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CEA-CONF--10732

DEVELOPMENT OF HIGH THERMAL FLUX COMPONENTS FOR CONTINUOUS OPERATION IN TOKAMAKS

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Communication présentée à : 14. Symposium of Fusion Engineering
San Diego, CA (US)
30 Sep - 3 Oct 1991

DEVELOPMENT OF HIGH THERMAL FLUX COMPONENTS FOR CONTINUOUS OPERATION IN TOKAMAKS

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High heat flux plasma facing components are under development and appropriate experimental evaluations have been carried out in order to operate during cycles of several hundred seconds. In Tore Supra, a large tokamak with a plasma nominal duration in excess of 30 seconds, solutions are tested that could be later applied to the NET/ITER tokamak, where peaked heat flux values of 15 MW/m^2 on the divertor plates are foreseen. The proposed concept is a swirl square tube design protected with brazed CFC flat tiles. Development programs and validation tests are presented. The tests results are compared with calculations.

INTRODUCTION

Several design and innovative concepts exist in large tokamaks to remove the deposited power on plasma facing components (PFC). At Tore Supra (TS), studies of high heat flux plasma facing components (which have to operate during duty cycles of several hundred seconds) have led to the development of :

- a concept of square-shaped copper coolant tubes covered with flat CFC tiles,
- thermal hydraulic tests in order to determine heat transfer and critical heat flux conditions,
- carbon fiber composites (CFC) as new low Z materials having high mechanical strength and high thermal conductivity,
- brazing techniques and quality controls of the braze joint,
- a heat flux cycling test program with an electron beam facility.

CONCEPTUAL DESIGN

The armor structure consists of carbon fiber composite flat tiles brazed to a heat sink of dispersion strengthened copper (glidcop Al-25). The heat sink has a square shaped cross section 14 to 23 mm wide. The diameter of the cooling channel varies from 10 to 14 mm (Fig. 1).

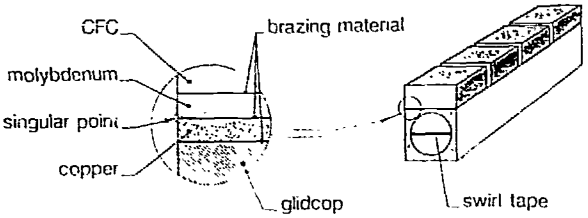


Fig. 1 : Design concept of brazed conductively cooled tiles

A swirl tape is inserted into the cooling channel to improve the heat transfer coefficient and also to increase the critical heat flux in the subcooled regime.

A compliant layer of soft copper (OFHC) compensates, by plastic deformation, the mismatch of thermal expansion between the CFC and the glidcop material during the braze cycle.

A molybdenum layer may be added to avoid crack initiation at the singular point.

This concept is an adaptation of those used in the Tore Supra plasma facing components [1].

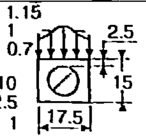
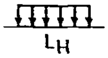
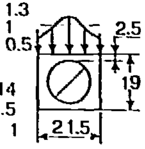
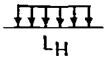
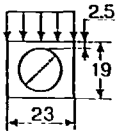
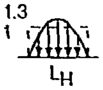
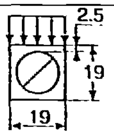
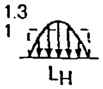
geometry and incident flux profile	longitudinal flux profile		T in (°C)	L_H (mm)	V (m/s)	Pmean (MPa)	W (kW)	ICHF (MW/m²)	WCHF (MW/m²)	tested at
TS 1a  ø10 twist ratio 2.5 tape thickness 1		1)	20	89	6.8	0.2	31.7	22.2	39	CEA
		2)	20	89	3.5	0.2	30.8	21.6	38	
		3)	20	164	3.5	0.2	51.3	20.0	35	
		4)	20	164	8.1	0.2	64.1	>24.0	>42	
		5)	20	109	8.1	0.2	62.7	32.3	56.5	
		6)	20	114	8.1	0.2	63.3	32.5	57	
TS 1b  ø14 twist ratio 2.5 tape thickness 1		1)	20	114	4	0.2	56	29.3	45	CEA
TS 2b  ø14 twist ratio 2 tape thickness 0.8		1)	15	175	9	0.56	108	33	54	JET
		2)	15	175	5	0.85	80	26	43	
		3)	50	175	5	0.87	80	23	38	
TS 2c  ø14 twist ratio 2 tape thickness 0.8		1)	15	175	9	0.56	116	38	52	JET

Table 1 : Test results of critical heat flux
ICHF : Incident heat flux, WCHF estimated wall critical heat flux

THERMAL-HYDRAULIC TESTS AND ANALYSES

Tests of square shaped cooling structures have been performed at CEA in a 200 kW electron beam facility and completed by tests at JET with the Neutral Beam Test Bed Team [2] (Table 1). The goal of the tests was to investigate the heat transfer to the cooling fluid and the critical heat flux.

