High Quality Actively Cooled Plasma Facing Components for Fusion

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This paper interweaves some suggestions for developing actively-cooled PFCs (plasma facing components) for future fusion devices with supporting examples taken from the design, fabrication and operation of Tore Supra's Phase III Outboard Pump Limiter (OPL). This actively-cooled midplane limiter, designed for heat and particle removal during long pulse operation, has been operated in essentially thermally steady state conditions. From experience with testing to identify braze flaws in the OPL, recommendations are made to analyze the impact of joining flaws on thermal-hydraulic performance of PFCs and to validate a method of inspection for such flaws early in the design development. Capability for extensive in-service monitoring of future PFCs is also recommended and the extensive calorimetry and IR thermography used to confirm and update safe operating limits for power handling of the OPL are reviewed.

1. Introduction

As fusion progresses, we are building larger experiments and adding more power to the plasma for longer times. With our success, we now have a significant new technical challenge -- the development of actively-cooled plasma facing components (PFCs) for handling the heat and charged particles during long pulse operation.

The basic problem of heat removal in a fusion device is well recognized. For a plasma with a steady state power level of one gigawatt, about 20% of this power, 200 MW, is carried by charged particles leaving the plasma. In a diverted¹ plasma, charged particles will deposit this power in two thin toroidal stripes, each a few centimeters wide on the inner and outer legs of the divertor, unless other processes intercede to mitigate this potentially very high localized power deposition. World-wide, the fusion program is currently focusing much of its attention on understanding these processes and insuring that such mitigation can be managed.

By necessity, this challenge will be met squarely in the next generation of fusion devices with the designs of PFCs for ITER and TPX.² In the designs for ITER and TPX, the stream of charged particles entering the

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¹ The two principal types of PFCs for heat removal are the limiter and the divertor. Limiters simply protrude to and define the edge of the plasma. "Diverted" plasma have a more complicated magnetic configuration that directs some magnetic field lines further from the plasma core and onto the surfaces of the divertor chamber.

² Acronyms denote the International Thermonuclear Experimental Reactor, ITER, the Tokamak Physics Experiment, TPX in the U. S. (projects in the design stage) and the Joint European Torus, JET, located at Culham in the United Kingdom.

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divertor collides with cold neutral atoms (or molecules) with the result that the power is spread, by radiation and charge exchange neutrals, over a much larger area than the "footprint" of the charged particle stream. In this way, the divertor heat loads are reduced to manageable levels.

There are also significant ongoing efforts to implement actively-cooled PFCs into existing tokamaks. The JET² Project extensively investigated hypervapotron as a potential basis for water-cooled armor for the Mark II divertor.[1] The mission of Tore Supra, a large tokamak operated by France's Commissariat à l'Energie de Cadarache (CE), includes long pulse operation and the development and use of several types of water-cooled limiters.

In collaboration with CE, Sandia National Laboratories has designed, fabricated and operated a series of outboard moveable limiters used in Tore Supra. These modular limiters are inserted through a port at the midplane of the torus and the position of the limiter can be adjusted between plasma pulses. The latest such limiter is the Phase III (water-cooled) Outboard Pump Limiter (OPL).

This paper draws from experience with Phase III OPL for some general observations about the challenges we face in developing actively-cooled PFCs for future fusion devices. Four themes to be discussed are: (1) how manufacturing flaws, e.g., flaw in joining, affect the thermal performance of a PFC, (2) the related and important roles of non-destructive evaluation and analyses of the impacts of these flaws, (3) shortcomings and developments in the thermal-hydraulic data base, and (4) the need for monitoring during the operation of actively-cooled PFCs to confirm safe operation.

2. Phase III Outboard Moveable Pump Limiter

With Tore Supra's Phase I and Phase II outboard limiters (and nearly all other PFCs in existing fusion experiments), the heat load during the plasma shot is absorbed and then conducted or radiated away between shots. Longer pulses required a design with active cooling and the result was the Phase III OPL installed in Tore Supra in March 1993. Its design goals included steady state removal of 2 MW and incident heat fluxes as high as 10 MW/m² on the face and 30 MW/m² on leading edges[2-5].

