FUSION TECHNOLOGY

Annual Report of the Association EURATOM/CEA

1998

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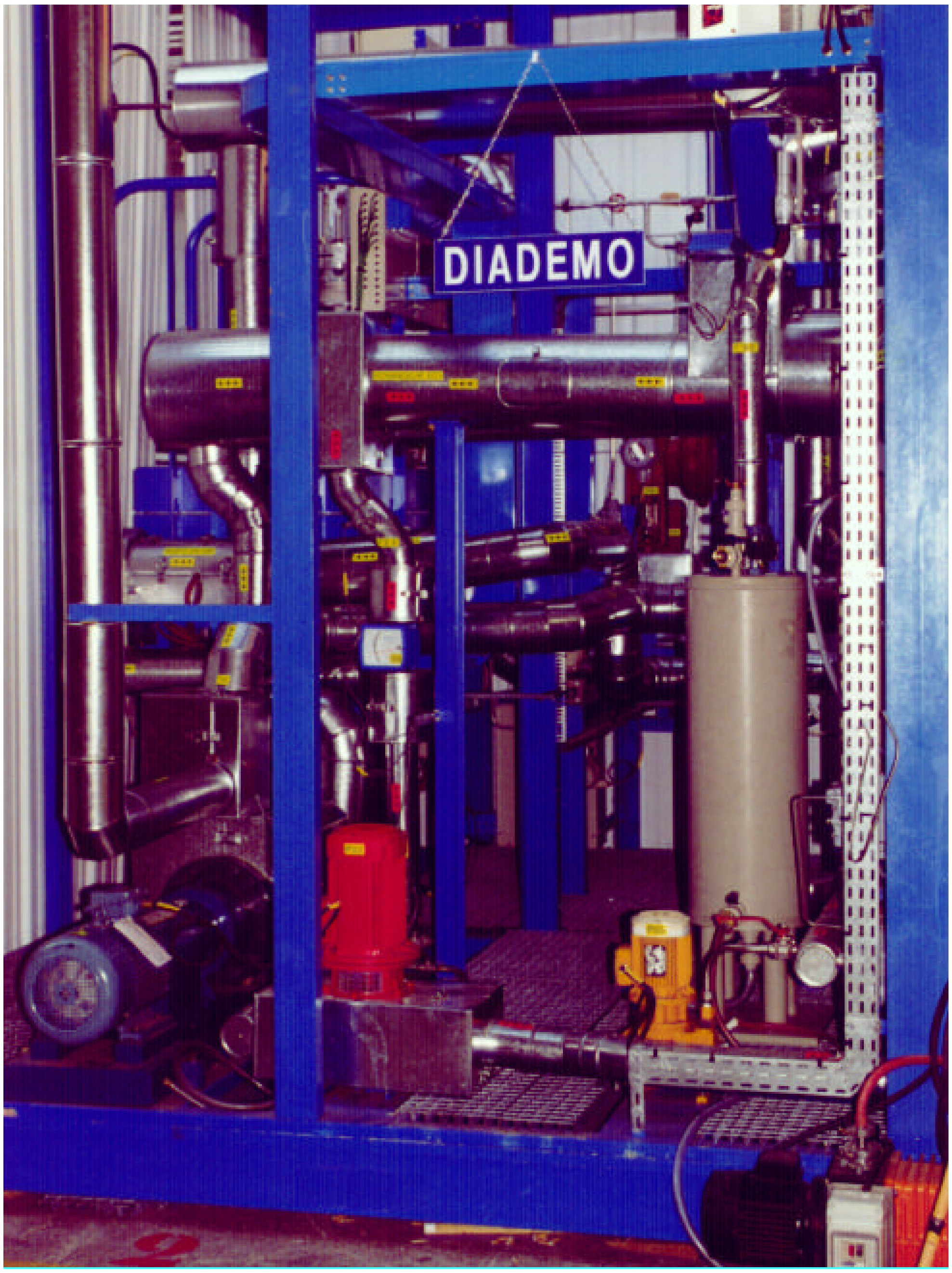

ASSOCIATION CEA/EURATOM
DSM/DRFC
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13108 Saint-Paul-Lez-Durance (France)

CNET 96-412

Task Title : ITER OUTBOARD BAFFLE : DESIGN, ANALYSIS, TECHNICAL SPECIFICATIONS & FOLLOW-UP OF FABRICATION & TESTING OF MOCK-UPS AND PROTOTYPES

INTRODUCTION

The ITER BAffle (BA) modules, which are the inboard and outboard bottom row of shielding blanket modules, have the main function of avoiding particle back-flow from the divertor chamber. For this reason they are considered to belong to the divertor system. As a consequence, the BA First Wall (FW) is submitted to an high thermal flux and its design needs the use of high-heat-flux component technology. The activities have been focused on the outboard BA-FW because of the more severe heat flux load conditions and the more complex overall geometry compared to the inboard one.

This contract, originally running from March 1996 to June 1998, covers the second phase of the ITER T232.10 subtask. It includes design and analysis of the BA-FW mock-ups (small-scale, medium-scale and prototypes), the prediction of the results on the mock-ups tests, the interpretation of the obtained experimental results, and the follow-up of the mock-ups manufacturing. In order to cover all the required expertise, these activities are supported by an established collaboration between members of different CEA Departments, in particular DMT, DRFC, DER, and DEM/SGM. Moreover, the work is performed in close collaboration with industry (EFET/Framatome).

Because of the new attachment system developed for the primary shielding modules by the ITER JCT at the end of 1996, significant design modifications for most in-vessel components have been required. In particular, the modularity of the shielding blanket has been modified. For an almost unchanged total number of modules, the new poloidal segmentation has been increased to 26 modules. Both inner and outer baffles are now formed by two modules, the lower and the upper baffles. Moreover, because the new ITER shielding blanket envisages frontal penetrations of 30 mm of diameter, the existing concept of belt-limiter using three rows of outboard shielding modules is no more acceptable. The main reason is the very high heat loads at which the armour material around the frontal holes will be submitted (15-20 MW/m^2, mainly located on the hole side walls). For this reason, a new concept of limiter, a port-limiter, which will be located in the horizontal ports and which can then be easily replaced during ITER BPP operations, has been preliminary designed by the ITER JCT. Reasonable heat loads (peak values of 10-15 MW/m^2) can be obtained with two identical limiters located in two toroidally-opposite horizontal ports.

This situation has lead to a significant modification of the time-scale and contents of the BA-related activities. It was decided by the NET Team that the medium-scale mock-ups will be manufactures, if necessary, as a demonstration of specific details (e.g., corners) of the BA-prototype, by the industry charged of the prototype manufacturing. Moreover, it was decided that the BA-prototype should also cover FW-designs relevant for the port limiters.

Therefore, the 1998 situation is the following: the fabrication of two different prototypes was launched in spring 98, one with CFC/W FW-protection and one with Be-protection. The manufacturing of both prototypes is expected by the end of 99 and their tests should be performed in spring 2000.

The CEA activity in 1998 has been focused on the predictions of the prototype behavior under thermo-mechanical testing (which can have an impact on the used prototype fabrication techniques), while the prototypes and testing follow-up have been extended to the years 1999 and 2000.

1998 ACTIVITIES

With reference to the 1997 Progress Report [1], the activities in 1998 have been focused on the two baffle prototypes (Be and CFC/W) as defined after a call for tender to which the CEA has participated in the framework of the present task. The first prototype (indicated hereafter as the ″CFC-prototype″) will have four FW-panels using respectively CFC-tiles, W-plasma spray, and two CFC-monoblock designs (see Fig. 1). It is under fabrication at Framatome (France). The second prototype (indicated hereafter as the ″Be-prototype″) will have four FW-panels using respectively Be-tiles 4 mm and 8 mm-thick , two Be-monoblock with the same design. It is under fabrication at NNC (England). The specificity of the baffle module and, therefore, of the proposed prototypes is the presence, in the poloidal direction, of two corners at the bottom and at the top of the FW-panel, which requires a challenging FW-panel arrangements and extrapolation of the selected fabrication techniques.

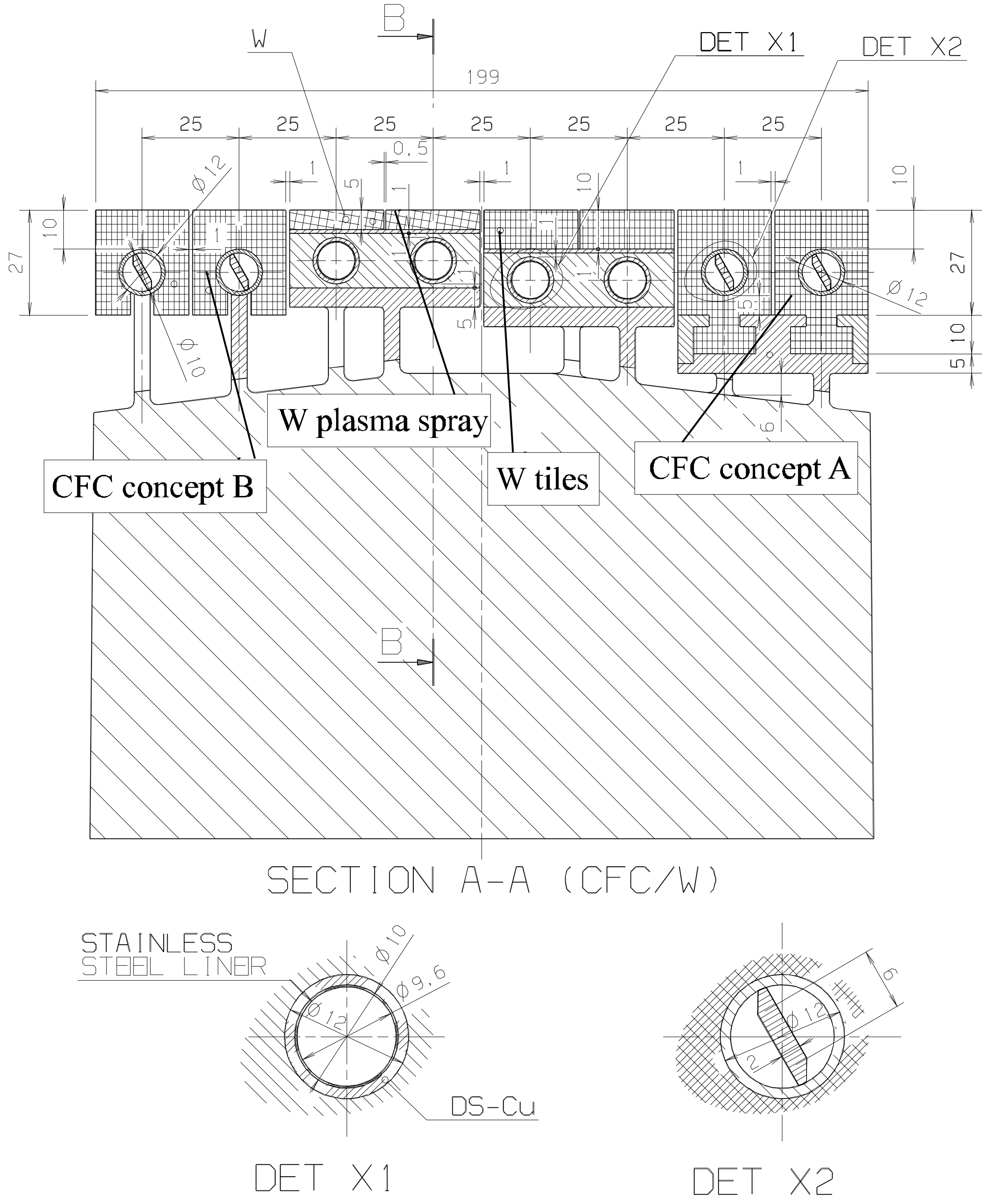

Figure 1 : CFC-prototype horizontal cross section

The objective of the work was to evaluate the thermal and thermo-mechanical behaviour of the various First Wall-panels when submitted to the EB-heat flux and using the cooling conditions available in the assumed testing facilities. It is recalled that the CFC-prototype is assumed to be tested in the EB-2000 facility located at Le Creusot (France), while the Be-prototype is assumed to be tested in the Neutral Beam facilities available at the JET site (Culham, GB). Because several analyses have already been performed in 1997 on Be-, CFC-, and W-tiles panels, the 1998-activities have been focused on the monoblocks panels of the prototypes.

