Recent High Heat Flux Tests on W-rod-armored Mockups[1]

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Abstract

In our initial high heat flux tests on small mockups armored with W rods, done in our small electron beam facility (EBTS) at Sandia National Laboratories, the mockups exhibited excellent thermal performance. However, to reach high heat fluxes, we reduced the heated area to only a portion (~25%) of the sample. We have now begun tests in our larger electron beam facility, EB1200, where the available power (1.2 MW) is more than enough to heat the entire surface area of the small mockups. Our initial results indicate that, at a given power, the surface temperatures of rods in the EB1200 tests is somewhat higher than was observed in the EBTS tests. Also, it appears that one mockup (PW-10) has higher surface temperatures than other mockups with similar height (10mm) W rods, and that our previously reported values of absorbed heat flux on this mockup were too high[1-3]. In our tests in EB1200 of a second mockup, PW-4, absorbed heat fluxes of ~22MW/m^2 were reached but the corresponding surface temperatures were somewhat higher than in EBTS. A further conclusion is that the simple 1-D model initially used in evaluating some of the results from the EBTS testing was not adequate, and 3-D thermal modeling will be needed to interpret the results.

Keywords: high heat flux, plasma facing component, tungsten

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1. Introduction

Interest in plasma facing components (PFCs) armored with tungsten (W) has increased greatly in the last decade, and effort on the development and testing of W-armored mockups worldwide over the last decade has been impressive.[3] Tungsten's low sputtering yield and high melting temperature are attractive features for armor. W plasma facing surfaces have been deployed in TEXTOR and in ASDEX; and W armor is proposed for the lower portion of the divertor of ITER (International Thermonuclear Experimental Reactor). In designs for a high performance, water-cooled PFCs with W armor, the heat sink is typically a copper alloy such as CuCrZr. Developing a robust joint is a challenge because of the significant mismatch in thermal expansion coefficients between W and copper.

In the US program, interlayers[4] and graded or multi-layer material[5] were studied as means for mitigating the severe thermal strains anticipated with tiles. After Watson's analysis[2] of castellated armor[6] showed that the width of a cut cell must be quite small (<5mm) to reduce thermal stresses significantly, the US began developing W "brush-type" armor[6-8]. As development proceeded, water-cooled mockups armored with W-rods were fabricated. Several of these were tested at Sandia National Laboratories in the Electron Beam Test Stand (EBTS), part of the Plasma Materials Test Facility[10], and absorbed heat fluxes in the range of 25-30MW/m^2 were reported. The primary purpose of this paper is to present initial data from new tests done in our large electron beam facility, EB1200, that we believe more accurately measure the thermal performance of the previously tested mockups.

2. Preparation and Testing Procedures

Fig.1 shows several small W-armored mockups after EBTS tests, including PW-10 and PW-4 that have now been tested in EB1200. Table 1 summarizes their main features. Ref. [1] gives details about the samples and Refs. [6-8] give details about methods of embedding rods and the joining to the heat sink.

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[2]This analysis was presented at ITER meetings and immediately used in the US design for the ITER divertor, i.e, brush armor, but was not published in Ref. 6 until about two years later.

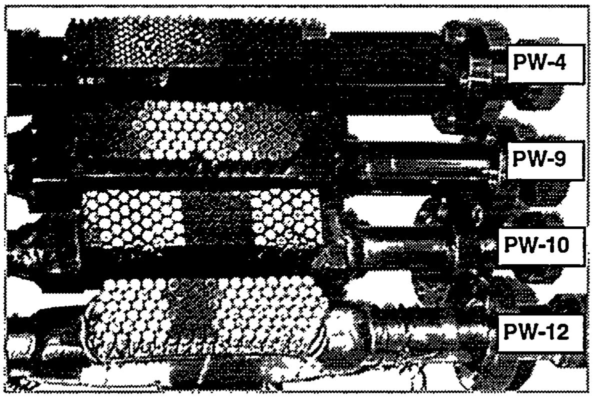

Fig.1. W-armored mockups after testing in EBTS.

Table 1. Mockup Features

Mockup Name	Rod Mat'l	Dia (mm)	Embedding Method	Heat Sink
PW-4	pure W	1.58	Plasma spray	CuNiBe
PW-9	W-2%La	3.16	HIP*	CuCrZr
PW-8&10	W-2%La	3.16	plasma spray	CuCrZr
PW-11&12	W-2%La	3.16	HIP	CuCrZr

*HIP (hot isostatic pressing)

The light sections on PW-10 received high heat fluxes in EBTS. The darker middle section received only low heat fluxes and retained the surface oxide on the rods that was produced during welding of the heat sink to the inlet and outlet pipes. The small, water-cooled mockups are typically 215mm in length overall with an area 18.5x65mm covered by W rods with 10mm of rod protruding from the heat sink. The heat sinks have a 10mm diameter cooling channel with no enhanced heat transfer (e.g., no twisted tape), and 6-8 embedded thermocouples.