The tests were carried out at low pressure (0.2 to 0.87 MPa) and low inlet temperature (15 to 50°C). The water longitudinal velocity ranged from 3.5 to 9 m/s (see table 1). The minimum copper thickness between the exposed surface and the cooling channel was 2.5 mm.

A square tube (23 mm width, 14 mm internal diameter) heated over a length of 175 mm removed 108 kW without water burn-out. This represents an incident thermal flux up to 33 MW/m². Another series of tubes (17 mm w., 10 mm i.d.) removed 63 kW without failure and sustained an incident thermal flux of 32 MW/m² over the 109 mm of tested length. The above values correspond to critical heat fluxes at the water channel boundary in the range of 54 MW/m² which is in good agreement with the Tong 75 CHF correlation [3] (Fig. 2).

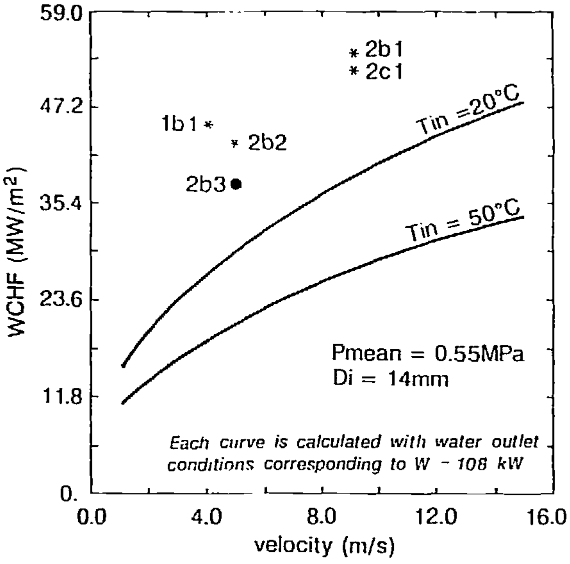


Fig. 2 : TONG 75
Correlation for 1b, 2b and 2c tests
(* • experimental results)

All tests were accompanied by finite elements calculations (FEM) using 2D analysis with isoparametric 8 noded elements. Materials were taken as temperature dependant. The heat transfer coefficient in the turbulent regime was increased taking into account an equivalent hydraulic diameter, a corrected water velocity and a fin effect factor. In addition a wall temperature dependency in the subcooled regime was calculated by Thom correlation [2] [4] (Fig. 3).

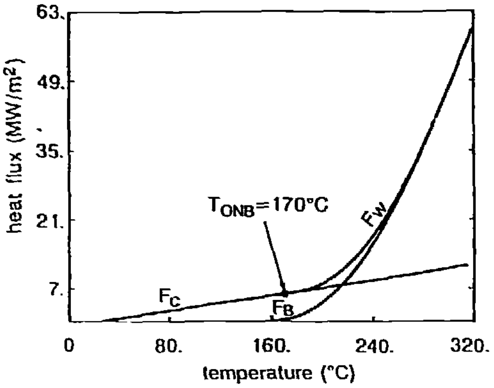


Fig. 3 : Wall heat fluxes versus Tw
(F_C : Convective flux ; F_B : Boiling flux)

The FEM calculations were done with an iterative method using the CASTEM 2000 Code [5].

The steady state temperatures were calculated at each increasing step of the test power density and compared with those measured in the cooling structure side wall (Fig. 4 and 5). Good agreement was found.