CFC-MONOBLOCKS PANELS

The steady state thermal analysis has been performed first with the incident heat flux as parameter (variation from 1 to 10 MW/m^2). For example, maximum temperature in the CFC-monoblock under 10 MW/m^2 is 1074°C. The first part of the Table 1 resumes the main results. Thermal transient has been performed for an incident heat flux of 10 MW/m^2. Values of the characteristic times, $\tau_{68\%}$ and $\tau_{90\%}$, are respectively 1.8 s and 3.8 s.

Mechanical calculations have been divided in two distinct parts : the first one concerned the straight part of the mock-up and the second one the bottom corner which is expected to be the most critical corner. Fig. 2 gives for example the stresses in each material direction in the CFC-monoblock for an incident heat flux of 10 MW/m^2.

Maximum displacements, useful in particular as boundary condition for the bottom corner calculations, are however calculated for an incident flux of 5 MW/m^2 (average). For the bottom corner, it has been necessary to distinguish the cases of the "slotted-monoblock" and of the "sliding-tie monoblock" (different boundary conditions). In each of the four cases performed for the "sliding-tie monoblock", even the most favourable free-tube case, a stress concentration appeared on the tube in the first element between two monoblocks. In any cases, the maximum level of stress was located in such a zone. In the case of the slotted-monoblock, for the bottom corner no difference in boundary conditions appears with and without incident flux on the straight part of the mock-up. Indeed, the FW being strongly attached to the shield through the steel pad, there is no FW elongation to be accommodated by the corners. Found maximum stresses are lower than those obtained for the "sliding-tie" monoblock concept.

Table 1: Main results of the parametric steady state thermal analyses

Temperatures (°C) obtained in the CFC-prototype parametric steady state thermal analysis						
incident flux	(max)	1 MW/m^2	2.5 MW/m^2	5 MW/m^2	7.5 MW/m^2	10 MW/m^2
CFC monoblock	min	145 °C	152 °C	163 °C	174 °C	185 °C
	aver.	164	202	269	341	420
	max	**208**	**320**	**534**	**788**	**1074**
OFHC layer	min	145	151	162	173	183
	aver.	151	168	195	221	247
	max	161	192	242	292	341
CuCrZr tube	min	144	150	160	169	179
	aver.	149	164	187	209	231
	max	158	185	228	272	312
Water	(mid)	142	146	152	158	164

Temperatures (°C) obtained in the Be-prototype parametric steady state thermal analysis						
incident flux	(max)	1 MW/m^2	2.5 MW/m^2	5 MW/m^2	7.5 MW/m^2	10 MW/m^2
Be monoblock	min	35	41	50	58	66
	aver.	45	68	106	145	186
	max	**87**	**177**	**347**	**546**	**776**
Glidcop tube	min	34	40	48	56	64
	aver.	42	59	85	109	132
	max	56	91	148	202	255
Water	(mid)	32	35	39	44	48

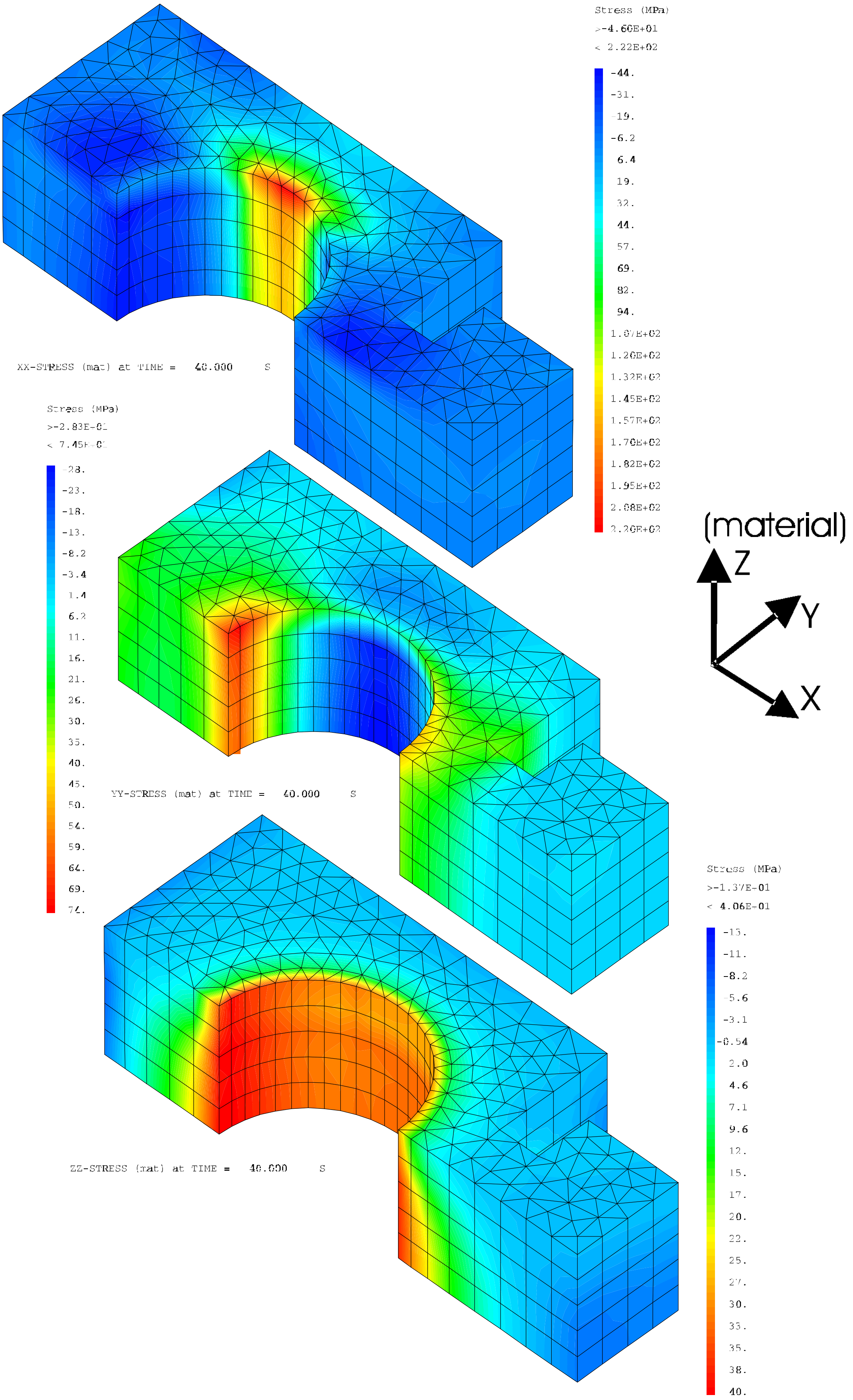

Figure 2 : CFC concept A, straight part: stress distribution in each material direction in the CFC-monoblock

BERYLLIUM-MONOBLOCK PANELS

Calculations performed for the Be-prototype are about the same than those performed for the CFC one. The parametric steady state thermal analysis has been performed first. The second part of the Table 1 gives the main results. Characteristic times, $\tau_{68\%}$ and $\tau_{90\%}$, obtained in the thermal transient analysis under 10 MW/m^2 are lower (respectively 1.4 s and 2.7 s).

Elastic mechanical calculations performed for the straight part of the Be-prototype have been repeated for the cases of 10 and 20 mm-long monoblocks. Von Mises thermal stress distributions have been obtained. It was observed that the maximum values of stress obtained in the case of the 20 mm-long monoblocks were about 40% higher than in the case of 10 mm-long monoblocks. But for both cases, it was not possible to conclude with this analysis neither on the structure lifetime nor on it's failure probability (problem of stress concentrations). However, taking into account the large difference between the maximum levels of stress, it is strongly recommended to manufacture the mock-up with 10 mm-long Be-monoblocks.

Because of the difficulty on the results interpretation, it has been decided to make a comparison with the stress levels obtained for a similar component already tested under flux during the small-scale mock-ups testing campaign. Thermo-mechanical calculations of Be-monoblocks which have been successfully tested in JET (able to withstand 10.1 MW/m^2 for 5s for a few hundred of cycles without damage) has been performed using the same type of modelling than the one used for prototype in order to compare the stress levels. The obtained stress levels are comparable. One can therefore expect similar lifetime.

Contrary to the CFC-prototype for which the inlet temperature is high, for the Be-prototype the bottom corner is submitted to stresses only when the mock-up is heated by the incident flux. During the shot, if one assumes that the Be-dove tails of the monoblocks will slide, the thermal expansion of the FW tube has to be accommodated by the two corners. It is supposed here that the bottom corner is submitted to half of the global expansion (which is 1.1 mm, as determined for the straight part with 10 mm-long monoblocks). The number of attached monoblocks after the corner was a parameter. Fig. 3 gives a visualisation of the boundary conditions (obtained displacements) in the case where the last 3 monoblocks are attached to the shield. As for the straight part calculation, maximum stresses in the Glidcop tube were located in some particular points of the mesh where the modelling is not enough precise (in term of nodes density and mechanical properties description) to have confidence in the accuracy of the results. However, as for the CFC case, lower stresses are obtained when only one monoblock (the last one) is attached to the shield.

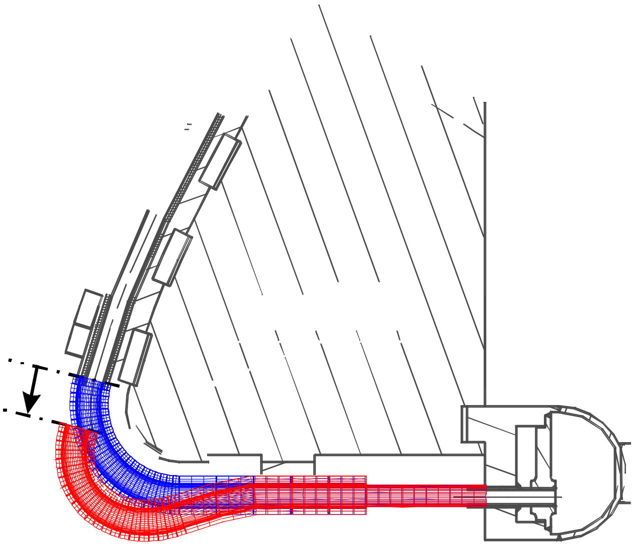

Figure 3 : Be-monoblock concept A, bottom corner displacements (ampl. 50), case with the last 3 monoblocks attached, average flux of 5 MW/m^2 on FW

CONCLUSIONS

Thermal & thermo-mechanical analyses have been performed for the FW-panels present in the CFC-prototype and the Be-prototype of ITER baffle being under manufacturing within EU. The analyses have been focused on the most-critical FW-panel designs (Be-monoblock and CFC-monoblocks) which are supposed to be tested under heat-flux conditions corresponding to the expected ITER baffle & limiter (when applicable) working conditions.