The head of the Phase III OPL has 14 water-cooled copper tubes with several hundred brazed pyrolytic graphite (PG) tiles (Figs.1 and 2). The contour spreads the heat load across the face of the limiter. The tubes are sized so that the burnout limit is roughly equal for all tubes. The leading edge tubes receive the highest power loading and have twisted tape inserts to enhance heat removal. Also, the water lines to the leading edges are separate from other tubes so that the inlet water temperature and flow rates can be controlled independently.

Particles that pass behind the limiter's leading edge are deflected toward the pumping duct. In the Phase II OPL, the distance into the scrape-off layer of the leading edge was 3.5 cm. In the Phase III OPL, this distance was decreased to 2.5 cm to increase pumping. Recent papers present a

preliminary estimate of the 50% increase in pumping from this change as well as calorimetric results from the initial operation of the limiter[6,7].

The fabrication of the Phase III OPL[8,9] will be briefly summarized here since some details pertain to later discussion. Each set of 46 rough cut PG tiles (for one side of one tube) was mounted as a group and a semi-circular groove (braze surface) was cut along a spline that matched the shape of the mating copper tube. The tolerances for fitting tiles to tubes prior to brazing were typically 0.09 mm down to 0.03 mm in key locations. In fixturing for the braze, independent, spring-loaded clamps maintained pressure between each tile and the tube while accommodating the thermal expansion of the assembly of 1 cm in length overall and 0.3 mm in height. Vacuum brazing was done at Sandia (~850° C for TiCuSil and ~830° C for CuSil ABA brazes). Shaping of the contours on the plasma side and deflector side of each tube assembly was done after brazing and before their placement on the limiter.

The quality of braze joints was evaluated after the brazing, and again after the contour machining, with transient heating tests[10]. In these tests, the surface temperatures of tiles were monitored with an infrared camera as hot (120° C) water passed through an initially cool tube assembly. The rising temperature of a tile with braze voids or cracks lagged behind the temperatures of adjacent well bonded tiles. "Bad" tiles were easy to detect and, when removed, revealed braze voids of roughly 50% of the joint area. Tiles were replaced in subsequent rebrazes on half the tubes. The relationship between flaw size and the temperature lags in transient heating tests was estimated using 2-D finite element thermal analyses.

3. Impact of joining flaws on thermal-hydraulic performance

A critical factor in judging whether tubes with joining flaws needed repair was an assessment of the impact that the flaw would have during operation of the OPL in Tore Supra, and extensive 2-D finite element thermal analyses¹ of the thermal-hydraulic performance of flawed tiles under heat loads (q_{surf}) appropriate for service in Tore Supra were performed. The output included various items such as the temperatures at the tile surface and at the braze joint and the local heat flux into the coolant interface at the surface of the copper tube.

A basic premise was that q_{peak} from the 2-D analysis was the appropriate value to compare with the Critical Heat Flux². Of particular interest was the relationship between flaw size and the ratio of the q_{peak} to q_{surf} .

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¹The 2-D analyses were performed using a PATRAN/ABAQUS model with a film boiling subroutine that selected either the Seider-Tate treatment for convective heat transfer or Thom's correlation for sub-cooled boiling. These analyses will be published elsewhere in the near future.

²The Critical Heat Flux is the value of the local heat flux at the coolant interface at which the formation of a vapor barrier inhibits heat transfer so that melting of the tube wall occurs and leads to rupture and loss of coolant, i.e., burnout.

Figure 3 shows a cross section of Tube 3 (large tube 3rd from center) with examples of the types of flaw used in the analysis. The percentage is the fraction of void along the braze joint. Figure 4 shows the local heat flux at the water interface as a function of the angle around the inner surface of the tube. (0° is at the top of the tube as indicated by the vertical line in the centered flaw in Fig. 3.)

The rather amazing result is that q_{peak} does not rise appreciably until the flaw size exceeds about 50%. The explanation is as follows. In the tile, heat flows around the flaw and concentrates in the well-connected braze ligaments at either side of the flaw. Just below this ligament, the concentrated heat flow disperses somewhat due transverse (circumferential) conduction within the tube wall.

