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HIGH HEAT FLUX TESTING CAPABILITIES AT SANDIA NATIONAL LABORATORIES - NEW MEXICO

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ABSTRACT

High heat flux testing for the United States fusion power program is the primary mission of the Plasma Materials Test Facility (PMTF) located at Sandia National Laboratories - New Mexico. This facility, which is owned by the United States Department of Energy, has been in operation for over 17 years and has provided much of the high heat flux data used in the design and evaluation of plasma facing components for many of the world's magnetic fusion, tokamak experiments. In addition to domestic tokamaks such as Tokamak Fusion Test Reactor (TFTR) at Princeton and the DIII-D tokamak at General Atomics, components for international experiments like TEXTOR, Tore-Supra, and JET also have been tested at the PMTF. High heat flux testing spans a wide spectrum including thermal shock tests on passively cooled materials, thermal response and thermal fatigue tests on actively cooled components, critical heat flux-burnout tests, braze reliability tests and safety related tests. The objective of this article is to provide a brief overview of the high heat flux testing capabilities at the PMTF and describe a few of the experiments performed over the last year.

INTRODUCTION

The Plasma Materials Test Facility (PMTF) is a dedicated United States Department of Energy high heat flux component test facility located at Sandia's site in Albuquerque, New Mexico. The facility is comprised of several major systems, including two electron beam systems. The 30 kW Electron Beam Test System (EBTS) has been in operation for over 17 years, while the 1200 kW Electron Beam System (EB-1200) was commissioned only recently. Other fine facilities exist in the United States for high heat flux (HHF) testing of optical components (Stapp, 1992), but the primary mission of the EBTS and EB-1200 is to expose actively cooled plasma facing components to the intense surface heat loads experienced in fusion devices. Related HHF applications such as microwave gyrotron cavities and neutral beam dumps are also studied.

The PMTF has been involved with many international collaborations involving government laboratories in the European Union, Russian Federation and Japan. Each of these parties has similar electron beam high heat flux facilities such as the 30 kW JUDITH e-beam in Germany, the 200 kW FE-200 e-beam in France, the 400 kW JEBIS e-beam in Japan and 60 kW TSEFEY e-beam in Russia. Several collaborative experiments are sponsored each year involving personnel from these international facilities and the PMTF. Currently, testing of plasma facing components is underway in all of these facilities in support of the International Thermonuclear Experimental Reactor (ITER). In addition to ITER, the PMTF will soon begin testing components for the Tokamak Physics Experiment (TPX) which will replace TFTR in 1996. Testing is also performed for small businesses under the Department of Energy Small Business Innovation Research Program to investigate innovative heat transfer technologies for both fusion and commercial applications. HHF test results from the PMTF are typically published in *Fusion Technology, Nuclear Fusion, Fusion Engineering, Journal of Fusion Energy, Journal of Nuclear Materials, Journal of Vacuum Science and Technology* and occasionally in the *ASME Journal* and in the *SPIE Proceedings*. Numerous references to the above tokamak experiments and international high heat flux test facilities may be found in the first four journals noted above.

The EB-1200 is used for testing of medium-scale (1 m x 1 m) components and prototypes, while the EBTS is used for HHF testing and research on small prototypes (10 cm x 10 cm). Both systems share a state-of-the-art, high-pressure, high-temperature flow loop, which can supply high-quality coolant water (de-ionized and de-mineralized) over a wide

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range of conditions: flow rates up to 30 l/s, pressures as high as 7 MPa, and inlet temperatures up to 280 °C to simulate those available in fusion devices. The EBTS is also equipped with a closed helium coolant loop for testing of helium-cooled components and heat exchangers. A fully equipped computer laboratory is also housed at the PMTF for analytical and experimental support of high-heat flux experiments.

THE EBTS

The EBTS is a multi-purpose device for studying the surface modification, thermal response and failure modes of high heat flux materials and components. Figure 1 presents a schematic of the EBTS showing a few of the diagnostics. Table 1 lists the operating specifications of the EBTS, while Table 2 describes the available diagnostics for HHF testing.