The obtained results show that all FW-panels are able to withstand the reference heat-flux when their thermo-mechanical behaviour is compared to previous small-scale mock-ups testing. It must be stressed that the obtained results do not take into account fatigue phenomena, because no data are available. The only available data are those obtained with the small-scale mock-ups testing. Using these data, the FW panels are expected to withstand a large number of cycles.

Unfortunately, the geometry of the small-scale mock-ups were significantly different of that used for the prototypes FW-panels. Therefore, unexpected fatigue phenomena, especially in the FW-panel corners, could occur. The used calculation models cannot predict them. On the other end, the tests results will be very useful to interpret the obtained computed results. This would allow to evaluate and interpret the results of future thermo-mechanical analyses.

PUBLICATIONS

[1] P. Magaud, F. Le Vaguères (eds.), Fusion Technology, 1997 Annual Report of the Association CEA/EURATOM, Task CNET 96-412, CEA DSM/DRFC, May 1998.

[2] J.F. Salavy, L. Giancarli, Thermo-mechanical analyses of the two baffle-FW prototypes being manufactured EB-tested by the ITER EU-HT, CEA/DMT Report, SERMA/LCA/RT/98-2425/A, October 1998.

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CNET 97-463

Task Title : HIGH HEAT FLUX TESTING OF PRIMARY FIRST WALL SMALL SCALE MOCK-UPS

200 kW electron beam gun test

INTRODUCTION

The scope of this contract is to test under high heat flux actively cooled mock-ups representative of the ITER first wall. Evaluation of the joining, mock-up preparation and post mortem examination are also included in this contract. The FE 200 high heat flux test facility is operated jointly by CEA and FRAMATOME since 1991. Various testing have been performed under NET contracts on this installation since 1991.

The ITER first wall technology is an integrated concept with a water cooled copper heat sink joined to the stainless steel blanket modules and covered by a beryllium plasma facing material. The average incident heat flux is in the order of 0.5 MW/m².

The aim of this study was to compare the different qualities of the copper to stainless steel joints and characterize the behavior of representative small scale mock-ups under high heat flux fatigue loading.

Nine Hipped (powder or plate) elements where delivered to DRFC:

- 4 produced by Studvick
- 4 produced by NNC
- 1 by CEA

All elements where prepared and examined by CEA. Only four where fatigue tested in FE200 under heat load higher than designed (X 10).

Figure 1 : MK1 and MK2 elements [CuCrZr (powder) Hipped to Stainless steel (powder and plate)] prepared for IR testing on SATIR

Four large element manufactured by solid Hipping where assembled two by two (FW2 & FW3) for fatigue testing in the FE200 test facility.

The comparison was always between a precipitation hardened (PH) and a dispersionned hardened (DH) copper.

FIRST TEST CAMPAIGN (FW2)

After a screening test up to 7 MW/m², the fatigue testing started at 5 MW/m².

The surface temperature measured during the testing where comparable for each elements.

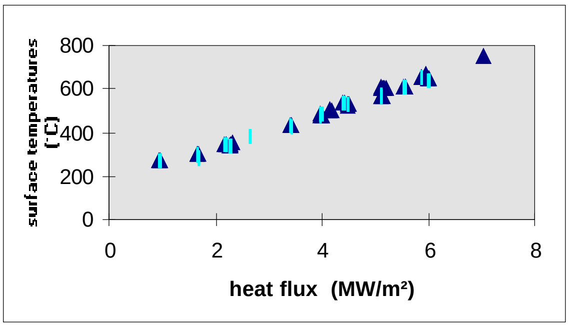

Figure 2 : Comparison of the thermal behavior of PH and DH Hipped element

The DS element started first to failed (hot spot) after 315 cycles. The testing continued until 960 cycles and the visual examination showed a large disbonding of a copper to copper joint and a deep surface crack (fig. 3, bottom element).

Figure 3 : FW2 mock-up after fatigue testing at 5 & 7 MW/m². Disbonding failure on DS element and surface cracking on PH element

The PH element survived 1000 cycles at 5 MW/m² without temperature excursion. A hot spot appeared after 300 cycles at 7 MW/m² but fatigue testing was pursued until 800 cycles.

Visual examination of the surface shows many small surface crackings (figure 4).

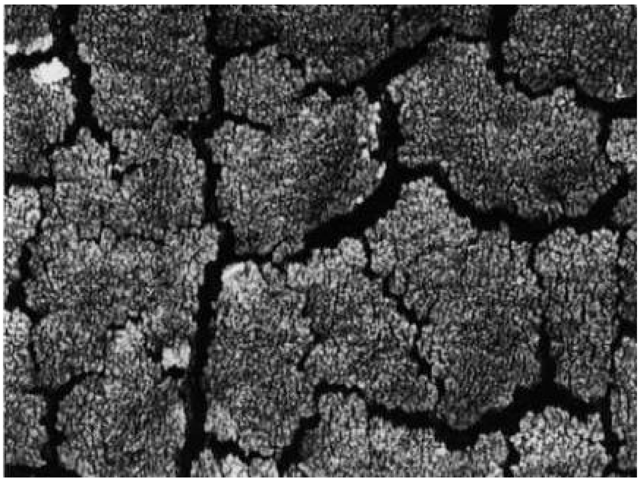

Figure 4 : Surface cracking on PH copper element of FW3 mock-up after fatigue testing (cell size # 2 mm)

SECOND TEST CAMPAIGN (FW3)

An improved DS copper element for the second pair of solid HIP components was produced after the first testing campaign (FW2).

Surface temperature remained constant during the 1000 cycles fatigue test at 5 MW/m² on both elements. After opening a large crack was visible between the copper heat sink and the stainless steel back part on the DS copper element. No crack was detected at the copper/copper interface.

After 150 cycles at 7 MW/m² on the PH copper element, a hot spot was detected at the center of the heated area.

POST MORTEM EXAMINATION

The DS copper element with a large crack at the copper to stainless steel interface had the largest deflection (0.5 mm / 200 mm).

The PH copper element showed the same orange skin as for the first test (FW2). The electrical conductivity (proportional to the heat conductivity) and the microhardness were reduced on the exposed area (50%). The DS element remained roughly with the same values.

CONCLUSIONS

The Hipping technology developed for these elements is not satisfactory for assembling DS copper and stainless steel when the component is subjected to high heat loads in the range of 5 MW/m². The PH copper assembled by the same technology has a better behavior but cannot survived at 7 MW/m². Nevertheless this technology could be sufficient for the low design heat loads (0.5 MW/m²) of the first wall.

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CNET 98-477

Task Title : THERMAL FATIGUE OF DIVERTOR MEDIUM SCALE COMPONENTS

200 kW electron beam gun test

INTRODUCTION

The scope of this contract is to test under high heat flux actively cooled mock-ups representative of the ITER divertor.

The FE 200 high heat flux test facility is operated jointly by CEA and FRAMATOME since 1991. Various testing have been performed under NET contracts on this installation since 1991.

The ITER Divertor requires to test different high heat flux technologies which could used in the full region of the divertor (dome, gas box, dump, vertical target). During the year 98, only one test campaign has been devoted to such qualification:

Prodiv1 : prototypical mock-up of the vertical target.

The aim was to characterise the behavior of a 400 mm long element made of 27 CFC (NS 31) monoblocks mounted with a sliding tail on a stainless strong back.

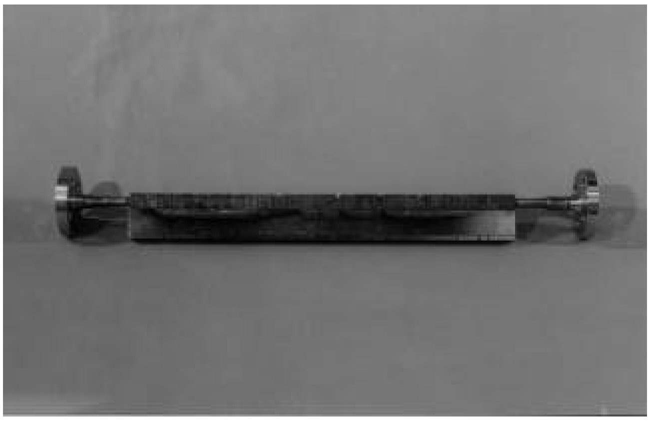

Figure 1 : PRODIV 1 mock-up after high heat flux testing

TESTING RESULTS

The testing campaigns took place in January and April 1998.
The Cooling parameters were identical to the ITER requirements (150°C, 12m/s, 3.5 MPa).

After 1000 cycles at 20 MW/m², done in January 1998, a slight increase of the heat flux (22 MW/m²) caused a CHF with a water leak. Melted copper had migrated through the CFC and could be seen on the heated surface. A white deposit was also present around the damaged area (fig. 2).

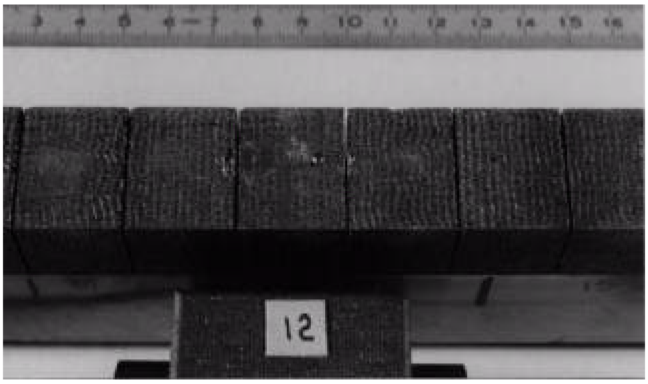

Figure 2 : Critical heat flux damage on the PRODIV 1

Chemical Analysis of this deposit showed that it was mainly Na, Ca, Fe and could originate from the water chemistry.

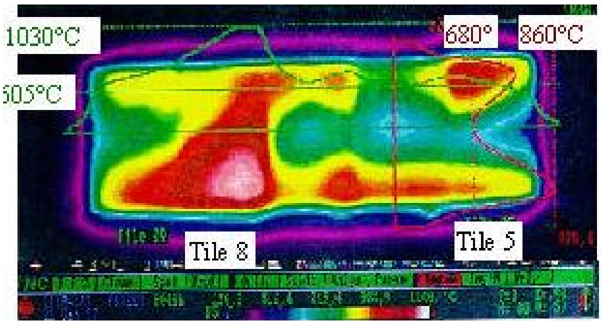

Figure 3 : Local view of Prodiv1 with an infrared surface temperature after 1000 cycles at 20 MW/m indicating a defect

During the last fatigue cycles a hot spot was visible on tile N°8 (figure 3). This indication of a local defect was confirm by the SATIR analysis done on the mock-up (figure 4).