The earlier high heat flux tests in EBTS were typically run with cooling water at 10-20°C and 4.2MPa; however, tests on PW-10 were run at 1.0MPa (while testing at this water pressure was also being done in EB1200.) Absorbed power levels were measured by water calorimetry. In EBTS, the fraction of absorbed power of W samples is low (30-35%) because reflection of 30keV electrons by W is high. With 30kW of power and anticipated absorbed heat loads of 25-30MW/m^2, we limited the heated area to ~250mm^2 (~15mm of the armored length). As the heated area decreases, the gradient in the heat flux at the edges covers a larger fraction of the heated area. This is a particular problem when the heat is intercepted by a relatively small number of discrete elements, e.g., the 3.2mm diameter W rods. As the excellent performance of the mockups made these concerns more pronounced, plans were laid to retest some W-armored mockups in EB1200.

To prepare the tests in EB1200, extensions were welded to the stainless inlet and outlet tubes and new thermocouples were installed. Data from the thermocouples will be used in future thermal analyses but are not reported here. One mockup at a time was mounted horizontally in EB1200 between heat shields above and below with the heated surface in the vertical plane and overlaid at each end by heat shields. The shields intercepted power outside the armored area of the sample so that the true heated area of the sample was well defined. Water conditions for the EB1200 tests were 18°C, 15m/s and 4.0MPa. Diagnostics for the EB1200 tests include water calorimetry, video and two IR cameras and four pyrometers. One IR camera (Inframetrics 600) was fitted with a 3X telescopic lens that provided a close-up view in which the individual W rods could be resolved. The absolute reference for temperature was a two-color pyrometer (1500-3500°C). Satisfactory calibration of this instrument was verified when the onset of melting was observed in the pure W rods on PW-4.

3. High Heat Flux Testing Results and Discussion

The results[1] of tests in EBTS on PW-4 and PW-10 are briefly summarized here. PW-4 received 500 thermal cycling tests at ~15*, ~22* and ~30*MW/m^2. The maximum average surface temperature at ~30*MW/m^2 was ~2800°C. Melting of rods on PW-4 occurred twice. In the initial test rods were melted due to operator error. In the second test, after 465 cycles at a nominal heat flux of 30*MW/m^2 a cluster of 10 rods increased in temperature, with power constant, and their tops melted. We assume this was due to a degraded thermal bond that subsequently regained good thermal contact because we continued testing and the temperature of the melted rod tips during the last 30 cycles was only slightly greater than before the melting (assuming the emissivity of the surface was the same after melting).

* These previously reported values of heat flux are revised later in this paper.

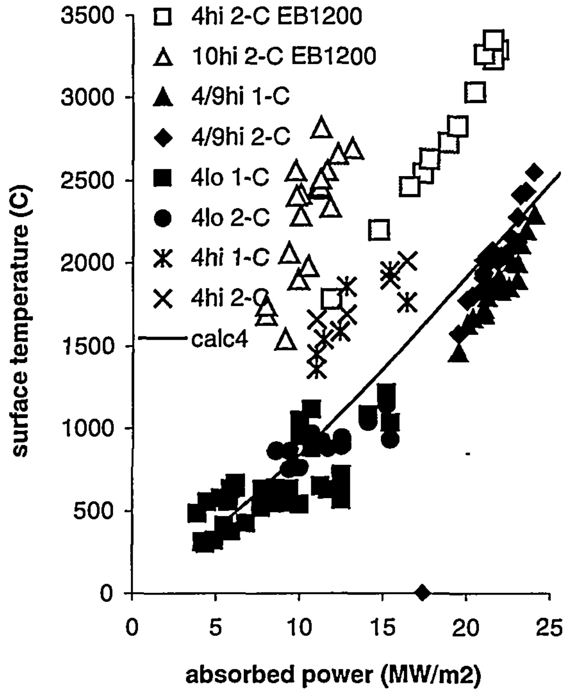

Fig.2. EB1200 and EBTS data on PW4. 9 and 10 and 1-D thermal model. EB1200 data are large open triangles and squares. "4lo 1-C" refers to PW4 and a one color low temperature pyrometer

Fig. 2 shows the results of our initial brief tests in EB1200 of PW-4 and PW-10 along with results from 1-D thermal modeling done at the time of the EBTS tests and some results from the EBTS tests. The results from the EBTS tests include both one color and two color pyrometers, as noted in the legend. While some data in the EBTS test of PW-4 (from the high temperature pyrometers at the intermediate heat fluxes) show a trend toward the higher surface temperatures observed in the EB1200 test of PW-4, the preponderance of data are consistent with the 1-D thermal analysis.