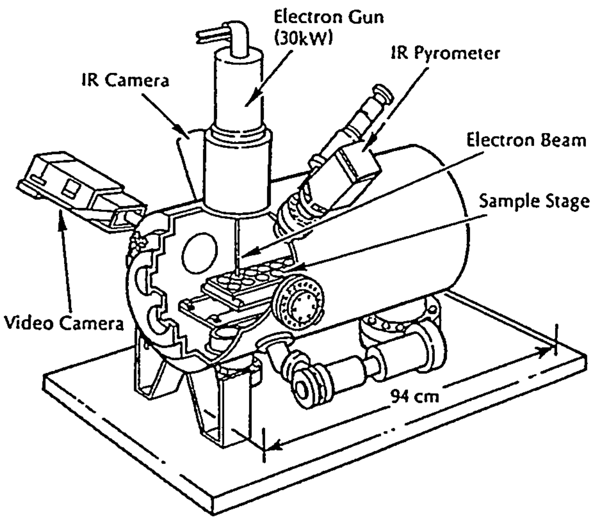

FIGURE 1. EBTS SCHEMATIC

TABLE 1. EBTS OPERATING PARAMETERS

Beam Power	30 kW
Accelerating Voltage	30 kV
Beam Current	1 ampere
Target Area	0.1 to 100 cm^2
Pulse length	from 2 ms to continuous

TABLE 2. EBTS DIAGNOSTICS

Diagnostic	Purpose
Pyrometers (2)	Surface temperatures
Infrared Camera & Video Digitizer	Surface temperature profiles
Thermocouples (16)	Bulk temperatures
Strain gauges	Bulk response
Residual Gas Analyzer	Partial pressures
Water calorimetry	heat removal capability
Bore scope	*In situ* surface observations
TV monitoring system	Visual records

The 30 kW, heated-cathode, electron gun is mounted in a stationary vertical position over the sample area. A hinged door at the end of the 0.6 m diameter, 1 m long EBTS vacuum vessel provides easy access for sample installation. Targets of all shapes varying in size up to 30 cm x 60 cm can be tested. A background pressure of 6 x 10^{-4} Pa is maintained with a cold-trapped diffusion pump. A large variety of ports and vacuum feedthroughs are available for diagnostics and utility connections.

The electron source is equipped with a tungsten or tantalum filament, and its maximum operating voltage is 30 kV producing 30 kW of electron beam power. The uncorrected beam at the target plane has a full-width-at-half-maximum diameter of 5 mm for the tungsten filament and 3 x 3 mm^2 for the tantalum filament. A magnetic lens and deflection yoke are used to focus, position and raster (up to 10 kHz in two orthogonal directions) the electron beam to cover a variety of sample surfaces with a finely tuned or defocused beam. The temporal and spatial current profile from the rastered electron beam is determined by a deep faraday cup equipped with secondary electron suppression, and the energy deposition is measured with a calorimeter or with water calorimetry of actively cooled samples.

Various scenarios can be simulated with the electron gun, since it provides a variable directed heat source. In the standard, steady state operating mode, which utilizes a tungsten filament, a 100 ms to continuous shot length over a heated area from 1 to 100 cm^2 is possible. In this operational mode, the EBTS has been used to create a variety of high heat flux tests from 25 kW/cm^2 deposited on 1 cm^2 for 100 ms to 10 W/cm^2 deposited on a 100 cm^2 area for over 900 s. The system can also produce high power density, short pulse length energy deposition. No raster is used in this mode. Peak power densities up to 200 kW/cm^2 over areas of approximately 10 mm^2 for times as short as 2 ms have been achieved.

There are five broad categories that high heat flux research in the EBTS can be divided in to. These include:

1) **Thermal Shock experiments** which are intended to subject many small test specimens to a systematic sequence of identical intense energy depositions so that limiting factors such as melting, cracking, delamination, and outgassing can be compared among materials.

2) **Thermal Response tests** which expose miniature mock-ups of complete high heat flux components to normal and off-normal thermal conditions to verify the overall design concept. This type of experiment is comprehensive in that material selection, thermal hydraulic design, and the robustness of the design are tested before the components are manufactured and installed in a fusion device.

3) **Thermal fatigue experiments** which are used to examine material failure and degradation due to repetitive thermal cycling. Typically, high heat flux components are subjected to hundreds up to thousands of energy depositions that are representative in power density and duration to that expected in a fusion device. Fatigue crack growth and/or interfacial failure have proven to be common concerns.

4) **Critical heat flux - burnout experiments** which are designed to determine the heat transfer coefficients and critical heat flux values for actively cooled components. The use of thermocouple arrays to determine the contact resistance across the interface between two dissimilar materials and the

use of water calorimetry to discover the critical heat flux for coolant tube burnout are examples.