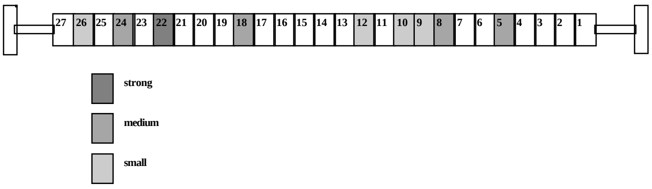

Figure 4 : Satir testing on Prodiv1 after heat flux testing with indication of the possible defects

CONCLUSIONS

This mock-up demonstrated the ability of the monoblock concept to sustain very high heat flux (up to 20 MW/m²). The critical heat flux negative margin could be explained by an increased peaking factor du to some local defects. A new test campaign was done to correctly evaluate this margin.

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Task Title : FULL SCALE MANUFACTURING OF HIGH HEAT FLUX COMPONENTS DESIGNS FOR DIVERTOR MODULES

INTRODUCTION

Tube-to-tube connections are necessary to connect the plasma facing components (PFC) to cooling water circuits. PFC are equipped with Cu alloy cooling tubes whereas ancillary circuits are type 316LN austenitic steel tubes. CuCrZr is weldable, so short tubular connections can be fabricated by HIP diffusion welding and welded to CuCrZr long tubes afterwards. On the opposite, DS-Cu alloys are not weldable, so the DS-Cu tubes must be equipped with steel ends before PFC fabrication. By the way, it would allow to weld the steel canister for HIPing to the cooling tube. The process used for this connection must thus be applicable to long tubes, i.e. it must not rely on HIP diffusion welding. Both HIP and non-HIP processes have been considered here.

High Heat Flux (HHF) plasma facing components are among the most highly loaded components in a fusion reactor. They are composed of a copper alloy tube (CuCrZr or DS-Cu), a compliant layer (Cu OFHC) and a plasma facing material (CFC, Be, W). Several design concepts have been developed, like the flat-tile concept, the macro-brush concept or the saddle-like monoblock. The former ones are easier to manufacture but their performance under glancing particle flow is not satisfactory. On the opposite, the monoblock concept potentially presents a better behaviour but its fabrication is more difficult due to the coefficient of thermal expansion (CTE) mismatch between the materials. The fabrication of tungsten monoblocks using diffusion welding has been investigated.

1998 ACTIVITIES

DEVELOPMENT OF CU ALLOYS / SS316LN TUBE TO TUBE CONNECTIONS

CuCrZr / SS316LN connections

Connections have been fabricated by Hot Isostatic Pressure Diffusion welding (HIP-DW). The principle of the process is to manufacture first a rod-to-rod joint with an overlap (figure 1) and to machine a tubular connection from this rough component.

The HIP parameters are 920°C, 100MPa for 1h. The cooling rate available with the HIP device is not fast enough to obtain quenching of the CuCrZr alloy. Thus, after the HIP cycle, the specimens are solution annealed at 990°C for 1h and water quenched. Following this heat treatment, an ageing treatment (4h at 480°C) is performed.

This procedure allows to restore the microstructure of the CuCrZr alloy. Machining of the specimens is made after HIP and post heat treatments.

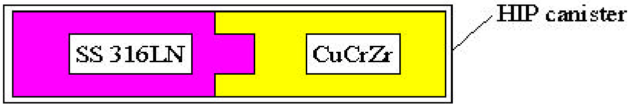

Figure 1 : Scheme of CuCrZr/SS316LN connection fabrication

DS-Cu / SS316LN connections

This technique is based on the thermal expansion mismatch between stainless steel and copper alloys. By choosing properly the joint design, it is possible to apply a force on the interface during heating provided that the CTE difference is significant, which turns out to be the case for DS-Cu but not for CuCrZr. Tubes ID/OD 10x12mm have been used.

The joint design is based on a conical fitting. After a surface preparation procedure, the DS-Cu alloy is fitted inside the SS part. Then the parts are heat treated for bonding under vacuum at 1000°C for 30mn. Imperfect bonding is obtained if no constraining ring is used. On the contrary, if a graphite ring is used, helium tight joints are achievable. However the process reliability is not satisfactory, as the tightness is not reproducible.

HHF COMPONENTS DEVELOPMENT

A scheme of the mock up is shown on figure 2. The tungsten alloy is W-1%La_2O_3. The Cu alloy tube must be joined to the tiles via an intermediate, compliant layer material (Cu OFHC).

In the case of CuCrZr it is advisable not to exceed 500°C as joining temperature, otherwise a post heat treatment is necessary, including quenching.

Quenching may damage the Cu-W joints due to the high CTE mismatch. This is why a high temperature step is applied for W-Cu joining while a low temperature step is applied for CuCrZr-Cu joining.

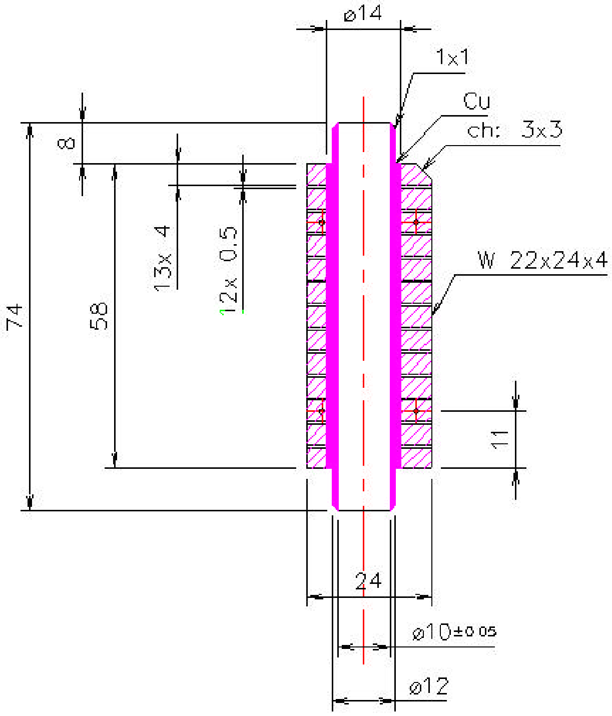

Figure 2 : HHF mock up

Development of W-1%La_2O_3/Cu OFHC joints and Cu OFHC/Cu alloy joints

W and Cu form an immiscible system and, even though direct joining is possible, an intermediate layer providing a "metallurgical transition" is desirable to obtain resistant joints. The interlayer choice was made on the basis of phase diagrams, diffusion coefficients and literature data. Best results were obtained with a 10µm thick nickel foil. The HIP cycle is based on a 2h step at 950°C. In the case of DS-Cu, the same HIP cycle is used for DS-Cu / Cu OFHC joining.

In the case of CuCrZr, several techniques have been investigated. Direct HIP DW at 500°C is achievable. The tensile properties of flat specimens are comparable to those of pure, annealed Cu OFHC, the rupture being located away from the interface. However, this result was not repeated with a tubular geometry due to CTE mismatch. Joining at 500°C using the so-called diffusion brazing process allowed better results. In this process, isothermal solidification of a brazing material occurs during the temperature step due to the dissolution of the braze by the base metal. The braze metal is pure tin.

The fabrication process is based on the use of a copper canister (figure 3). After surface preparation, the tungsten alloy tiles as well as Cu OFHC tube and Ni foil are inserted in the canister. The canister is sealed by electron beam welding. A first high temperature HIP cycle is applied. Then, CuCrZr tube and a Sn foil are inserted in the canister which is sealed again by EB welding. A second HIP cycle (low temperature) is applied. Only one HIP cycle is necessary in the case of a DS-Cu alloy.

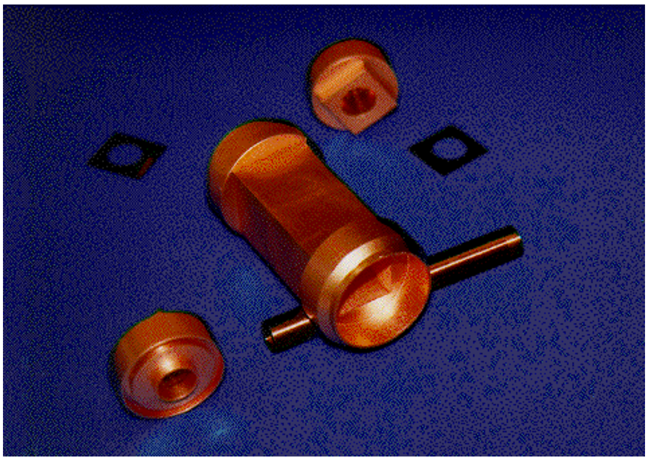

Figure 3 : Canister for HHF components mock up fabrication

Joint design

Finite Element Modelling has been used to evaluate the effect of the interface geometry on the stress and strain, using FE code Castem 2000.

The model chosen is an axi-symmetric representation of two tiles in which a OFHC copper tube ID/OD 12/14mm is inserted. The calculation takes into account the cooling from 950°C (HIP joining temperature) to 50°C.

Different joint geometries have been considered : 90° joint (reference), 0.5mm 45° chamfer, rounded edge 0.5mm. In the latter case, copper filling of the angle has been taken into account.

The results are shown on figures 4-6. In all cases high stress concentration develops on cooling in the tungsten tiles. Conversely, plastic deformation of the copper OFHC occurs. Though the value of the maximum Von Mises stress shall not be considered as an exact result because of calculation divergence, a qualitative comparison can easily be made between the different configurations considered.

The peak stress is greatly reduced when a 45° chamfer is machined on the tiles or when the tile edge is rounded. It decreases from 1.8GPa to 680MPa and finally 210MPa. In the second and third case it is worth noting also that the location of the stress concentration in tungsten does not coincide with a free edge of the joint, whereas it does in the case of 90° tiles.