For the Phase III OPL, an increase in the q_{peak} is not a concern until the braze flaw exceeds 50%, at least for symmetric braze flaws. This is important first because the safety margin based upon the CHF (Critical Heat Flux - the burnout limit for the tube) is basically a "safe" multiplier times the ratio of CHF/ q_{peak} . On this basis, the design for the Phase III OPL appears to be quite tolerant of (symmetric) braze flaws. Second, this relationship (CHF versus flaw size) can become the basis of an inspection criteria for the manufactured component.

The case is, of course, not this simple. We also find asymmetric flaws, (some are probably cracks). And the q_{peak} is more sensitive to asymmetric flaws. Figure 5 compares the heating profiles of symmetric and asymmetric flaws for several values of absorbed surface heat flux and flaw size for a water temperature of 120°C . For the asymmetric flaws, there is a more rapid increase in q_{peak} with flaw size and concentration of more heat flux into a narrower portion of the interface. Other features are also evident in this figure.

In the profile for no flaw and 0.4 MW/m^2 , no boiling occurs while the transition from the non-boiling portion of the surface to the boiling portion is evident from the change in slope at $\pm 60^\circ$ in the profile for no flaw and 0.8 MW/m^2 .

In the profile for 0.4 MW/m^2 and a 32% side flaw, the flaw begins at just under -90° and extends to about -60° . The peak heat flux is still at the top of the tube but the redirection of heat flow has increased q_{peak} just above the threshold for boiling in a small area near 0° , as indicated by the small bump on the top of this profile.

The effect of a flaw on the surface temperature of the tile is also important. For a given heat load, the surface temperature of a tile increases drastically with flaw size (Fig. 6). Excessive surface temperatures could cause melting of metal components and, for carbon tiles, has been associated with carbon blooms. Furthermore, the relationship between surface temperature and flaw size can be, and is in Tore Supra, the basis of a diagnostic to monitor the soundness of the plasma facing armor (discussed further later).

4. Thermal-hydraulic data and analysis

Examples from the Phase III OPL are given below to support a later argument that adequate development of the data base on thermal-hydraulics is an important issue for fusion. There are fundamental problems in extracting relevant data for fusion applications from the abundant data for nuclear and other applications, which are typically generated from experiments on coolant channels where the heat load was symmetric around the circumference of the channel.

The first point is that the thermal-hydraulic data base needed for PFCs that utilize sub-cooled boiling is in part empirical and requires tests on prototypical configurations. For example, in the developing a data base on burnout for design work on fusion PFCs at Sandia, various correlations were compared by Koski with data for heat transfer tests done in Sandia's electron beam facility. The Tong 75 correlation best fit the data and was used in designing the Phase III OPL.[2]

A second point supported by analysis from Tore Supra is the non-linear nature of the heat transfer solutions. A naive observer might guess that heat transfer in PFCs should be basically be a linear problem (per Fourier's law of heat conduction) perhaps complicated by some variations in materials properties that are non-linear with temperature. However, an important non-linear aspect is introduced for the case of channels with both one-sided heating and sub-cooled boiling because much higher heat transfer occurs over a portion of the coolant boundary with sub-cooled boiling¹, compared with non-boiling heat transfer, and this portion changes with the applied heat flux.

Sometimes a "focusing factor" is used to characterize the relationship between q_{peak} and q_{surf} . For one-sided heating with the sub-cooled boiling, use of this factor is problematic since it is not constant with heat flux due to the non-linearity noted above. Figure 7 shows the ratio of $q_{\text{peak}}/q_{\text{surf}}$ versus q_{surf} for Tube 1 over a range of heat flux.² After the onset of boiling, this ratio increases with q_{surf} . As the regions of boiling get wider, the fraction of the total heat load transmitted through the boiling regions increases faster than the geometric ratio of areas because of the higher heat transfer coefficient due to boiling. For a similar reason, the ratio also increases with larger flaw size; this trend is evident in several of the previous figures.

A third point relates to the degree of conservatism to be used in guiding the design for water-cooled PFCs. For example, restricting a design to non-boiling flow is very conservative, at the price of larger surface area or greater water flow due to much reduced heat transfer coefficients. The higher heat transfer coefficients with sub-cooled boiling flow were needed for the Phase III OPL and the further enhancement from twisted tape

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¹ Sub-cooled boiling flow means that boiling occurs in the boundary layer adjacent to the wall of the coolant channel but the (steam) bubbles collapse and are absorbed when they are ejected from the boundary layer into the cooler water in the bulk coolant stream.