5) **Development of non-destructive evaluation techniques** for use in the International Thermonuclear Experimental Reactor (ITER) qualification tests and feedback control systems. An example of a non-destructive technique is a real-time, radiation-hardened diagnostic for reliable detection of intense boiling, such as acoustic emission, which can be used to detect the onset of critical heat flux limits and provide active feedback to safety control systems to mitigate tube burnout. Another example is IR thermography screening which involves passing a well-defined slug of hot water through a cold component (a thermal Heaviside function) and measuring the rate and uniformity of surface temperature increase. This technique is used to ascertain the integrity and thermal efficiency of braze joints.

When performing thermal shock experiments on the EBTS, a water-cooled, computer-controlled, x-y table is used to process as many as 32 2.5 cm x 2.5 cm x 1.0 cm passively cooled, v-notched,, shock specimens under one pump down.

During fatigue testing, "A-B" or "A-B-C" cycles are used to deflect a continuous beam to different areas on the target or to several different targets with dwell times as short as 100 ms. This cycle is created by using a wave generator(s) to input a square wave(s) into the beam raster offset control. This is a very efficient technique when performing thousands of fatigue cycles on targets which reach equilibrium very quickly. In many instances, it permits water calorimetry to be used for a continual check of absorbed power in an actively cooled target. The other mode used for fatigue testing is to perform separate shots by cycling the beam on and off for the required number of cycles and on/off durations using computer control. This mode is effective when testing massive, mechanically attached, passively cooled targets which require long times to reach steady state temperatures, particularly on cooldown.

The diagnostics of the facility are designed to gather comprehensive data from a variety of energy deposition experiments. A video monitoring system and an infrared camera and colorizing system are used to observe all tests in the EBTS. Video recorders are used to document all video signals that can be analyzed with a frame-by-frame playback system. A high-speed movie camera with a 10,000 frames/s maximum speed is also available to record rapid sequences of events. An array of optical and IR pyrometers is used to monitor the sample surface temperatures in conjunction with the IR camera over a range of 20 to 3000 °C. The bulk thermal response of the sample is measured with a bank of imbedded thermocouples to record the internal temperature distribution. Strain gauges are used to measure the mechanical response of structural members. A residual gas analyzer (RGA) is used to measure the temporal history and quantities of evolved gas species.

The post-experiment analysis of high heat flux testing in the EBTS involves many in-house capabilities. Data analysis involves the processing of recorded data such as the extraction of temperature contours using IR camera records or the comparison of thermocouple records over a series of tests. Processed data such as temperature profiles, calorimetry data, mechanical responses, and thermal hydraulic results are compared with predictions from analytical models. After samples are removed from the EBTS, they are subjected to further characterization such as scanning electron microscopy (SEM), profilometry, surface analysis (EDX, ESCA, AES, SIMS), and cross sectioning for metallographic studies.

THE EB-1200

The EB-1200 is a dual triode-type, solid cathode, varioanode electron gun system which can produce 1.2 MW of electron beam power. The system is designed to study the thermal response of medium-sized, high heat flux components under energy depositions of the magnitude and duration expected in fusion devices. The EB-1200 was built primarily for HHF testing of actively cooled beryllium clad divertor and first wall components for the ITER program and carbon-carbon clad plasma facing components for the Princeton Tokamak Physics Experiment (TPX). The EB-1200 is comprised of two EH 600 S Von Ardenne electron guns each equipped with dual focusing and deflection coils. The beams can be rastered at 10 kHz for high heat flux testing. A schematic of the EB-1200 system is shown in Figure 2. Table 3 describes the operating parameters for the EB-1200 system.

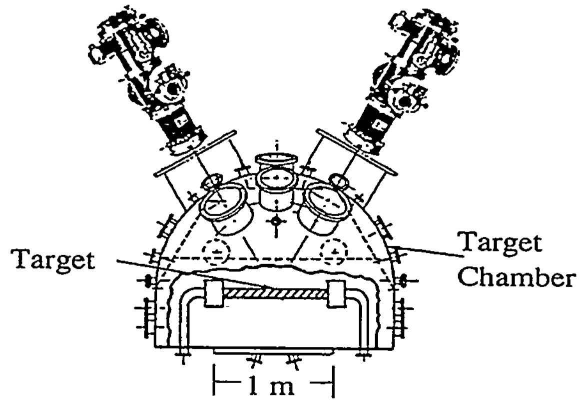

FIGURE 2. EB-1200 SCHEMATIC - TOP VIEW SHOWING LOCATION OF ELECTRON GUNS.