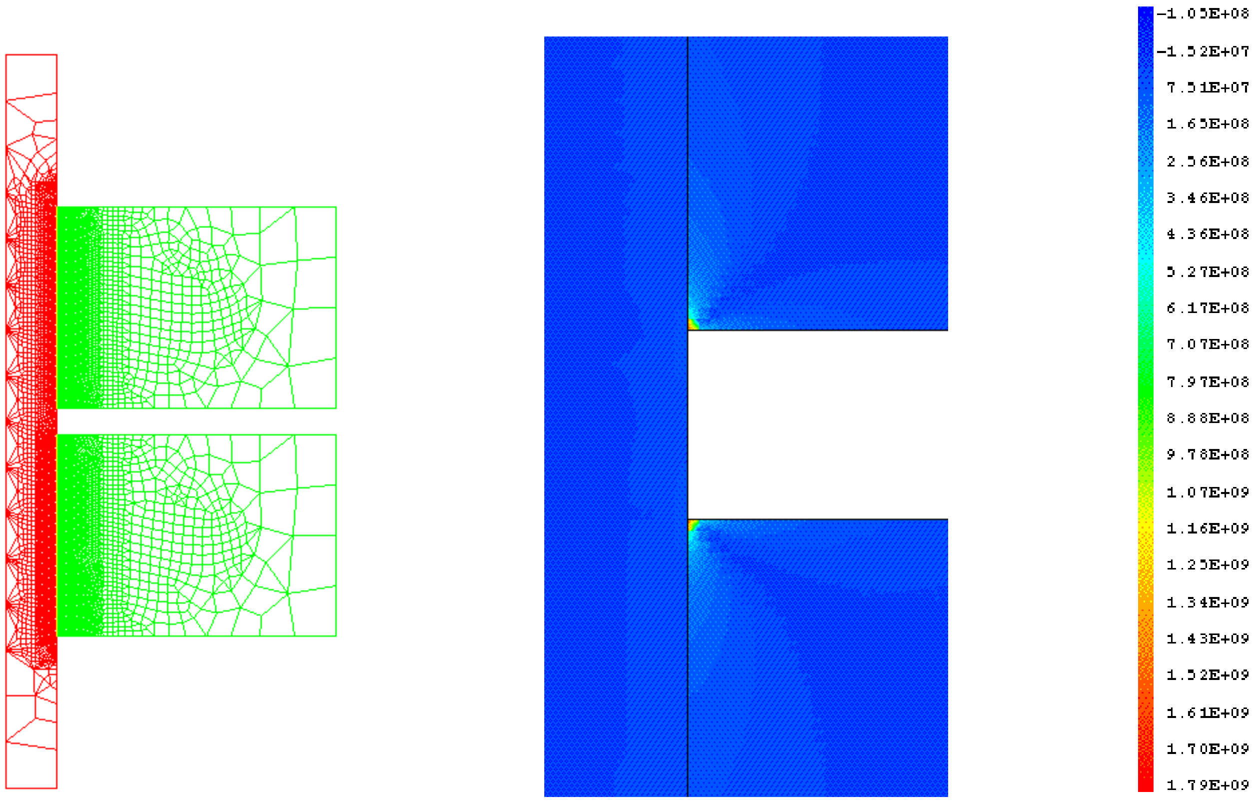

Figure 4 : FEM calculation of Von Mises equivalent stress (unchamfered tile)
From left to right : mesh, enlarged view of Von Mises stress, scale (Pa)

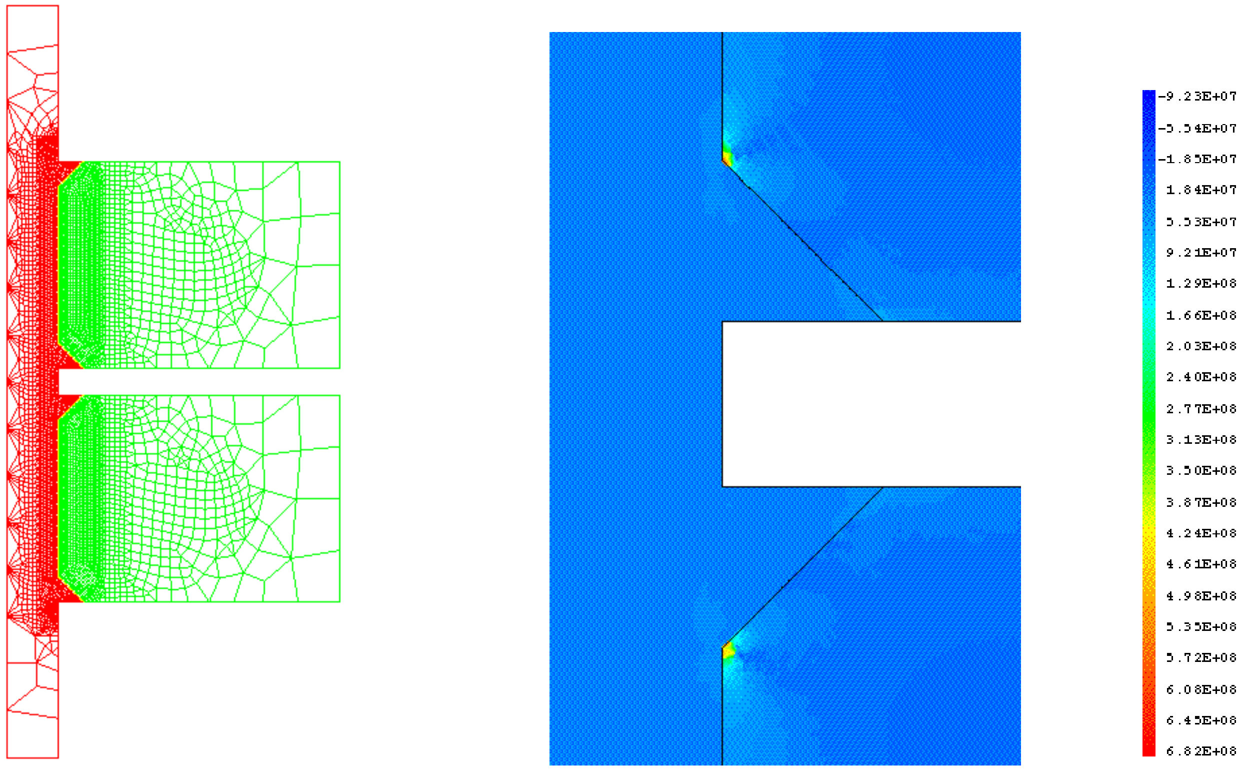

Figure 5 : FEM calculation of Von Mises equivalent stress (45° chamfered tile)
From left to right : mesh, enlarged view of Von Mises stress, scale (Pa)

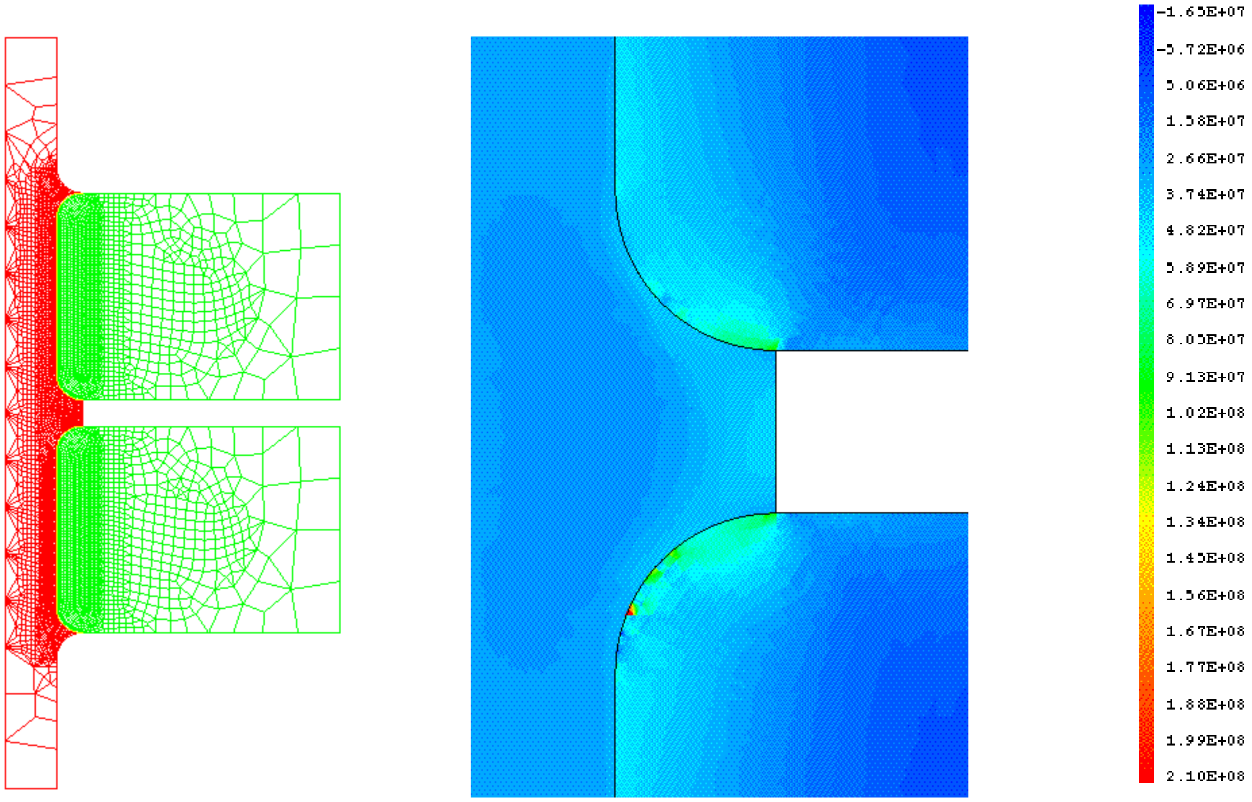

Figure 6 : FEM calculation of Von Mises equivalent stress (rounded tile with copper filling)
From left to right : mesh, enlarged view of Von Mises stress, scale (Pa)

CONCLUSIONS

A HIP diffusion welding technique has been used to fabricate CuCrZr / SS316LN bimetallic tubular connections. Single and double overlap tubular connections (CuCrZr/SS316LN and SS316LN/CuCrZr/SS316LN) have been fabricated and delivered to Forschungzentrum Jülich for tensile, pressure and low cycle fatigue testing respectively. The application of a diffusion bonding technique to DS-Cu tubes was not successful.

Using HIP diffusion welding with a copper canister, it is possible to manufacture monoblock HHF mock ups. This process allows to use smaller tubes than dia. 14mm because the expansion of the tubes can easily be obtained. It is thus adapted to the fabrication of curved shaped HHF components. However in that case the canister design has to be improved to reduce the machining costs.

For CuCrZr alloy a two step HIP process is proposed. A first HIP cycle is used to diffusion weld Cu OFHC and W-1%La_2O_3 at 950°C using a Ni foil, and a second HIP cycle is used to diffusion braze Cu OFHC with CuCrZr at 500°C, using a Sn foil. For DS-Cu alloy a only one HIP cycle is necessary thanks to the thermal stability of DS-Cu.

Finite Element Modelling has shown that a 90° joint angle leads to very high stress concentration on cooling. Much better designs are obtained by chamfering the tiles.

Four mock ups, three of which with chamfered tiles, have been fabricated and delivered to Forschungzentrum Jülich for irradiation at 0.2dpa and 1.0dpa.

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T222.4ter

Task Title : MANUFACTURE AND TESTING OF PERMANENT COMPONENTS OPTIMISATION OF COOLING SYSTEM

Critical heat flux and thermo-hydr. of representative elements (continuation T222.4); Non destructive testing, calibrated defects, heat load influence (T222.15)

INTRODUCTION

The work on task T222.4 has been actively pursued in 1998 :

- after round robin tests performed in 1997 in Sandia Nat. Lab. (US) new tests were performed in JAERI (Japan),
- various tentative of the manufacture of brazed swirl tape insert were launched,
- two tube-in-tile concept mock-ups were tested on the FE200 facility.

1998 ACTIVITIES

ROUND ROBIN TESTS [1 to 9]

A new mock-up named ST22ter identical to ST22 tested at FE200 and to ST22bis tested in Sandia Lab. [7] was tested during October in JAERI (2mm thick twisted tape with a twist ratio of 2) . As the mock-up was tested on the PBEF of JAERI (Particle Beam Engineering Facility) it was not possible to control the beam profile which is roughly a gaussian one, the reference profile used at the FE200 being about an half of this gaussian profile (Fig. 1).

