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# Actively Cooled Plasma Facing Components for Long Pulse High Power Operation*

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## Abstract

This paper reviews the development of heat removal technology for water cooled plasma facing components (PFCs) and focuses on near term, high power applications and the experience from Tore Supra, LHD and ITER. Water-cooled PFCs with C armor have been developed for Tore Supra, ITER, LHD and W7-X. W or Be armor is of interest for ITER and other devices. Reliably joining of the armor has been a significant challenge.

## Keywords:

high heat flux, divertor, armor, plasma facing component

## 1. Introduction

A fusion device with long pulse and high power requires continuous active cooling to remove heat from its plasma facing components (PFCs). Tore Supra has led the way, and neutral beams in JET (Joint European Torus) have operated with water-cooled hypervapotron targets since 1986. Actively cooled PFCs are being used in the Large Helical Device (LHD) and are planned for the modular divertor in Wendelstein 7-X [1-3] and for the second phase of KSTAR [4] (Korea Superconducting Tokamak Advanced Research Project). There has also been development for ITER (International Thermonuclear Experimental Reactor).

The problem of obtaining reliable and repeatable armor joints was well known to those who developed the early actively cooled PFCs. As multi-disciplined research on the divertors for NET and ITER involved institutions world wide, the "joining challenge" gained wider recognition. Thermal-hydraulic performance is another key area. This paper first describes the thermal-hydraulics related to high power heat removal, then reviews the development of actively cooled PFCs for Tore Supra, LHD, and ITER.

## 2. The Inside Story: Thermal-hydraulics

Fusion PFCs, unlike most heat exchangers, are heated from one side. Convection, transition boiling and subcooled boiling can occur simultaneously at different locations around the coolant channel. The large databases and widely used correlations in thermal-hydraulics were inadequate for the one-sided heating applications in fusion, and the extension of this area of research over the last 15 years by the fusion program has been impressive.

The critical heat flux, or CHF, is often what limits a PFC's performance. We confirm values of CHF experimentally for each heat sink configuration and set of water conditions.

At the CHF, excessive vapor inhibits heat transfer at the wall (sketch b, Fig. 1), its temperature rises to

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sustain the heat flow, and typically the heat sink melts (burnout).

Fig. 1 shows heat flux into the coolant (4.2 MPa, 10 m/s) versus the wall temperature for a 10 mm channel (code by Marshall [5]). In the top curve, for water at 25°C and a twisted tape (twist ratio 2), the CHF is nearly 100 MW/m$^2$ and the heat transfer coefficient (slope of curve) is high over the large range for sub-cooled boiling. At higher heat loads, the fraction of heat flowing through the portion of wall cooled by sub-cooled boiling increases, so the pattern of heat flow changes.

The use of hot water greatly diminishes the range of sub-cooled boiling heat transfer and the performance of the heat sink. The lower curves are for a bulk water temperature of 150°C with and without a twisted tape. The twisted tape increases the CHF by about a factor of two.

Developing a sound database on heat transfer and CHF for one-sided heating has taken a significant and sustained effort for many years. It began with data for uniformly heated channels, but differences were found [6-10], e.g., for large sub-cooling, CHF in one-sided heating experiments was about twice that from predictions using Tong [11].

In the 1980's, initial development of water-cooled PFCs for Tore Supra [9-13] and hypervapotrons for JET [14] was done. In the 1990's, thermal-hydraulics testing was done for new PFCs for Tore Supra [9,10,15-20] and for NET and ITER. Falter and others tested hypervapotrons for ITER and NET [14,21-23]. The Russians extended these data [24] and introduced porous coatings to promote turbulence that enhanced CHF by 40–50% [25]. Dual parallel channels with twisted tapes, larger channels with helical wire inserts and annular flow, and circular channels with screw threads were among many configurations tested.