TABLE 3. EB-1200 OPERATING PARAMETERS

Beam Power	0 to 1200 kW (cw)
Accelerating Voltage	0 to 40 kV
Beam Current	15 amperes each gun
Angle of Beam Incidence	0° to 90 °
Cathode Lifetime	≥ 200 hours
Magnetic Lenses	2 coils
Magnetic Deflection	2 yokes (orthogonal)
Max. Angle of Beam Deflection	±30° at < 200 Hz ±7° at 10 kHz
Maximum Raster Frequency	10 kHz
Unrastered (pulsed) Spot Diameter at 600 kW and a Distance of 1.5 m	3.5 cm
Maximum Heat Flux (unrastered)	>1000 MW/m^2
Maximum Heated Area at 1.5 m, 10 kHz	37 cm x 37 cm
Heat Flux at Maximum Area	8.7 MW/m^2
Maximum Pressure in Chamber	≤3 Pa
Cooling Water Consumption	2.2 m^3/hr

Two independent electron guns operating in a steady state mode provide a great deal of flexibility in the EB-1200. For instance, two targets can be tested at the same time provided that the required total power deposition on each target does not exceed 600 kW. The beam raster patterns may be interlaced or even placed adjacent to one another to cover larger areas or test longer heated lengths. For example, heated lengths of 74 cm can be produced by using adjacent raster patterns. The EB-1200 can be used in a variety of high heat flux tests from 1200 kW/cm^2 deposited on a 1 cm^2 for 100 ms to less than 1 W/cm^2 deposited on a 2700 cm^2 area for times greater than 900 s. Although peak power densities greater than 100 kW/cm^2 over areas of approximately 12 cm^2 are possible, none of the beam dump plates can survive this heat load. Presently, the EB-1200 does not perform pulse mode (<100 ms) shots.

The vacuum system consists of a large (~3 m^3) D-shaped target chamber shown in Figure 3. This chamber has over 50 ports viewing the target surface available for target diagnostics. The sources are mounted on side ports equipped with large isolation valves so sample changeout or filament replacement has minimal effect on the overall vacuum system. The system is pumped with four 3000 l/s commercially available cryopumps.

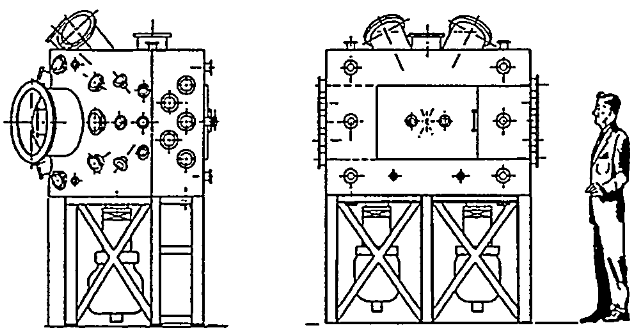

FIGURE 3. EB-1200 VACUUM CHAMBER

Diagnostics on the EB-1200 are similar to the EBTS. Four spot infrared pyrometers are used over their appropriate ranges to determine target surface temperatures. An IR camera is also available for surface temperature profiles. More than 20 channels of thermocouples (K,T,E,R,S) are available for bulk temperature measurements under the heated area, as well as a variety of strain gauges. A residual gas analyzer is available to determine the species of outgassed constituents. A complete water calorimetry system is used to determine the actual power absorbed by actively cooled targets. In addition, three different length bore scopes are available along with a TV/video recording system to visually characterize the target during the experiments. A new optical probe, laser displacement interferometer which operates in a line-scan mode will soon be used for sample deflection measurements to infer stress and strain information. Table 4 summarizes the diagnostic capabilities of the EB-1200.

The EB-1200 completed qualification tests in early 1994. Its first HHF tests will soon be performed on the Berkeley neutral beam dump plates (Rinehart et al., 1989) which were designed to survive a heat flux of 20 MW/m^2. A four element array of these dump plates is currently used on the EB-1200 as beam stops. In addition, a large (1.5 m x 1.5 m) x-ϕ translation table can be installed in front of the dump plates for target positioning and rotation. The EB-1200 can operate uninterrupted for as long as 200 hours before cathode replacement is required. However, staffing requirements restrict operation to 6 to 8 hours per day.