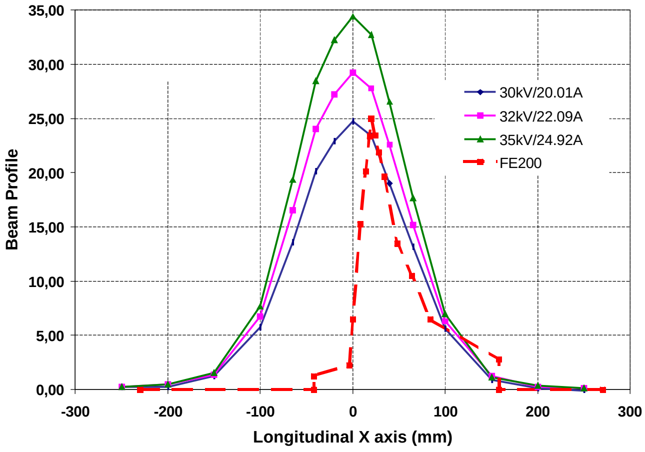


Figure 1 : PBEF profile (MW/m^2) compared with reference profile (dashed line)

It was not possible on this facility to have a wide range of thermal hydraulic conditions, especially for the inlet temperature. Fourteen critical heat flux were performed at the following thermal hydraulic conditions :

P = 2.05 MPa,	V = 12.8 m/s	Tin = 24.7°C
P = 0.32-0.39 MPa,	V = 5.0, 7.5, 10.2, 12.8 m/s	Tin = 21-27 °C
P = 1.0 MPa,	V = 5.3, 7.6, 10.2, 12.7 m/s	Tin = 20.5-25.5 °C

Observed phenomena's were very typical of CHF behaviour with hot points and visible transient excursions both on near-surface thermocouple and on infrared measured temperature.

Results obtained are very consistent in regards to velocity (Fig. 2) but not to local subcooling (Fig. 3). This suggests that the water local pressure was poorly estimated leading to important errors on the evaluation of the subcooling. Surprisingly the CHF values are in agreement with those obtained on the FE200 for other thermal hydraulic conditions and a different heat flux profile. Nevertheless the tests have confirmed the high value of 37 MW/m^2 obtained at CEA with a axial velocity of 12 m/s.

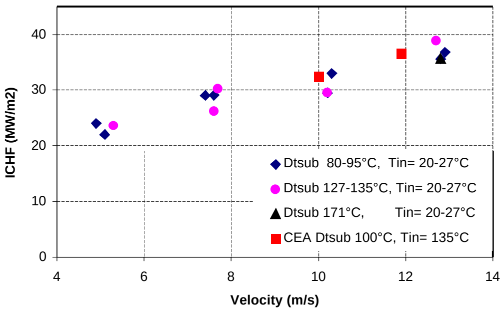


Figure 2 : JAERI CHF results versus velocity compared with CEA ones

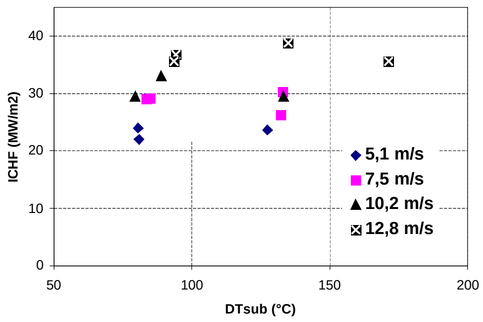


Figure 3 : JAERI CHF results versus local subcooling

BRAZING OF A THICK SWIRL TAPE [10]

After the difficulties encountered with the first selected manufacturer who resigned after some tries, a new call for tender was launched grouping together the swirl tape specific manufacturing and the brazing.

The problem was found too critical by the industry and the asked prices were not compatible with CEA budget. The study will be pursued in 1999 in Tore Supra laboratory.

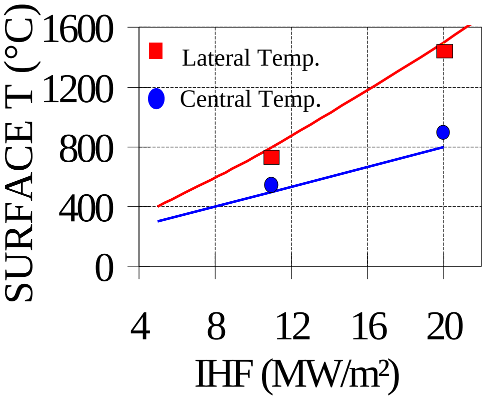


Figure 4 : Screening test on the Prodiv1 Prototypical mock-up; comparison between tests (points) and FE calculations (lines) on a without-defect zone

PROTOTYPICAL MOCK-UP : THERMAL FATIGUE TESTING [11 to 15]

A prototypical mock-up made of 22 monoblock tiles was received in December 1997 and prepared for tests on the FE200 in January 1998. The component was screened (Fig. 4 and 6) and thermal fatigue tested in the FE200 electron beam facility. A thousand cycles at about 20 MW/m^2 were performed over an heated length of 110 mm (Fig. 5). Although defects were visible at the beginning (Fig. 6 left) and propagated slowly during the 1000 cycles (Fig. 6 right) the mock-up sustained well the fatigue cycling.

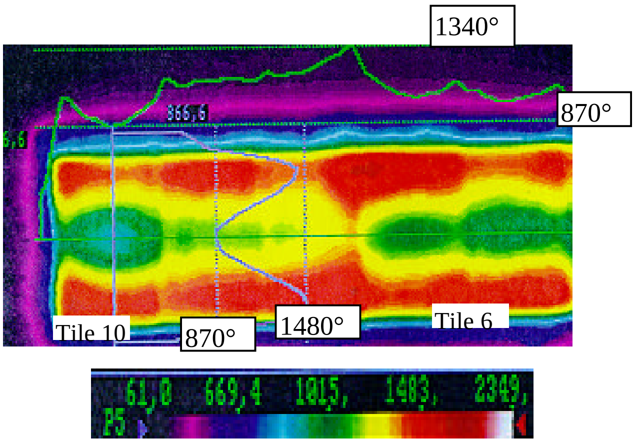


Figure 5 : Surface temperature during the last cycle, after 1000 cycles at 20 MW/m², 12m/s, 3.4 MPa, 140°C, shot 2047

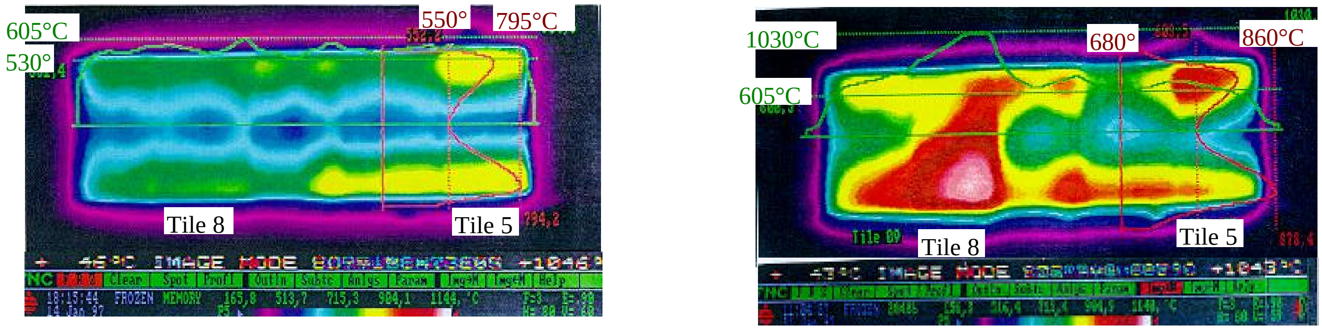


Figure 6 : Screening test performed before (left, shot 2041) and after (right, shot 2048) the thermal fatigue testing, IHF = 11 MW/m², 12m/s, 3.4 MPa, 140°C

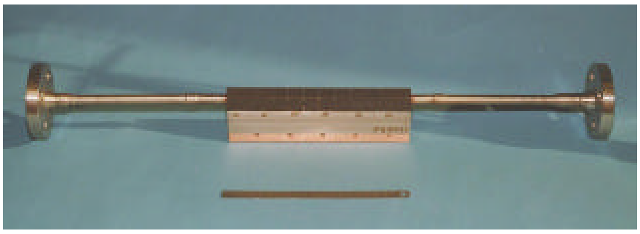
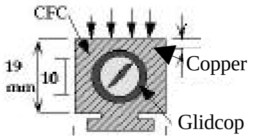


Figure 7 : View of PRODIV2 mock-up (tiles 16 to 27) before its installation on FE200 test bed

PROTOTYPICAL MOCK-UPS : CRITICAL HEAT FLUX TESTS [12 to 17]

Two mock-ups were CHF tested during two campaigns: PRODIV1 and PRODIV2 (Fig. 7). This latter was built from the non tested part of PRODIV1, after the water leak during the first campaign, and was extensively tested on the infrared test bed SATIR of CEA Cadarache; some defects were visible and well correlated with the screening during FE200 testing (Fig. 8).

Table 1 : Interpolated CHF results (3.5 MPa, DT$_{sub,out}$=100°C, V=12m/s, ID = 10 mm)

Mock-up	Geometry	Twist Ratio	ICHF (MW/m^2)		Pressure drop (MPa/m)	Pumping power (W/m)
			flat	peaked		
Thick tape						
PRODIV1 PRODIV2		2	~22	~30	0.61	428

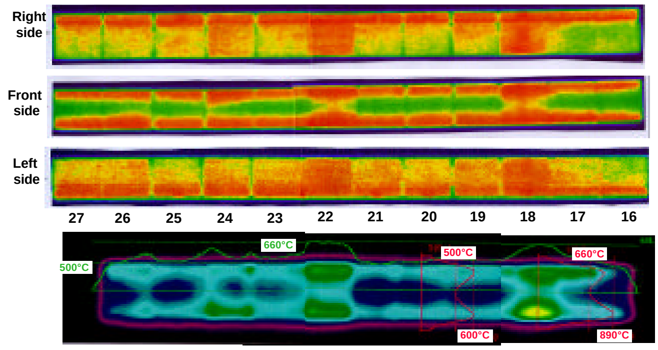


Figure 8 : Comparison between SATIR testing and 11 MW/m^2 FE200 screening for PRODIV2

For these mock-ups it was not possible to detect the CHF by looking at the infrared (IR) camera screen so that each time the mock-up was damaged up to the water leak. The IR images of the surfaces just before water leak are given Fig. 9 and 10.