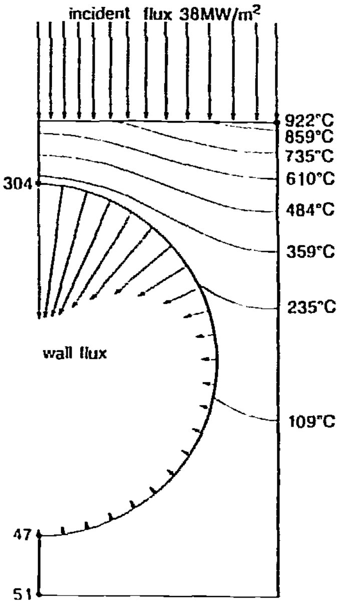


Fig. 4 : Temperature isovalues and heat fluxes, TS 2c (tube width 19 mm, cooling channel diam. 14 mm, wall thickness 2.5 mm).

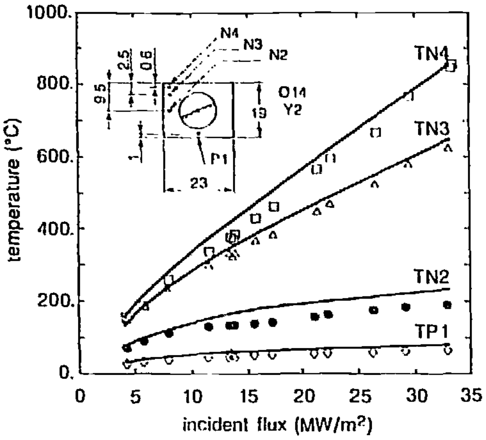


Fig. 5 : Side wall temperature versus incident heat flux.
Typical comparison between measurement (□ △ ● ◇)
and F.E. calculations (——)

DEVELOPMENT OF CARBON FIBER COMPOSITES

Carbon fiber composites (CFC), as low Z materials, were chosen for their better thermal conductivity and superior thermal shock resistance.

Two CFC materials have been developed in France :

- Aerolor A05 fabricated by "Le Carbone Lorraine",
- Sepcarb N112 fabricated by "Sep-Bordeaux".

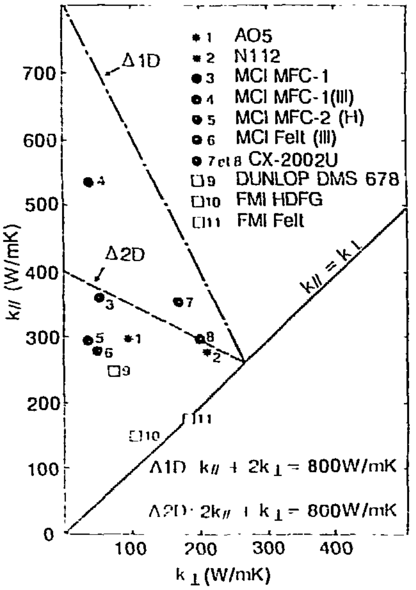


Fig. 6 : Typical thermal conductivity of high conductive C/C composites and carbon materials

	Density (10^3 kg /m^3)	Specific heat (10^3 J /kg °C)	Thermal conductivity at room temperature (W/m/°C)		Thermal expansion coefficient (10^{-6}/°C)		Bending strength /tensile strength (MPa)		Shearing strength (MPa)	
			k//	k⊥	α//	α⊥	σ//	σ⊥	σ//	σ⊥
MCI MFC-1	1.83	0.72	361	51	- 0.9	8.3	250	8.2	--	--
MCI 'MFC-1 (III)	1.98	0.71	535	35	- 0.6	4.3	350	10	--	--
CX - 2002U	1.74	--	350 300	160 200	1.9	7.07	--	61	--	22*
Sep N112	1.95	0.75	280	210	2.0	2	/65	/35	40	30
A05	1.70	0.88	285	100	1.1	8	/54	/9	42	19

// Direction mainly parallel to carbon fibers [x (and y) direction]

⊥ Direction mainly perpendicular to carbon fibers [z direction]

* *measured by CEA.*

Table 2 : Typical properties of high conductive C/C composites

The first is a random fiber composite, the structure of the second is made of woven layers needled to each other by PAN fibers.

These two materials are compared in Fig. 6 and Table 2 with other composites at room temperature.