TABLE 4. EB-1200 DIAGNOSTICS

Diagnostic	Purpose
Pyrometers (4)	Surface temperatures
Infrared Camera & video digitizer	Surface temperature profiles
Thermocouples (20)	Bulk temperatures
Strain gauges	Bulk response
Residual Gas Analyzer	Partial pressures
Water calorimetry	heat removal capability
Bore scopes (3)	*In situ* surface observations
TV monitoring system	Visual records

The EB-1200 will be able to test the thermal response and critical heat flux limits of medium-sized divertor mock-ups (1 m x 1 m). It is possible to perform critical heat flux tests up to 120 MW/m^2 over areas of 10 cm x 10 cm, normal divertor heat loads of 10 MW/m^2 over areas of 34 cm x 34 cm, or first wall heat loads of 1 MW/m^2 over 1 m x 1 m areas. Because of the large heated area, it will also be possible to study flow instabilities in parallel channels. The EB-1200 will be used to test medium-scale divertor mock-ups with multiple (5-10) parallel water-cooled channels in the subcooled flow boiling regime where two-phase flow instabilities may exist at heat loads in the range of 10-100 MW/m^2.

All of the ITER-relevant conditions for measuring critical heat flux (CHF) can be achieved with the EB-1200. Critical heat flux correlations developed for uniform, circumferential heat loads are not applicable to one-sided heating (Araki, 1994). This area of thermal hydraulics requires extensive investigation. Although Araki et al. (1994), Celata et al. (1993) and others have proposed correlations, none are widely accepted for design studies. Empirical correlations for heat transfer coefficients, pressure drop, and burnout limits due to one-sided heating for a variety of advanced heat sink designs such as hypervapotrons, inserts, fins, and internal porous coatings can be obtained on the EB-1200 for medium-sized divertor mock-ups, as well as on the EBTS for small scale mock-ups (Koski et al., 1988).

The EB-1200 can also be used for fatigue testing of medium-scale components or testing of many small components at one time. The two electron guns can be used to fatigue test two medium-scale components side-by-side, if the required heat flux is below 8.7 MW/m^2. The same fatigue modes, which include the "A-B" cycle and the computer-controlled, continuous cycle mode, used for the EBTS are also available on the EB-1200.

Another important feature of the EB-1200 is the digital raster control. Very complex heat flux patterns can be attained in the EB-1200 by utilizing its computer-controlled, digital sweep generator supplied by Von Ardenne GmbH. In addition to controlling pattern size and position, raster patterns such as sine-filled, sawtooth-filled or triangular-filled rectangles, ellipses or trapezoids can be generated as well as arcs and TV raster scans with flyback. Other patterns include spirals and figure eights of various density gradients. New patterns can be programmed into the pattern library as required.

The raster controls also allow the operator to set the density or dwell time of each of 10 sections of a pattern. This allows some sections of the pattern to contain a higher heat flux than others. Therefore, tokamak divertor X-point sweeping can be simulated very easily in the EB-1200. Although the raster patterns are continuous, selected sections can be nulled out by setting their dwell time to zero. Therefore two pseudo-circles at a separation distance of 1-3 cm can be rastered by nulling out the intersection point of a figure eight pattern, or rings can be rastered by nulling out the center portion of a spiral. With the two independent 600 kW electron beams on the EB-1200, different patterns can be juxtaposed to create intricate pattern shapes. The EBTS, which is restricted to a rectangular raster shape, will be upgraded to the EB-1200 rastering system in late 1994.

HIGH PRESSURE, HIGH TEMPERATURE FLOW LOOP

The High-Pressure, High-Temperature (HPHT) flow loop provides high-quality, high-temperature, pressurized water to high heat flux targets in the EBTS and EB-1200 vacuum chambers. The flow loop gives the PMTF operator full control over pressure, temperature, flow and water chemistry over a wide range of conditions as shown in Table 5. All flow loop parameters are controlled by the PMTF computer system.

TABLE 5. PMTF HPHT FLOW LOOP PARAMETERS

	Metric	English
Flow:	3 to 30 l/s	50 to 500 gpm
Temperature:	40 to 280 °C	100 to 540 °F
Pressure:	0.1 to 7.0 MPa	15 to 1000 psi
Target Pressure Drop:	0.01-1.4 MPa	1 to 200 psi
pH:	7 to 11	7 to 11
Oxygen:	200 ppb max.	200 ppb max.

The most important part of the flow loop is the variable speed pump that permits flows from 3 to 30 l/s (50 to 500 gpm). The loop is pressurized to 6.9 MPa (1000 psi) by a positive displacement pump, permitting flow and pressure at the target to be varied independently. A surge tank is provided to damp pressure fluctuations in the system. Stainless steel piping designed to American National Standards Institute (ANSI) power plant standards is used throughout the system. The flow loop also has water treatment capabilities similar to nuclear power plants.

