be some damage between the braze and the CuCrZr. The reason for this damage is still being investigated. Shear test results on these brazed assemblies at room temperature have shown values of up to 75MPa, compared with values of 143MPa achieved using the same equipment for InCuSil 'ABA' brazed assemblies. However, the failure does appear to originate in the braze/CuCrZr interface. This holds out the prospect of an excellent braze for Be once the braze/CuCrZr interface problems have been overcome. This development was performed by J.H. Vincent, S.P. Sangha, D.R. Wallis and D.M. Jacobson at GEC Marconi, Hirst Division, Borehamwood, Herts, WD6 1RX, UK, under a contract to NET.

Diffusion soldering [9] is a hybrid of soldering and diffusion in which tin is used as a low temperature solder to produce a soldered joint, the tin then being allowed to diffuse in to the copper substrate to homogenise the joint which will consequently have a much higher remelt temperature. The technique relies upon bonding a copper layer onto Be and then joining the copper metallisation to the CuCrZr with the diffusion soldering technique. This technique (metallisation followed by diffusion soldering) produces excellent bonds between the copper layers and apparently seamless joints on Be/CuCrZr assemblies. Scanning Acoustic microscopy did not reveal any features in the joints. Strengths of up to 48 MPa were achieved in shear tests with failure occurring at the metallisation/Be interface. Further development of this solution relies upon improving the metallisation of the Be.

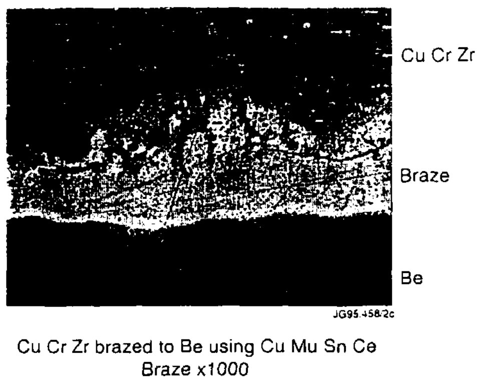


Fig. 11 Micrograph section of CuMnSnCe brazed joint between BeS65C and CuCrZr

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