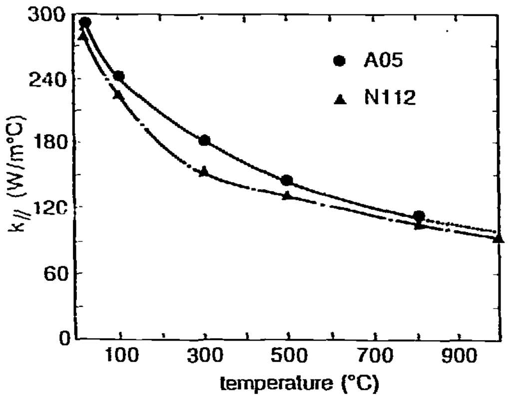


Fig. 7 : Typical parallel thermal conductivity versus temperature k// (W/m°C)

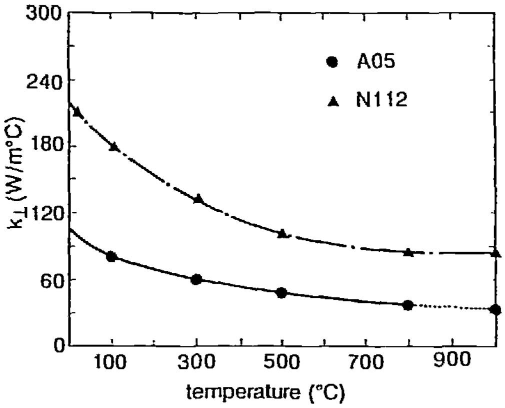


Fig. 8 : Typical perpendicular thermal conductivity versus temperature

The N112 CFC is close to an isotropic material.

Fig. 7 and 8 show a comparison of the conductivities versus temperature.

The tensile stress-strength curve of N112 is given in Fig. 9 at room and maximal working temperatures.

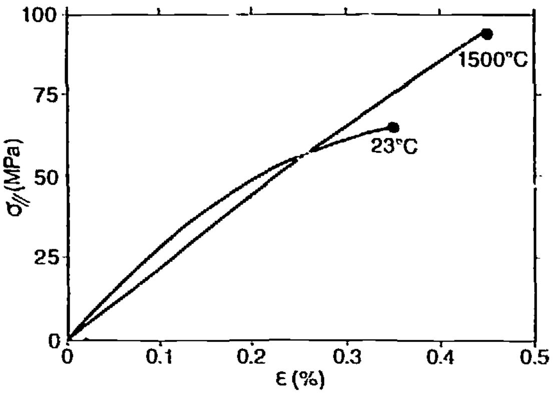


Fig. 9 : Tensile stress-strain curves at room temperature and at 1500°C in X direction for Sepcarb N112

BRAZING TECHNIQUES AND QUALITY CONTROL

In Tore Supra the inner first wall is made of 5890/PT graphite flat tiles brazed to a stainless square tube [1]. Brazed semi-cylindrical tiles were also used on other plasma facing components but it was always more difficult to obtain a good quality brazing. This led to the choice of flat tiles for the NET/ITER divertor.

For each component, special brazing tools were developed allowing sufficiently high pressure (> 2 bars) on each tile during the brazing cycle.

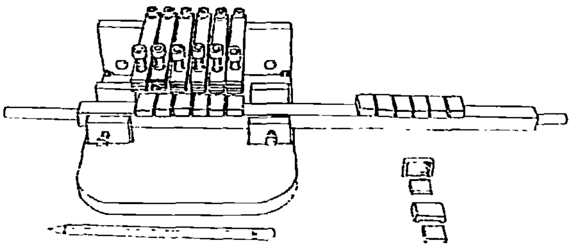


Fig. 10 : Net divertor model and brazing jig (Tiles and compliant layers are machined in such a way as to remain in the correct position.)

All brazing is done using TICUSIL and TICUNI braze materials with melting points $T_m \geq 900°C$.

An appropriate thermal cycle is used in accordance with the metallurgical requirements of the different materials.

In order to verify the mechanical integrity of the tiles and of the joint, destructive and non-destructive tests have been applied.

Destructive tests

The following test means were used during the brazing development campaign :
- micrography (Fig. 11).
- measurement of the ultimate shear stress at the braze joint (Table 3).

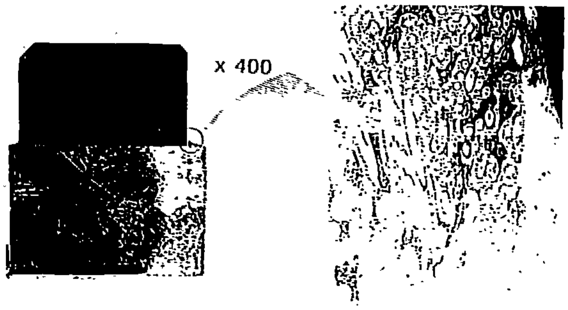
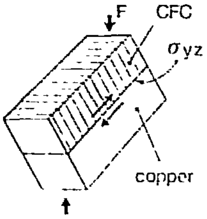


Fig. 11 : Micrography of A05 braze on OFHC-Cu block showing crack near the singular point



CFC	σyz with Mo MPa	σyz without Mo MPa
N112	37.8 33	36 28.6
A05	22 23.6	24 25.4

Table 3 : Ultimate shear stress value at the brazing joint (room temperature)

Different destructive tests have shown the following defects :
- unbrazed areas,
- localized cracks or propagated cracks.