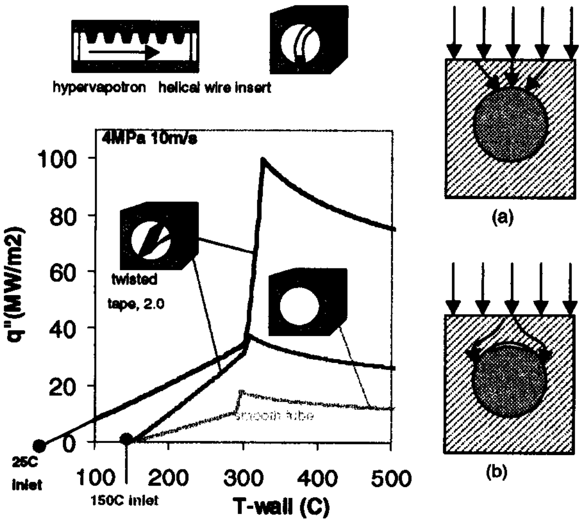

Fig 1. Heat flux at the coolant-wall interface (q") vs. temperature at this location; also several types of heat sinks.

In the early 1990's, Schlosser and Boscary [16,17], analyzed data from 17 series of tests on channels with twisted tape inserts and smooth channels. They compared their data and thermal analyses with well-established thermal-hydraulic correlations and large databases for uniform heating. The best agreement was with Seider-Tate (convection) and Thom CEA (sub-cooled boiling); a modification of Tong 75 ($CHF^* = CHF_{Tong75} / 0.6$) fit their data for CHF over a large range of sub-cooling. After 103 more tests in 1995–96, they differentiated between the incident heat flux at CHF and the CHF defined at the coolant interface [26] and found enhancement factors (compared to Tong 75) of 1.97 and 1.84 for hypervapotrons, 1.67 and 1.44 for dual channels with twisted tapes, 1.3 and 1.57 for two annular flow designs and 1.16 for a smooth tube.

Steady state heat fluxes significantly higher than the nominal CHF are even possible [27,28] due to a "post-CHF regime" unique to one-sided heating. Above the CHF, heat flows further around the sides of the channel to reach areas where sub-cooled boiling still occurs, e.g., b in Fig. 1.

## 3. Tore Supra PFCs

Long pulse operation with 25 MW of input power is a central goal for Tore Supra. A water loop (4 MPa) provides cooling for limiters and the inner wall, typically at 120°C, and is utilized for baking at up to 230°C. The primary heat sinks were the inner wall and a set of modular limiters that included the Phase-III (water-cooled) vertical pump limiters and a Phase-III version of a retractable modular mid-plane limiter (Outboard Pump Limiter or OPL). The OPL was designed to receive 2 MW with ~10 MW/m$^2$ on its face and up to 30 MW/m$^2$ on a leading edge, cooled by a separate 50°C water loop [29]. Ref. 30 summarizes the experience from operating these PFCs and dicusses water leaks, calorimetry, infrared monitoring of the components, interlocks and safety, and operation of the PFCs.

One important lesson was that the quality of the joints between the armor tiles and heat sinks was crucial. Local hot spots due to braze flaws significantly limited the heat removal possible in Tore Supra. As the problem became apparent, efforts to improve quality control were instituted. Vertical limiters were rebuilt, and before replacement of the first wall (part of the CIEL), 40% of the inner bumper was replaced with parts made with more rigorous quality control to confirm that better performance could be obtained [31].

A second important lesson was the vulnerability of modular limiters in Tore Supra to damage from runaway electrons. The potential for such damage was recognized. The OPL was designed with the coolant tubes in the leading edge ~15 mm back from the last closed flux surface so that, as runaways drifted radially outward, scattering from many toroidal passes through increasing amounts of graphite in the center crown of the OPL would protect the leading edge from damage. This was not the case. Damage to a leading edge tube by outward motion in one or a few toroidal passes terminated use of the OPL-III [32].

Another lesson dealt with rapid recognition of signals from interlocks on the OPL. When inlet water to the leading edge exceeded 50°C, the water control system issued a "stop shot" prompt and stopped water flow to the OPL. The main control system did not recognize the prompt in time to stop the shot, and the OPL leading edge overheated. This occurred as a new control system for Tore Supra was being developed [33] and contributed to the overall assessments being done to improve that system.