²Tube 1, used for this example, receives the highest heat flux on the face of the limiter.

inserts was necessary for the leading edge tubes where heat fluxes of 30 MW/m² were anticipated.

One would like to predict accurately the real margin of safety (against burnout) of a component for the conditions of interest. In operating the Phase III OPL for a given set of conditions, somewhere on the limiter is one tile that is the most vulnerable. However, the location (tile) may vary with the operating conditions. For a power scrape-off length¹, λ_q , of 1 cm or greater, the margin of safety against burnout is least for the leading edge tubes. However, if λ_q decreases to 0.75 cm, Tubes 1i and 1e, at the center of the OPL, become the most vulnerable. For the conditions now observed in Tore Supra, the most vulnerable tiles on the Phase III OPL are probably the tiles on the leading edge tubes at the top of the portions well-wetted by the plasma for several reasons.²

Increasing power deposition on the leading edges adversely affects performance in two additive ways. First, increasing the deposited power increases q_{peak} ; however, the increase in q_{peak} is disproportionately greater, as noted above. Second, the CHF decreases somewhat due to the increase in bulk water temperature near the outlet.

In shot 11044, the OPL received about 0.8 MW, and the temperature rise in the ion-side leading edge tube, which received 0.135 MW, was 81° C. For these values, the calculated CHF decreases from 65 MW/m² at the inlet to 35 MW/m² at the outlet. If we increase the power to the leading edge by 20%, to 0.162 MW, the outlet temperature increases by about 20% from 131 to 147° C but q_{peak} increases by about 35%. Also, there is a further decrease in the CHF by about 7% and the overall effect on the safety margin ($\text{CHF}/q_{\text{peak}}$) is a reduction by 32%.

A practical consequence of the considerations above (but somewhat aesthetically unpleasant) is an operating protocol with the plasma center positioned somewhat below the center of the OPL. The increase in q_{peak} along the bottom portion of the limiter, where the water temperature is lower, can be balanced the higher values of CHF there and vice-versa in the upper portion.

Another point in this regard is that the impact of a joining flaw on a leading edge tile is location dependent. For power deposited evenly along

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¹The power carried by charged particles is assumed to drop off exponentially with the distance into the scrape-off layer. A smaller value of λ_q means that power deposition is concentrated into a thinner layer at the edge of the plasma.

²Cases with λ_q 0.75 to 2.5 cm were analyzed as a part of the design trade-offs with 1 cm being the nominal reference. For ohmic shots in Tore Supra, λ_q has been found to depend inversely on plasma current to the 0.5 power.[11] For a nominal plasma power of 1 MW (I_p of 1 MA and loop voltage of 1 V), the observed λ_q is about 1.7 cm; thus, the fraction of power to the limiter that falls on the leading edges is greater than the reference case used to optimize the design. Furthermore, the fraction of power received by the leading edges (based upon initial results of calorimetry) appears to be 20-30% higher than is predicted using a simple model of exponentially decreasing power deposition in the scrape-off layer.[6,12]

the leading edge, a flawed tile on the lower part of the leading edge may still have a margin of safety greater than a well-joined tile near the outlet due to the lower water temperature and associated increase in CHF for the flawed tile near the inlet.

There is a final but somewhat ambiguous point regarding the robustness of the leading edge tubes. Initial operation of the Phase III OPL concluded when the ion-side leading edge tube burned out during an 8 second shot which proceeded without coolant flow to the limiter¹. Some amazing aspects of this incident are (1) a large leak apparently did not develop until after the shot since a small but steady increase in the oxygen impurity began about halfway through the shot and eventually led to a disruption and (2) the electron-side leading edge tube survived.

5. In-service performance monitoring

The goal with the early operation of the OPL is to optimize power handling, particularly during power sharing with other limiters and the inner wall. In learning to operate the limiter safely, extensive water calorimetry and IR monitoring are regarded as indispensable.

The power distribution on the Phase III OPL is carefully monitored during operation with an infrared (IR) camera for observation of the surface temperature of the OPL and water calorimetry. Water flow in the OPL is monitored by flowmeters on the 10 exit lines downstream from the 14 tubes and two shelves on the limiter head. Water temperatures are monitored with 34 thermocouples (TCs). On the head itself are 17 TCs, 14 on the outlets of all tubes attached to the copper tubes just above the last tile and 1 each on the inlets of the leading edge tubes and Tube 2i.[6,12] Excellent results were obtained with these thermocouples, even those in close proximity to the plasma.