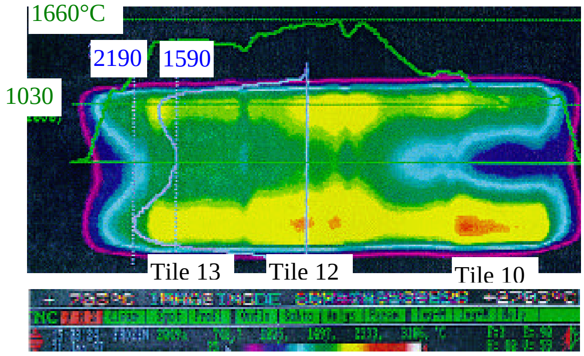


Figure 9 : IR image of a flat profile at 21 MW/m^2 on PRODIV1 mock-up, Shot 2049, 100 mm, 47 kW

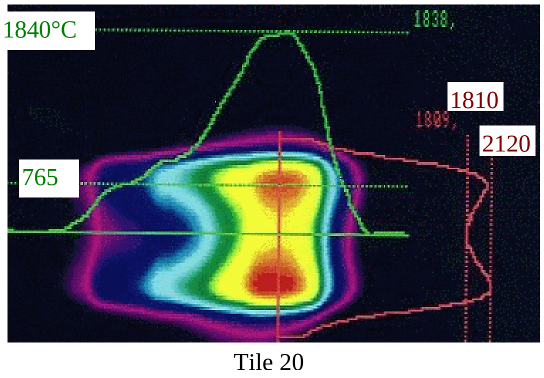


Figure 10 : IR image with a peaked reference profile at 29 MW/m^2 on PRODIV2 mock-up, Shot 2094, 45 kW

The low CHF values (Table 1) are attributed to defects at the bond between CFC and Cu layer or between this layer and the Glidcop tube. A limit at 22MW/m^2 was found under a flat profile whereas 27 MW/m^2 was expected after tests on Glidcop mock-ups; under peaked profile the limit was 30MW/m^2, the lowest value of the range 30-37 MW/m^2 expected. However the problem of CHF is a stability one and the low thickness of copper in the tube-in-tile concept (0.5 mm of copper and 1 mm of Glidcop) could also explain a trend to decrease the CHF. FE calculations show a good correspondence, in terms of wall heat flux distribution, between Glidcop blocks and tube-in-tile concept, so that the CHF decrease cannot be attributed to that. The temperature profile under peaked heat flux given by the IR image is influenced by the IR camera resolution (about 5 mm compared with the 23 mm mock-up width). After CHF tests, an examination of PRODIV1 was undertaken. A cross section of tile 12 showed that the CHF occur on the middle of the tile at the place where swirl tape is perpendicular to the heated surface (Fig. 11 and 12). It is clear that at CHF the copper was molten and drew up by the porous CFC (Fig. 13).

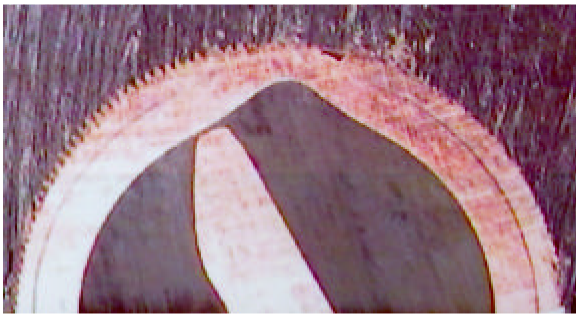


Figure 11 : Destructive examination of tile 12 after CHF, cross section AA near the middle of the tile

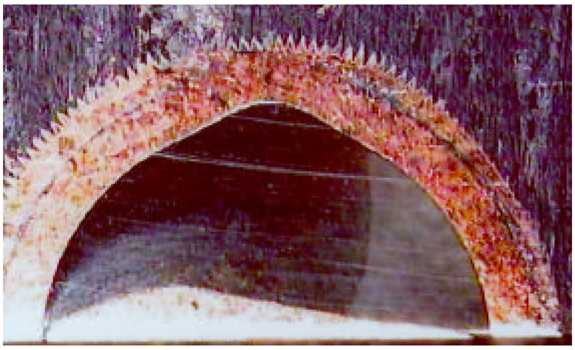


Figure 12 : Destructive examination of tile 12 after CHF, cross section BB on the side of tile 12

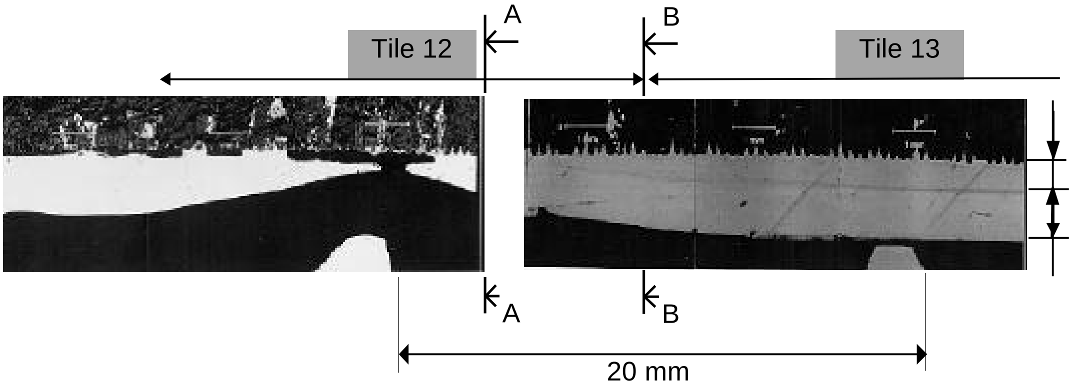


Figure 13 : Destructive examination of tiles 12 and 13 after CHF, longitudinal section showing how the copper layer has been drawn up at CHF

CALIBRATED DEFECTS, NON DESTRUCTIVE TESTING AND HEAT LOAD INFLUENCE

The definition of the calibrated defects has been done in 1997. During 1998 the mock-up was in fabrication in Plansee. The mock-up should be delivered in March 1999 and be tested on the SATIR test bed and the FE200 facility. The objectives of this study are to demonstrate the capability of the CEA Infra Red Test facility SATIR to detect a certain size of defect in the bonds between the tiles and the copper tubes and to correlate the defects to the lifetime of the element under heat flux; the life time being evaluated by cycling tests on the FE200 facility.

CONCLUSION

After CHF tests on Glidcop swirl tubes in 1997 which led to the choice of a thick twisted tape with a twist ratio 2, the task was pursued in 1998 with round robin tests in JAERI which confirmed the high values obtained at CEA and with fatigue tests and CHF tests on 2 prototypical mock-ups. These mock-ups, made of Si doped CFC monoblocks with a thin Cu layer of 0.5 mm and a cooling Glidcop tube equipped of the selected twisted tape, sustained well the 1000 cycles at 20MW/m^2.

This result validates the concept, despite some defects which did propagate during the cycling. Low values of CHF were obtained compared with those expected, however the value of 30MW/m^2 sustained with a peaked profile gives a good margin for these mock-ups. Nevertheless the process of manufacture has to be improved by the industry (Plansee).

The task will continue in 1999 with complementary destructive tests of the prototypical mock-ups, the test of a medium scale mock-up and with the testing of the calibrated defect mock-up.

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Task Title: DESIGN AND ANALYSIS OF VACUUM VESSEL AND INTERNALS

INTRODUCTION

The task UT-SM&C-VVI is a contribution to the European Fusion Underlying Technology Programme. This task is intended to maintain/develop the DMT competence and analysis tools in the field of the design of the tokamaks vacuum-vessel and internals (divertor, limiters, baffle, first wall, shielding blanket, breeding blanket).

1998 ACTIVITIES

The main performed activities in 1998, some of them to be seen as a continuation of those described in [A], have mainly addressed two components : the ITER Breeding Blanket (BB) in support to the Task CNET 98-474 activity, and the ITER baffle in support to the ITER JCT activity. In particular, for the ITER BB the work included : 1) thermal analysis of slow high-power plasma Vertical Displacement Event (VDE), and 2) thermo-mechanical analysis of the BB module box. For the ITER baffle the work concerned the « reference » transient thermo-mechanical analyses of the ITER baffle module Nb. 26.

THERMAL ANALYSIS OF SLOW HIGH-POWER VDE

The most critical design condition to be considered for the first wall consists in slow high-power VDE. During such event, between 20 and 60 MJ/m^2 are dumped on the First Wall (FW) in ~ 0.3 s, leading to the melting of a thin layer of the Be protection. The FEM computer code CASTEM 2000 has been used to evaluate the thermal transient in the FW during a high-power VDE [B]. A local two-dimensional model (Figure 1) including the Be protection and the stainless steel FW appeared to be sufficient to analyse this temperature transient. As melting of beryllium will occur during each VDE, thick Be protection - at least 10 mm - have been considered here.

In the present CASTEM 2000 model, the Be melting is taken into account by adding the melting latent heat (1300 kJ/kg) to the heat capacity of the Be over a pre-defined temperature interval of 40°C. Moreover, energy-absorbing phenomena such as evaporation, impurity [1] or blackbody radiation (surrounding structures taken at 500°C) have also been taken into account by the use of appropriate laws. An energy dumping of 60 MJ/m^2 in 0.3 s has been here considered in the analysis, corresponding to an incident surface heat flux of 200 MW/m^2 during 0.3 s.

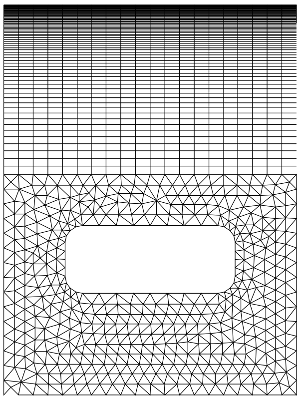

Figure 1 : Local 2D thermal mesh of the First Wall for VDE analysis

Table 1 : Thermal results for a slow high-power VDE in the first wall (60 MJ/m^2 in 0.3 s) with a 10 mm thick Be protection. Thermo-hydraulic parameters set to nominal value

Max. surface temperature		1991 °C
Surface temperature	t = 0.1 s	1974 °C
	t = 0.3 s	1991 °C
	t = 3 s	557 °C
Max. T at different depths	at 1 mm from surface	1128 °C
	at 2 mm from surface	886 °C
	at 3 mm from surface	761 °C
	at 10 mm from surface (Be/SS interface)	493 °C
Be melted thickness	t = 0.3 s	0.6 mm
Minimum water sub-cooling	t = 3 s	31 °C

Thermohydraulic parameters are those defined for the nominal case (T_{water} = 150°C, 40 bars) and the corresponding convective heat transfer coefficient is calculated as a function of the wall temperature.

The main thermal results for the most critical energy dumping - 60 MJ/m^2 in 0.3 s on a 10 mm thick Be tile - can be summarised as follow (see Table 1 and Figure 2) : i) the maximum temperature reached at the Be surface is about 1991°C, which is higher than the melting temperature of Be (1283°C) ; ii) the melted Be thickness is evaluated to 0.6 mm ; iii) the risk of exceeding the CHF is null, as a significant minimum sub-cooling of 31°C is maintained in the coolant flow ; iv) the maximum temperature reached at the Be/stainless steel interface is evaluated at 493°C, reached 2.5 s after the beginning of the transient.

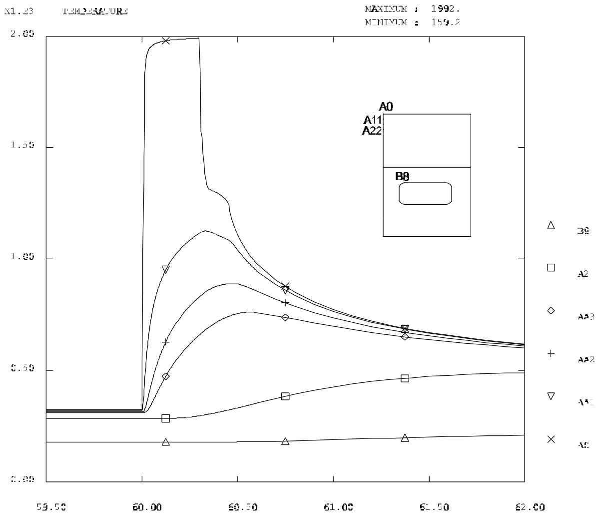

Figure 2 : Thermal transient of the First Wall during high-power VDE (60 MJ/m^2 in 0.3 s).
A0 at front surface, A11 (resp. A22) at 1 (resp. 2) mm from front surface.