Since higher values of absorbed heat flux were previously reported[1-3], a brief explanation is given here of the circumstance. Our new data from EB1200 suggest that our previously estimated values of absorbed heat flux in the EBTS tests on W-armored mockups were too high in general. We believe this is likely due to the relatively small heated areas combined with axial conduction of heat in the heat sink away from the heated rods. This would reduce the temperature at the base of the rods and the effect would be systemic in these tests. We plan to confirm this through a 3-D thermal analysis.

We also found a discrepancy between the values of measured surface temperature versus absorbed heat for PW-10 specifically and those measured for the other mockups. We believed at that time that our estimate of the heated area of PW-10 was in error, and derived what we considered to be an appropriate value through comparison with the 1-D model, since the model was consistent with data from the other mockups. This judgment was wrong; the thermal response of PW-10 is not similar to the other mockups. A likely contributing factor is that some annealing of the CuCrZr heat sink may have occurred in the joining of end pipes onto PW-10. Metallurgical observations of the sample are planned but have not yet been undertaken. The decrease in thermal conductivity with annealing is a concern for fabrication of PFCs that use CuCrZr (or other heat-treatable copper alloys) and has been studied.[10]

4. Conclusions

The current limitation in the thermal performance of the W-armored heat sinks appears to be the surface temperature of the rods. This is true for our samples. And, in European tests, mockups with "macro-brush" 4.5x4.5mm lanthanated W armor tiles 10mm tall were tested to ~16MW/m^2 in thermal cycling tests and the experimenters indicated that concern with excessive surface temperature limited the heat flux to which these mockups were exposed[11], although surface temperatures of the W tiles were not given.

We can increase the heat load that can be accepted by W-armored water-cooled PFCs by reducing the armor thickness from the current 10mm used in many ITER samples. However, there may also be some inherent safety in having the rod tips melt before the critical heat flux of the PFC is exceeded.

Three specific conclusions from this recent work are as follows:

1. The surface temperatures in the EB1200 tests on W-rod-armored mockups are higher than those in EBTS tests at the same attributed heat loads.
2. The simple 1-D thermal model of W-rod armor does not fit the data from EB1200. Since it is now clear that a 3-D model is probably needed to describe the EBTS tests with a small heated area; we must conclude that the earlier agreement of the 1-D model with data from the EBTS tests is to some degree fortuitous.

3. The surface temperature of PW-10 is much higher than that of PW-4 at the same heat load. Therefore, the thermal response of PW-10 not similar to PW-4 (and the other samples tested in EBTS, PW-9 and PW-11).

Our main conclusion is that, despite the somewhat overestimated the heat fluxes in the initial tests, the general response of these W-rod-armored mockups has been very robust. The mockups have performed well in thermal cycling tests in which the temperature of the rods reached and in some cases, even briefly exceeded the melting temperature. Indeed, the performance of PW-4 indicates that absorbed heat fluxes in excess of $20MW/m^2$ are possible for W-armored PFCs.

5. References

[1] R.Nygren, D. Youchison, R. Watson, J.S. O'Dell, 5th Int. Symp. on Fus. Nucl. Tech., Rome, July 1999, to be pub.

[2] J. S. O'Dell, T. McKechnie, 4th IEA Int. Workshop on Beryllium Technology for Fusion, Karlsruhe, Germany, Sept. 15-17, 1999

[3] R. Nygren, Actively Cooled Plasma Facing Components for Long Pulse High Power Operation, Proceedings of 10th Int. Toki Conference, Toki, Japan, January 18-21, 2000, to be published

[4] R.E. Nygren, 17th IEEE/NPSS Symp. on Fus. Eng., ISBN 0-7803-4226-7 (1998) 901

[5] R.A. Neiser, R.D. Watson, G.R. Smolik, K.J. Hollis, 1993 Nat. Thermal Spray Conf., Anaheim, CA

[6] R. Watson et al., Fusion Tech. 34(#3/pt.2) (1998) 443-453

[7] K. Slattery, B. Odegard, T. McKechnie, R. Watson, 17th IEEE/NPSS Symp. on Fusion Eng., ISBN 0-7803-4226-7 (1998) 888-891

[8] D. Dreimeyer, K. Slattery, G. Wille, R. Nygren, 18th Symp. On Fusion Eng., Albuquerque, NM, Oct.21-25, 1999.

[9] D. Youchison, R. Watson, T. Marshall, J. McDonald, SPIE 2855 (1996) 299

[10] U. Holzworth, 5th Int. Symp. on Fus. Nucl. Tech., Rome, July 1999, to be pub.

[11] G. Vieider et al, Fus. Eng. & Des. 39/4 (1998) 211