A major rebuild of Tore Supra's vessel (CIEL) with a new first wall, guards for antennae and a toroidal limiter [34,35] is in progress. In launching this ambitious project, the Tore Supra team continues its development of actively-cooled PFCs [36-41]. Joining in the "fingers" of the toroidal limiter involves flat surfaces (except at the end of the element) because experience has shown this type of joint to be reliable in fabrication and performance. In the design 10 MW is radiated and 15 MW goes to the limiter with heat fluxes of 5 MW/m$^2$ on flat surfaces and 8 MW/m$^2$ on the toroidal leading edge. Tests [31] with 3500 cycles at 10 MW/m$^2$ and 1000 cycles at 14 MW/m$^2$ show that reliable performance can be expected, but that some damage may accumulate slowly at the higher heat fluxes. To fabricate the fingers, the joining surface of the CFC (carbon fiber composite) is first infiltrated with thick copper layer using a technique developed by Plansee, Inc. [42] which has been used successfully to develop robust, high performance PFC mockups for Tore Supra, NET and ITER. The copper layer can then be brazed or electron-beam-welded with a deep penetration weld along the edges to the CuCrZr heat sink.

Procurement of fingers for the CIEL toroidal limiter is a change from a one-of-a-kind part to a production lot of many units (576 fingers in the limiter). One desires in such a "scale up" that both project and vendor have confidence that repeatable fabrication processes with verifiable quality is not only possible but the expected outcome. This issue of quality, an important one in assessing the "readiness" to proceed with facilities that will utilize actively-cooled PFCS, is discussed again later.

## 4. LHD Divertor Plates

Long pulse high power operation is part of the mission of LHD (Large Helical Device), a large stellerator (R, 3.9 m; plasma, 30 m$^3$) located at the National Institute for Fusion Science in Toki, Japan. LHD began operation in 1998 [43] and has a "natural" divertor in the spaces that lie poloidally between the Dewars for the two superconducting helical coils. The relatively large divertor in relation to the plasma volume means that high power steady state operations can be sustained with moderate heat loads on the divertor.

A divertor capable of sustaining a steady state heat load of ~0.5 MW/m$^2$ with CFC tiles clamped to a stainless steel (SS) cooling pipe (Fig. 3) has been deployed for the initial phase of operation [1]. The carbon armor is bolted to a copper backing plate. A stainless steel (SS) plate clamps the copper and an interlayer of compliant graphite sheet to the SS pipe. Repeated deformation under thermal cycling of a mechanical joint is always a concern. The limiting heat flux here is due to distortion of the copper plate if its temperature exceeds ~300°C [44-46].

A divertor design like a helical ladder with brazed CFC armor elements was explored for the second phase of LHD [47]. Also, there has been some exploration of W-coated tiles. But Kubota's continuing progress on clamped tiles has been so impressive that this design is now considered the reference for LHD Phase II. "Super mechanically joined modules" can sustain steady state heat loads of nearly 4 MW/m$^2$ and accept 2 MW/m$^2$ in thermal cycling. [44] A new design uses CX-2002U (a CFC) for both the armor and backing plate and a "super graphite" sheet made by Matsushita Co., Ltd. as a compliant layer. Use of a copper cooling pipe in this design rather than SS has extended the capability by about a factor of two.

## 5. Water Cooled PFCs for ITER

ITER's requirements for PFCs (thick armor to mitigate against erosion, handling tritium, radiation damage and remote maintenance) complicate the already challenging task of developing robust PFCs. The design, analysis and testing of heat sinks for the ITER divertor[48-50] has been an extensive effort, with particular attention to joints between the armor and heat sink [2,23,51-75] and only a brief review with examples can be given here.

Heat sinks for high power water-cooled PFCs are typically copper. Its high conductivity minimizes the temperatures of the armor joint and plasma facing surface. ITER heat sinks must have sufficient strength in fatigue and creep to contain the coolant at 4.2 MPa and withstand stresses from repeated heat loads of 15–20 MW/m$^2$ and large mechanical loads from disruptions. A precipitation-hardened alloy, CuCrZr, is now preferred for ITER heat sinks, and its aging during armor joining processes has been studied [51]. Dispersion strengthened copper (DSCu), copper-nickel beryllium alloys [52] and TZM [53,54] were also studied.