These results strongly indicates the interest of considering a large Be protection thickness - at least 10 mm - related to the expected number of VDE encountered by the FW during the EPP of ITER. The choice of a Be/stainless steel interface material, which is strongly related to the maximum temperature reached, should also take into account the temperature increase due to the reduction in thickness of the Be protection during each VDE.

THERMO-MECHANICAL ANALYSIS OF THE BB MODULE BOX

The finite element code CASTEM 2000 has been used to evaluate the transient thermo-mechanical behaviour of the outboard module box during normal cyclic operation [C]. A two-dimensional model of a cross section of an half outboard module #19 box including first wall, cooling plates and shield block has been used and detailed geometry and cooling conditions are given in [C]. Mechanical calculations have been performed using the generalised plane strain option. The transient calculations have been performed assuming the nuclear heating cycle simulating the fusion power ramp-up of a normal operating cycle in ITER [2]. The main results on temperatures and thermal stress level at steady-state are summarised in Table 2.

The maximum temperature of the module box is located at the corner of the first wall and at the back of the side wall. This indicates that cooling circuit design should be now optimised for detailed areas like corners, side walls and shield block. The corresponding thermal stress level shows a stress concentration at the corner of the module box and in the side wall (Figure 3) which is due to stress level induced by the global deformation of the structure. The stress level reaches its maximum of 495 MPa at the corner.

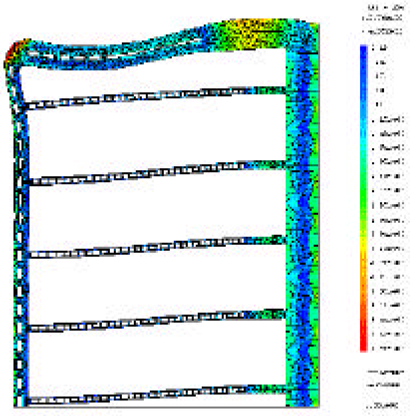

Figure 3 :Von Mises thermal stress (MPa) distribution at steady state under 100% nuclear heating (F_{inc} = 0.5 MW/m^2, NWL = 1.25 MW/m^2). Zoom on the side part of the module

Table 2 : Temperature and von Mises stress level of the outboard module at steady-state under 100% nuclear heating (F_{inc} = 0.5 MW/m^2, NWL = 1.25 MW/m^2)

	T min. (°C)	T average (°C)	T max. (°C)	Von Mises max. (MPa)
First Wall (FW)	150	208	373	495
Cooling Plates (CP)	171	202	285	220
Shield Block (SB)	150	218	278	293
Total Module Box (FW + CP + SB)	150	211	373	495

This study has shown clearly the need to define detailed design of the cooling circuit in shield block, side walls and at the front corner of the stainless steel module box. The thermal stress level in those regions are indeed often very high (~495 MPa) and could be minimised with appropriate design of the cooling circuits.

TRANSIENT THERMO-MECHANICAL ANALYSES OF THE ITER BAFFLE MODULE N°26 [D]

Transient thermo-mechanical analyses have been performed for the ITER baffle, module 26 (lower outboard module) with tungsten-tiles. Calculations concerned the equatorial section of the module (straight part) and didn't take into account the fixing holes. They have been used as the "baffle reference" analyses included in the ITER Comprehensive Design Report edited in July 1998 and which has concluded he ITER EDA period.

Taking into account the typical ITER transient loads (see Table 3), thermal calculations have been performed for two cycles ; the main results are indicated in Table 3, while Fig. 4 shows the temperature distribution in the FW at the end of the first cycle. Elastic and elasto-plastic transient mechanical calculations, with various modeling of the hardening law assumed for the OFHC-layer have been performed after taking into account the thermal evolution.

The main results were that thermal gradients and temperature level have been found acceptable in any part of the structure, and from the thermal-hydraulic point of view, the FW concept presented a large margin against critical heat flux event. The level of stress at the top of the W-tiles being reasonable (less than 600 MPa) even with a 2D generalised plane strain mechanical analysis, the 3D calculation taking into account the 5 mm-thick poloidal castellations has not been judged necessary.

Table 3 : Temperatures reached in baffle materials at various times of the transient calculation

Load Histogram for Baffle analysis (first cycle)						
time (s)	0	150	200	1200	1210	2200
Heat Flux (MW/m^2)	0.12	0.12	3	3	0	0
Nuclear Heating (%)	0	0	100	100	0	0

Thermal transient calculation results (Temperature in °C)					
		t=1200 s	**t=3400 s**	**t=2200 s**	**t=4400 s**
W1%La$_2$O$_3$-tiles	min.	355.9	355.9	140.0	140.0
	ave.	504.2	504.2	140.0	140.0
	max.	652.1	652.1	140.0	140.0
OFHC-layer	min.	343.5	343.5	140.0	140.0
	ave.	352.7	352.7	140.0	140.0
	max.	364.7	364.7	140.0	140.0
DSC-heat sink	min.	227.1	227.1	140.0	140.0
	ave.	271.8	271.8	140.0	140.0
	max.	348.9	348.9	140.0	140.0
SS-liner	min.	191.1	191.1	140.0	140.0
	ave.	239.6	239.6	140.0	140.0
	max.	312.9	312.9	140.0	140.0
SS-shield	min.	181.7	181.7	140.0	140.0
	ave.	**216.0**	**216.1**	141.1	141.1
	max.	265.7	265.7	**149.9**	**150.0**
Total	min.	181.7	181.7	140.0	140.0
	ave.	**224.1**	**224.2**	**141.0**	**141.1**
	max.	652.1	652.1	**149.9**	**150.0**

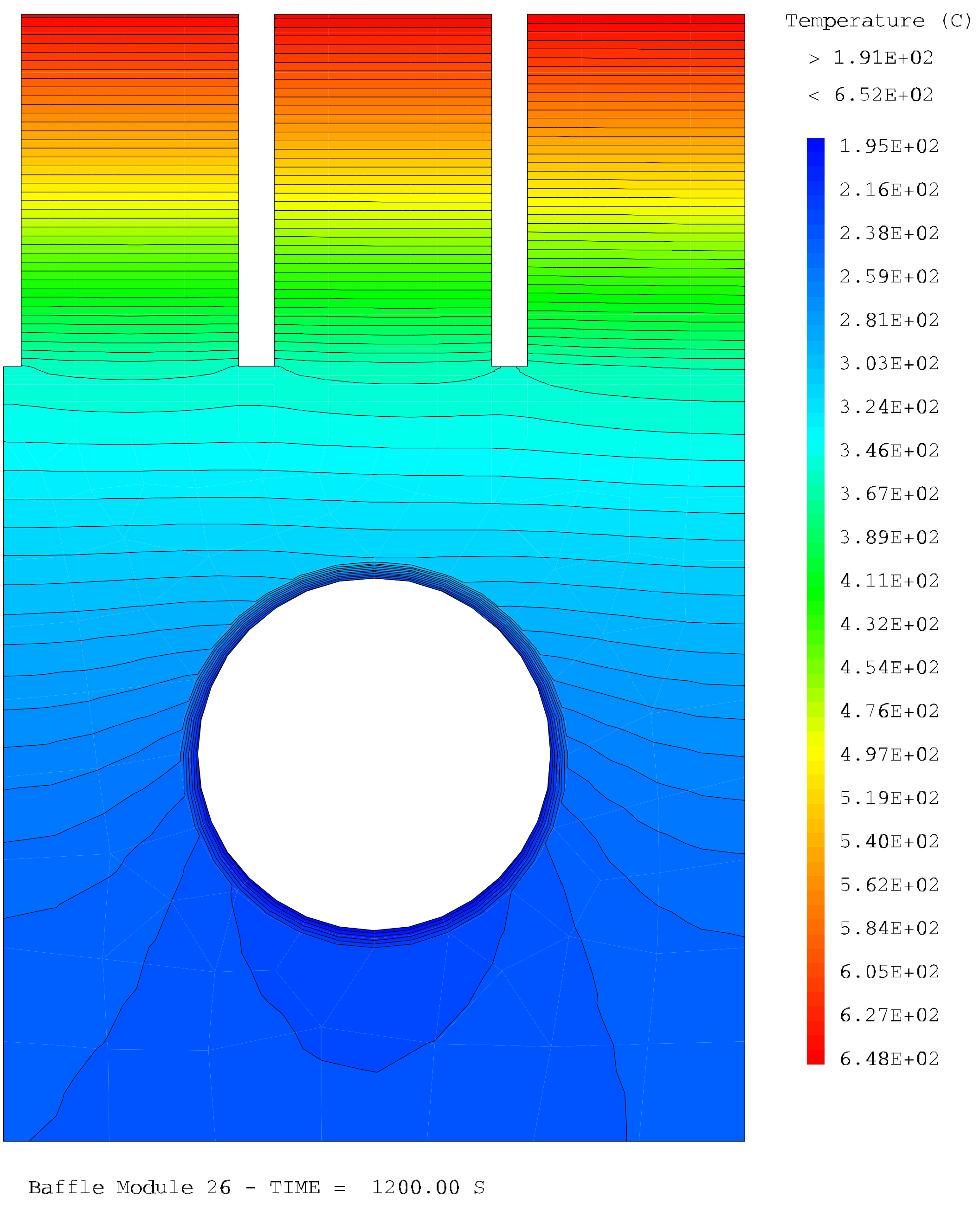

Figure 4 : Baffle transient thermal analysis: temperature distribution in the FW

Von Mises thermal stresses obtained with an elastic calculation are within allowable values (below 3Sm) for the shield, the liner and the major part of the DSC-heat sink. Elasto-plastic analysis has also been performed, in particular because of the high level of stress found in the OFHC compliant layer. SS-liner and DSC-heat sink were also treated with an elasto-plastic model. Relevant fatigue curves necessary to correctly predict lifetime for these materials are not available at present. However, levels of plastic strain found in these calculations are far below those computed for the various high heat flux component mock-ups which have been tested under thermal cycling with success. Even if these conclusions have to be verified with relevant tests and checked when data will be available, plastic strains are considered acceptable. Therefore, suitable fatigue lifetime for this component can be ensured.

CONCLUSIONS

The activities performed within this task have been of significant importance, both for the contribution to the in-vessel components designs and for the understanding of critical issues related, in particular, to the severe conditions to which are submitted the FW of plasma-facing components. Main achievements in 1998 have been the identification of some improvements required for the ITER BB, such as the use of thicker Be-tiles and the need of modifying the BB module box cooling circuit, and the establishment of the reference thermo-mechanical analyses for the ITER baffles. These and past activities in the field of ITER in-vessel components designs have permitted to give significant contribution to papers presented at various 1998 international conferences [E, F, G, H].

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