The presence of some flawed tiles on the OPL was recognized and accepted at the outset. An important objective in the monitoring program is measurement of the surface temperatures of individual tiles in order to characterize the thermal conductance of tiles with flaws or cracks. By comparing a suspect tile with adjacent, well-bonded tiles, the flaw size can be deduced from the 2-D analyses discussed earlier. This mapping is a part of the program for safe management of the OPL since the information on flaw size is used to revise the margin of safety ($\text{CHF}/q_{\text{peak}}$) for critical tiles. Once the "as installed" condition of the OPL is established, then the tile map can be updated periodically.

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¹Flow was shut off by the auxiliary water control system 4 s before the shot when the OPL inlet water temperature exceeded 50° C (setpoint). A simultaneous "halt shot" signal was not recognized by the main computer until well after the shot. This problem resulted in a redesign of the interlocks for the OPL and some other water-cooled systems.

6. Discussion: Future Actively-Cooled PFCs

In the development of future actively-cooled PFCs, our strategy for quality must include (1) analysis of probable manufacturing flaws and their impact on performance, (2) evaluation of realistic success rates in manufacturing, (3) confirmation that the selected inspection process can reliably detect flaws greater than some size deemed critical by (1), and (4) adequate in-service monitoring to insure safe operation. The experience from Tore Supra is relevant with respect to all four of these points. Design details may not be applicable, for example, the current carbon fiber composite materials with very high thermal conductivity might have been used but were not available when the Phase III OPL was designed. However, the general considerations in framing the design and the problems faced in implementing the design contain useful lessons for the development of future plasma facing components (PFCs).

6.1 Flaws and Flaw-tolerance in Joining of PFC Armor

Our collective experience to date indicates that the joining of armor to an actively-cooled substrate has repeatedly been a problem area, even when such problems are not necessarily evident from design analysis. For example, the Tore Supra inner bumper limiter is made of rectangular isotropic graphite armor brazed to flat stainless steel plates and one might expect brazing to be straightforward. Nevertheless there have been continuing problems with the quality of the brazes.

Various approaches in quality control are possible. In the current rebuilding of the inner bumper limiter, a "Zero Defect" approach is being used. Modules with imperfectly brazed armor tiles will be rejected. To increase the probability that all tiles are joined successfully (minimize the rejection rate), the size of each inner wall module has been reduced. In contrast, in fabricating the Phase III Outboard Pump Limiter, fairly large flaws were considered acceptable, at least on the larger tubes (see earlier discussion).

An assessment of realistic success rates in joining is quite important as illustrated in the following example. For the Phase III OPL, 18 of 726 tiles on 15 tubes, about 2.5%, were replaced.¹ For a success rate (s) of 97.5% for individual tiles, the expected overall success rate for a unit of 40 tiles (critical center section of tube) is s^{40} or about 36%, i.e., a failure rate of 64%. And in fact, for the Phase III OPL, two thirds of the tubes (10 of 15) had to be rebrazed, and two were rebrazed a second time.

The number of tiles with some apparent flaw was actually larger than the number of 18 cited above; the completed OPL had 27 tiles with apparent flaws or cracks that were judged to be acceptable. Only two tubes had no apparent flaws.

Data are not yet available on the rejection rate for the new inner bumper limiter modules. Moreover, the relatively high rejection rate of the Phase

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¹Numbers include a replacement tube and exclude deflector side tiles.

III OPL tubes could be attributed to difficult geometry and the relatively large number of tiles on each tube. Nevertheless, we must also face up to the fact that we are designing and building one-of-a-kind components for our fusion devices and the development efforts are likely to be insufficient to optimize the production techniques.

The flaw tolerance of at least the larger tubes of the Tore Supra Phase III OPL suggests a more general concept of flaw tolerance that may be useful for the designs of advanced PFCs. For example, if burnout is the primary failure mode of interest and the minimum armor thickness is determined by the erosion rate of the armor, the greatest margin of safety for an unflawed component may occur for highly conductive armor joined to a thin-walled tube. However, the flaw tolerance will decrease with decreasing (lateral) conductance of the tube wall, i.e., with a decrease in either wall thickness or thermal conductivity. Further data from the analysis of 50% centered braze flaws of tubes on the Tore Supra Phase III Outboard Pump Limiter shows this effect.