Propagated cracks in the graphite material were mostly avoided in Tore Supra where ~ 7500 flat rectangular tiles were brazed using molybdenum and cooper compliant layers. The goal of the brazing development program is to optimize the brazing procedure and the component geometry at the point of singularity as well as the layer thickness (Fig. 12).

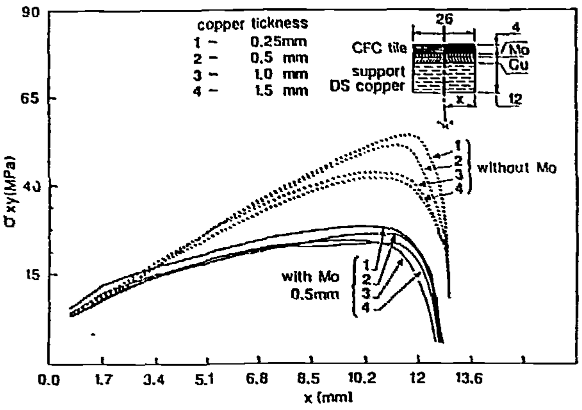


Fig. 12 : F.E. calculated brazing-induced shear stresses in a typical neutralizer graphite tile as a function of compliant layer thickness. A thermal dependent perfect plastic behaviour is taken into account for copper during the cooling cycle.

Non-destructive tests

The aim of these tests is to check the PFCs before their in-vessel installation. The following tests have been used for the Tore Supra components :

- visual inspection and sound testing,
- infrared testing,
- focused ultrasonic testing.

An infrared test image of a TS inner first wall section is shown in Fig. 13. The infrared method is based on the detection of delayed heated areas on the tile surface when a hot or cold water flow is applied in the cooling structure.

Fig. 14 shows a ultrasonic test image of semi-cylindrical tiles. Tiles are 2.5 mm thick.

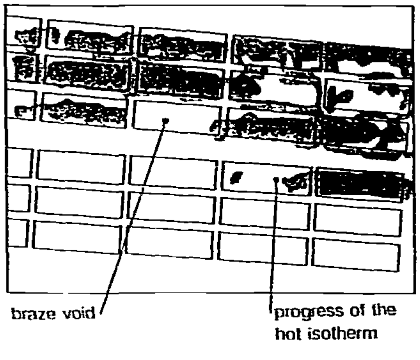


Fig. 13 : Infrared testing of inner first-wall graphite tiles showing delayed heated areas

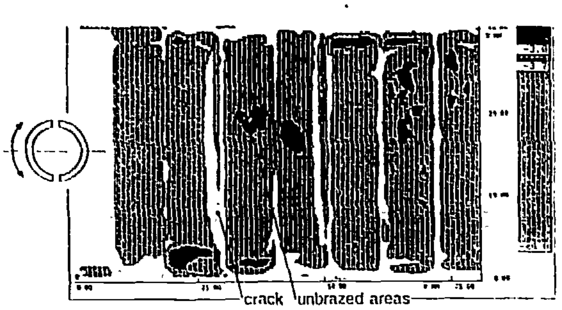


Fig. 14 : Focused ultrasonic testing of semi-cylindrical pump limiter tiles

HEAT FLUX TESTING

The aim is to determine the fatigue limit of the first wall armor structure under high heat flux conditions, representative of those expected on the NET divertor. Therefore the CEA and FRAMATOME have developed an electron beam facility of 200 kW with a pressurized coolant loop (P_{max} = 4 MPa, $T_{inlet-max}$ = 230°C, G_{max} = 1.6 kg/s).