ITER armor must withstand transient heating events, e.g., from energetic runaway electrons and plasma disruptions (in tokamaks), and be thick enough to mitigate erosion. Be (beryllium), CFC, or W (tungsten) armor in thicknesses of 5–30 mm have been evaluated for ITER. Differing thermal expansion of the armor and heat sink causes residual stresses from fabrication and thermal stresses in service.

Lower fabrication temperatures using hot isostatic pressing (HIPping), compliant interlayers, materials with graded compositions, "monoblock" armor, and division of armor into cells (castellation) were investigated to mitigate against the concerns above. Watson [68] showed that only a relatively fine cell size (< 5 mm) would substantially reduce thermal stresses in armor. "Soft" joints [64,69] were studied.

The choice of Be armor for the ITER first wall was based on its use in JET. Castellated armor was developed [21,54] for the upper divertor (baffle region). The primary limitation is its relatively low melting point, 1283°C. Be and Cu form inter-metallics, and diffusion barriers are used at joints. Joining of Be armor or plasma spraying to copper heat sinks was studied for the first wall in NET and ITER [61-67,70,76-85]. Be lamellae have also been studied [86]. Work was often presented at "Beryllium Workshops" [85].

Carbon armor, used in most large confinement experiments, sublimes rather than melts under extreme heat, is a low-Z plasma impurity and, when properly conditioned, rapidly pumps hydrogen. (Codeposition of tritium with carbon is a concern for ITER [87].) Pyrolytic graphite and high quality fibers have high thermal conductivity (400–800 W/m-K), but this drops as the temperature increases and with even low neutron dose (< 0.1dpa). Various CFCs and armor types have been tested [21,22,57,59,63,64,73-75,86]. The CFC monoblock design (Fig. 2) favored by the EU ITER Team reduces thermal stresses and, by locking the tile onto the tube, prevents loss of a tile and overheating of an adjacent tile. To accommodate the large net thermal expansion, the heat sink slides on a backing plate. A medium scale divertor prototype (monoblock section) was tested to 2000 cycles at 20 MW/m$^2$ and at 25–28 MW/m2 for a few cycles [73]. JAERI has tested several mockups with CFC "saddle block" armor for 1000 cycles at 20 MW/m$^2$ [75]. A medium-scale mockup with CFC armor and W armor (each on half the length as in the ITER divertor design and EU prototype) tested at 5 MW/m$^2$ failed in the DSCu tube at the boundary between the two armor types after 400 cycles.

W armor has been proposed for the lower portion of the ITER divertor where the edge temperature and

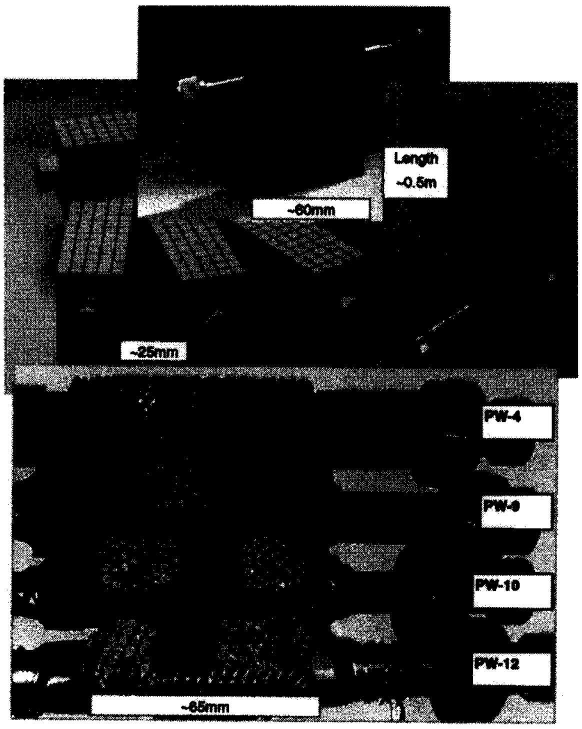

Fig. 2 Mockups by EU (above) and US (below).