Figure 8 compares the earlier data (Fig. 7) on $q_{\text{peak}}/q_{\text{surf}}$ versus q_{surf} for Tube 3, a thick-walled tube, with similar data for Tube 5, a relatively thin-walled.¹ For the case of no braze flaw, the curves for Tubes 3 and 5 are similar but the configurations are such that the ratio is higher for Tube 5. With a significant flaw present, Tube 5 has a greater sensitivity to burnout margin from braze flaws in that there is a faster rise in the peak heat flux Q_{peak} as the (absorbed) surface heat flux Q_{surf} increases.

6.2 Thermal-hydraulic Database

Certainly there is a large volume of data on sub-cooled boiling and the assertion that the thermal-hydraulic data base for that ever popular coolant water could be deficient may surprise some people. But most of these data were developed for heat exchangers or other cases where uniform circumferential heating of channels may be assumed and the heat load occurs over an appreciable length. For the more critical heat transfer problems in fusion PFCs, the coolant channels are heated from one side, often with a large peak heat flux over a short portion of the channel's length. Of the large amount of data on sub-cooled boiling heat transfer and burnout, data with parameters relevant to fusion is quite sparse. Development in this area has been encouraged by an international group of experts who hold an informal annual workshop.[13]

Consider the following dilemma regarding data on CHF (Critical Heat Flux or burnout limit). The approach of fusion researchers and designers has been (1) to use an established correlation (e.g., Tong 75) outside the parameters and configurations for which it was developed, (2) to develop limited experimental data on the configuration of interest, and (3) to

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¹Respective values of inside diameter and wall thickness for Tubes 3, 5 and 7 are 15.88, 0.49; 10.21, 0.31; and 7.19, 0.14 mm. Fig. 2 shows geometries. Also, in the case of Tube 7, the applied heat flux peaks along the plasma-facing surface of the tile, whereas the applied heat flux is essentially constant across the surfaces of Tubes 1 and 5.

verify or modify the correlation of interest for the specific application. Here is the dilemma. When a wide variety of data are plotted against a correlation such as Tong 75, the scatter is typically a factor of 4-5 with some data falling a factor of 2 below the correlation.[14] For confirmation of a specific design application in fusion, CHF tests typically might provide a limited data set that has much less scatter than the factor of 4-5 noted above but also is not large enough for a valid statistics on scatter. What margin of safety should be used?

A somewhat different consideration regarding burnout is how one might develop more robust designs against burnout. The advantage of thicker-walled channels being less sensitive to braze flaws was noted earlier, and there may also be an advantage with regard to burnout. In fusion-relevant (one-sided) sub-cooled boiling heat transfer tests of thick-walled copper channels, Russian researchers observed stable conditions for steady state heat transfer while a vapor blanket voided heat transfer over a significant fraction of the coolant channel wall.[15] If a design were developed so that this condition, called "post-crisis" boiling¹, was a reliable precursor to burnout, then the opportunity to diagnose and prevent burnout might be greatly enhanced.

6.3 In-service Monitoring of PFCs for Safe Operation

The program for monitoring power deposition on Tore Supra's Phase III OPL, described briefly in Section 5, is regarded as crucial for the safe operation of this PFC. The data, from observation of surface temperatures of tiles on the Phase III OPL with an infrared camera and calorimetric measurements of the deposited power in each of the 14 tubes, will also be used to optimize the power handling capability of this limiter.

What is the minimum in-service monitoring needed for future PFCs?