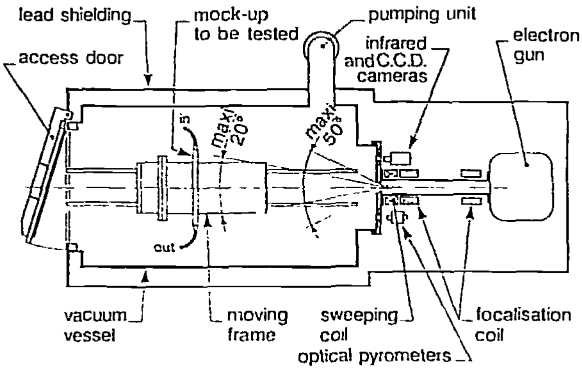


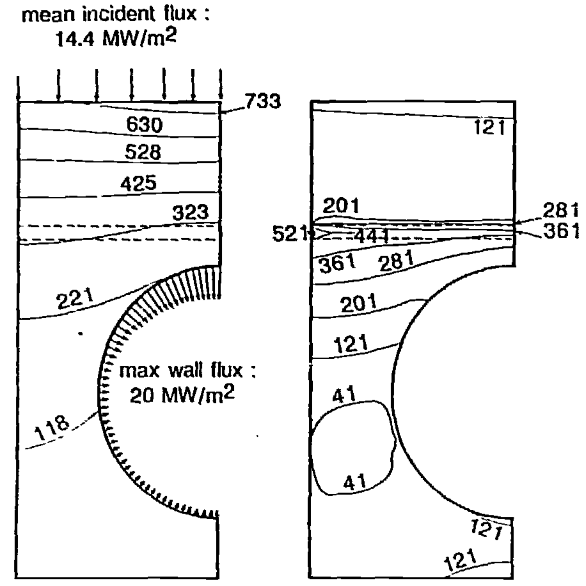
Fig. 15 : EB 200 facility copper view

The size of the chamber is such that a 2 m long divertor element can be introduced and tested with a heat flux of 20 MW/m^2 over an area of 0.50 × 0.02 m^2.

A target prototype (Fig. 10) made of DSCu and A05 tiles (length 20 cm) has been tested without failure under a mean incident thermal flux of 15 MW/m^2 with a surface temperature of 1400°C (after 10 cycles of 30 s pulse length).

The total power removed per tube (56 kW) was more than twice the value which is expected to be deposited on one tube of the Net divertor outer plate during the physics phase.

All tests are generally accompanied by thermal-hydraulic and mechanical calculations (Fig. 16 and 17).



temperature isovalues (°C) Von Mises stresses (MPa)

Fig. 16 and 17 : Thermohydraulic calculation accompanied by an elastic calculation (generalized plane strain conditions ; the initial stresses due to the brazing cycle are not taken into account)

DEVELOPMENT OF THIS CONCEPT IN TORE SUPRA

The concept of CFC flat tiles brazed on DS copper square tubes with a swirl tape inside the coolant channel will be tested in a new version of TS pump limiters (Fig. 18).

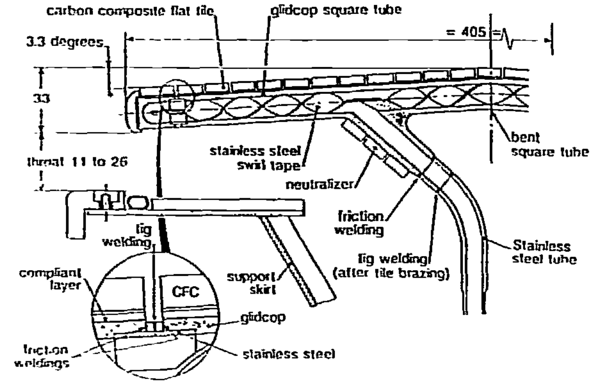


Fig. 18 : Counterflow tube design of the vertical pump limiter of Tore Supra

CONCLUSION

High heat flux candidate structures of square shaped dispersion strengthened copper tubes with heat transfer enhanced swirl tape inserted into the cooling channel have been successfully tested in the CEA-FRAMATOME EB facility and in the NB test bed at JET. An incident power deposition up to 33 MW/m^2 has been removed without damage.

CFC materials manufactured by Carbone Lorraine and SEP have been brazed to OFHC copper substrata. Despite the stress singularity at the braze joint, the concept appears promising based on these first results.

CFC flat tiles brazed on these same cooling structures have successfully withstood incident heat fluxes up to 15 MW/m^2.

The installation of high heat flux structures in the Tore Supra tokamak will complement these studies in a plasma environment.

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