particle flow are such that eroded W will redeposit without significant W impurity flow back into the core plasma. Initial studies on W armor tiles showed the need to accommodate severe thermal strains, and the use of interlayers [88] and graded or multi-layer material [89] were investigated. Lanthanated W is generally preferred because it fabricates more easily than pure W and is available in several forms. W armor applied by plasma spray [89,90] or CVD [75,91] has been tested. The US led the way in developing W "brush" armor [68,71] for ITER. US mockups armored with 3.2 mm W rods have performed well in thermal cycling tests. For example, US mockups PW-4 and PW-9 (Fig. 2) received 500 thermal cycles at heat fluxes up to ~22 MW/m$^2$. The higher heat fluxes initially reported have been revised after subsequent testing with a larger heated areas. The results are still very impressive [72].

The EU has tested mockups with W lamellae or "brush" armor [63,68,73,92,93]. A mockup with W macro-brush armor withstood 2000 cycles at 15 MW/m$^2$; 3 tiles failed after 1000 cycles [73]. A prototype for the ITER divertor wing with plasma sprayed W armor 5 mm thick was fabricated and successfully tested in thermal cycling [90]. A Japanese mockup with 5 mm CVD-W tiles on a W-Cu heat sink survived 1000 cycles at 5 MW/m$^2$ and a steady heat flux of 15 MW/m$^2$; tiles detached at 20 MW/m$^2$ [75,94].

Russian mockups with W in various grades as castellated blocks, single crystals, and lamellae have been tested in Russia and at Sandia National Laboratories [74]. They have used "fast brazing" to maintain the properties of the CuCrZr heat sink in joining W or Be [67] armor.

Development for ITER included fabrication of divertor cassette prototypes. The primary issues addressed were the accuracy of surfaces for the PFCs and the mounts for the cassette itself, the pressure drop through the network of internal cooling channels and the fabrication costs. The "classical solution" for the large (25 tons) cassettes for ITER was to machine and weld large pieces of SS, as was done for the EU prototype [73]. The cassette body for the US cassette prototype was made by a precision casting process. This prototype was a first-of-a-kind procurement used to confirm that precision casting could be used to make a full size cassette body and that its accuracy would result in a net savings by reducing machining costs [95, 96].

## 6. Some Comments on Quality

Deploying PFCs in any fusion experiment with long pulse, high power operation is a significant challenge and implies a commitment to confirm their quality. We confirm quality in the designs by anticipating the operating conditions and showing through analysis and testing that we can expect acceptable performance. We confirm quality in production by appropriate specifications and documentation and through examination and testing procedures, for example by specifying a maximum flaw size in the armor joint that is known to be both detectable and acceptable. We confirm quality in performance by providing an adequate operating system and monitoring surface temperatures, water conditions, plasma edge conditions, etc.

Let us look at some examples of these aspects of quality. The technology for the first wave of actively-cooled PFCs relied on graphite or CFC armor brazed to a heat sink made of oxygen free high conductivity copper (OFHC Cu), or a copper alloy (e.g., CuCrZr or DSCu). High thermal conductivity in the materials was desired to keep the surface temperature of the armor as low as possible. Brazing the armor and heat sink was a problem because the thermal expansion coefficient is high for Cu and much less for graphites. For example, the Tore Supra OPL-III, made by Sandia National Laboratories, had several hundred pyrolytic graphite (PG) saddle block tiles brazed to 14 OFHC Cu tubes. From 25°C to 930°C, used for a reactive metal braze such as TiCuSil, a 0.5 m-long Cu tube would grow in length by ~10 mm. During cooling, differential thermal strain would cause yielding in the Cu tubes and large residual stresses, and even pull the tube apart [97].

Although the brazing was difficult, with complex fixtures and hand fitting, and produced flaws - a typical braze flaw was a void under the center of the "saddle," the design was quite tolerant of even large flaws [98,99]. For example, at an absorbed heat load of 10 MW/m$^2$ on the face of the limiter, for a tile with a centered braze flaw covering more than half the braze surface, the peak local heat flux at the coolant interface increased from 18 to only 20 MW/m$^2$.