The need for in-service monitoring that can verify the continuing safe operation of actively-cooled PFCs may sound like simple "common sense" or even platitudinous. However, the requirements for even intermittent observation of all PFCs using optical techniques presents severe and perhaps overwhelming requirements for diagnostic access. In "deep" divertors (e.g., TPX), a direct view into the critical areas of the divertor may not even be possible. Nevertheless, "adequate design margin" alone is not an appropriate hedge against the potential loss of operating time that might occur from repeated leaks from unmonitored water-cooled

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¹The common conception of burnout is that local heat transfer reaches the point where bubbles that form near the channel wall no longer collapse in the adjacent layer of sub-cooled water but instead begin to coalesce into a layer of vapor. This vapor blanket, with its much reduced thermal conductance, cannot support the previous rate of heat transfer until a rapid rise in the temperature of the channel wall occurs. When this rapid rise in temperature results in a loss of the structural integrity of the channel (e.g., melting), burnout occurs. For the case of one-sided heating, heat conduction through the channel wall around the vapor blanket to a portion of the wall still in sub-cooled boiling is possible given sufficient thermal conductance in the wall of the channel. The situation is somewhat akin to the redirection of heat flow around a braze void, described earlier.

PFCs and vigilant continuing assessments of the power handling capability of PFCs will obviously be prudent.

While calorimetry and IR thermography offer rather direct measures of heat removal capability, the development of other thermal-hydraulic monitoring techniques, for example, acoustic monitoring of "boiling signatures" that precede burnout may be more appropriate for future fusion devices. The technique is used in other applications. Some work on acoustic monitoring was done in the early development and testing of the Phase III OPL at Sandia and there has been promising recent work in developing the technique for fusion applications.[16,17]

7. Conclusion

Developing at least one adequate solution for power and particle handling, such as a radiative divertor, for the next generation of fusion devices is perhaps the most critical technical challenge the fusion program now faces. Hand-in-hand with this development is the engineering challenge of designing, testing, redesigning and retesting actively-cooled armored heat sinks until we have developed robust and reliable PFCs that can fulfill the challenging goals for power and particle handling.

The edge of a fusion plasma presents a unique and severe environment for components. There is as yet no experience removing significant power from fusion plasmas during long (~1000s) pulses. Moreover, our practical experience in building and operating actively-cooled PFCs in fusion is quite limited. There is some experience with water-cooled PFCs¹ developed for Tore Supra that holds relevant lessons for the development of actively-cooled PFCs for future fusion devices.

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¹Helium cooling of fusion PFCs is also possible. There is a well established technology, primarily for gas cooled fission reactors. And there have been important advance for fusion applications that reduce the flow rates and pressures that would be required for plasma facing components. A paper in this conference addressed the development of a helium cooling divertor module for ITER.[18]

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Figs

- 1 sketch showing piping in the head of the Phase III Outboard Pump Limiter
- 2 cross section of half of the OPL head
- 3 cross sections of tube3 showing sample flaw types
- 4 heat flux at the tube water interface vs angle for symmetric flaws in tube 3
- 5 heat flux at the tube water interface vs angle for symmetric flaws in tube 3
- 6 peak heat flux (into water) and surface temperature of tile vs absorbed surface heat flux for symmetric and asymmetric flaws, tube 3
- 7 $q_{\text{peak}}/q_{\text{surf}}$ versus q_{surf} for Tube 1 for a range of q_{surf} and flaw sizes
- 8 $q_{\text{peak}}/q_{\text{surf}}$ versus q_{surf} for Tubes 1, 5 and 7

ISFNT-Nygren in H1
Fig. 1. single column

Figure 1. Phase III Outboard Pump Limiter Piping
Copper tubes (light gray), stainless steel (dark gray),
and a few pyrolytic graphite tiles (black) are shown.

ISFNT - NYGREN in H1
single column

Fig 2. Cross section: ion-side half of Phase III limiter head

53% center flaw

50% side flaw

ISFNT - NYGREN in H1

Figure 3. Cross sections of Tube 3
with examples of center and side flaws

Figure 4. Effect of center flaw on local heat flux at tube water interface ofr Tube 3.

Figure 5. Comparison of the effect of center and side flaws on the local peak heat flux at the tube/water interface for Tube 3.

Figure 6. Increase in (plasma facing) surface temperature of tile with size of braze flaw for Tube 3, two values of Q_{surf} .

Figure 7. Ratio of peak local heat flux to applied heat flux versus applied heat flux for several values of center flaw size. Sharp rise occurs with the onset of subcooled boiling.

Figure 8. Comparison of trends of Q_{peak}/Q_{surf} versus Q_{surf} for thick-walled tube (Tube 3) and thin-wall tube (5)