Assessing the size of the braze flaws was another aspect of the quality assurance. A non-destructive method using infrared thermography and rapid transient heating of an armored tube was developed for this purpose [98]. A similar method was used later by CEA to evaluate other components for Tore Supra [100].

Making "one-of-a-kind" items like the one above may be successful through exceptional care by individuals in maintaining process conditions, such as hand fitting joints, preparing the coatings on surfaces for joining, controlling temperature variations in a braze furnace, or cleaning of a sample before hot isostatic pressing (HIPping). A one-time procurement is likely to include development, trial samples and testing. To qualify a vendor, one must then (a) verify that the same degree of control will be possible and is likely to be provided, and (b) require checkpoints, inspections, samples and documentation by which the vendor can verify the product.

A change in scale from fabrication of one or a few components for research to the production of hundreds or thousands of parts, such as the procurement of the 574 "fingers" for the CIEL toroidal limiter requires vigilance in addition to that previously described. One must verify that the lots of materials have the same properties as the lot used for development, that cleaning solutions and procedures will continue to be the same in the production run as for development samples, that resupply of any materials or change of suppliers does not introduce unwanted changes, etc.

Before CIEL, CEA already had experience building (and replacing) PFCs for Tore Supra. This included, for example, reducing variability in CuCrZr by setting stricter limits on the composition of minority elements than the industry standard and identifying appropriate suppliers, and learning that controls in commercial brazing operations were not sufficient for their purposes. Through the 1990's the CEA team developed a preferred configuration (e.g., flat tiles and dual channels with twisted tapes) for their heat sink and worked with Plansee, Inc. who introduced active metal casting for preparing armor and also X-ray inspection techniques to assess the integrity of the joint between the armor and heat sink [42].

A complete review of water-cooled PFCs for high power, long pulse applications (not possible here) would also discuss the quality of operation of the PFCs. This involves the systems to monitor and control the coolant, diagnostics to monitor the plasma edge and the peformance of the PFCs, procedures to identify when overheating of a PFC occurs, and evaluation and decision making to assess the consequences of poor performance. For example, complete and continuous monitoring, such as full coverage by IR cameras and temperature set point alarms, may be an overwhelming burden. A likely compromise is to document some reference responses in the PFCs and then monitor intermittently to identify problems. Provisions to minimize damage to equipment and down time from water leaks is another necessity. Again, the experience from Tore Supra is a starting point and we are informed by the continuing progress on Tore Supra, LHD and ITER.

## 7. Closing Comments

Our PFCs have evolved. Joining problems are being minimized by clever designs (brush armor and sliding heat sinks) and low temperature fabrication techniques (HIPping and e-beam welding). The CIEL and development for ITER are also providing information on the cost of deploying advanced PFCs. These developments indicate we can deliver robust PFCs for long pulse, high power fusion devices.

Many of the advances in PFCs have come through strong continuing collaborations between industry and the laboratories and universities in fusion. These partnerships with industry promote an infusion of good ideas from all sides, including the ability of the fusion program to draw upon technology being applied elsewhere. Overlapping of experience and new ideas through strong continuing collaborations that also draw in new talent is important.

This paper reviewed water-cooled PFCs for near term applications. For future fusion power, such technology will likely not be relevant. The desire for high efficiency in power conversion may lead to solutions with helium as the preferred coolant, as in the ARIES-AT design study [101]; and novel applications using flowing liquid surfaces are under exploration in the APEX and ALPS Programs in the US [102,103].

Today, however, water-cooled heat sinks are still very much needed to realize high power long pulse operation in current and near term experiments. Recent progress in developing water-cooled plasma facing components indicates that we are meeting this challenge.

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*abbreviations
JNM: Journal of Nuclear Materials
SOFT: __th Symp. On Fusion Techn., Elsevier
SOFE95: 16th IEEE/NPSS Symp. on Fus. Eng., ISBN 0-7803-2926-4 (1996); SOFE97: 17th IEEE/..... ISBN 0-7803-4226-7 (1998); SOFE99: 18th IEEE/.... to be pub.
ISFNT99: 5th Int. Symp. on Fus. Nucl. Tech., to be pub.