Although the loop has the capability to use de-ionized, de-mineralized water, high resistivity water is not required for most tests conducted at the PMTF. Chemical injection pumps provide for control of oxygen and pH for corrosion mitigation through the use of hydrazine and ammonia. A 225 kW in-line electric water heater provides for faster heating of the loop water. High temperature water up to 280 °C can be delivered to the target inlet without reducing the allowable operating pressure or maximum flow capabilities of the system. Such water coolant capabilities are necessary to perform thermal response and CHF-burnout tests under a wide variety of thermal hydraulic conditions.

HELIUM FLOW LOOP

The EBTS is equipped with a closed helium coolant loop which can operate at a maximum pressure of 4.1 MPa and temperatures as high as 300 °C. Helium mass flow rates as high as 22.0 g/s have been achieved for sample pressure drops near 7 kPa (~1.0 psi) and total pressures of 4.0 MPa. The maximum pressure drop for a sample that can maintain a steady flow in the present loop is 55 kPa (~8 psi) at 4.0 MPa. Current plans include an upgrade to the EBTS helium loop featuring a high capacity helium blower capable of producing mass flows near 100 g/s and handling pressure drops across the samples as high as 186 kPa (27 psi). The helium loop specifications are summarized in Table 6.

TABLE 6. EBTS HELIUM FLOW LOOP PARAMETERS

	Metric	English
Flow:	0 to 22 g/s	0 to 0.049 lb_m/s
Temperature:	40 to 300 °	100 to 570 °F
Pressure:	0.1 to 4.1 MPa	15 to 600 psi
Target Pressure Drop:	7-55 kPa	1 to 8 psi

The EBTS helium flow loop (HeFL) has successfully been used to test three types of helium-cooled heat exchangers in 1993. The first of these was manufactured by Creare, Inc. and makes use of microfin technology (200 μm channels) and helium flow normal to the heated surface. This technology provides for enhanced heat transfer at relatively low flow rates and much reduced pumping requirements. The Creare heat exchanger was tested in the EBTS to a maximum heat flux of 5.8 MW/m^2 with a 20 cm^2 heated area. The background pressure was 1.4 MPa, the pressure drop across the test specimen was 17.2 kPa, and the helium mass flow rate was 4.0 g/s. The maximum surface temperature was 547 °C. The Glidcop Al-15[1] face-plate thickness under the heated area was 0.5 mm. The electron beam penetration depth in Glidcop was estimated to be less than 1 μm. Testing of this heat exchanger ended prematurely due to a braze failure at the face-plate.

The second helium-cooled divertor mock-up was designed and manufactured by General Atomics (Baxi et al. ,1993). It consisted of millimeter-size, axial flow channels machined in Glidcop Al-15. This design used low pressure drops and high mass flow rates to achieve good heat removal. The General Atomics specimen was tested to a maximum heat flux of 9 MW/m^2 rastered over a 20 cm^2 area while maintaining a surface temperature below 400 °C on the Glidcop. This temperature was selected to be compatible with a 2 mm thick beryllium tile at the plasma interface where the maximum surface temperature must be below 700 °C. The background pressure was 4.0 MPa, the pressure drop across the heat

[1]an alumina dispersion strengthened copper manufactured by SCM Corp. containing 15 v/o alumina.

exchanger was 55 kPa, and the helium mass flow rate was 22 g/s. The wall thickness under the heated area was 3 mm. The ΔT across the face-plate was approximately 43 °C, and the estimated heat transfer coefficient was 46,000 $W/m^2 \cdot °C$ (Baxi, 1994).

The third specimen was an Glidcop Al-15, axial flow, helium-cooled divertor mock-up filled with a porous metal wick designed and manufactured by Thermacore, Inc. (Rosenfeld, 1994, 1993). The internal porous metal wick effectively increases the available heat transfer area. This divertor module was characterized by low mass flow (0.7-1.1 g/s) and high pressure drop operation (45 to 65 kPa) at 4.0 MPa. It survived a maximum heat flux of 16 MW/m^2 rastered over a 1 cm^2 area and reached a steady state surface temperature of 613 °C. The minimum wall thickness under the heated area was 2.5 mm. At the maximum heat flux, the ΔT across the face-plate was calculated to be between 63 and 73 °C, and the estimated convective heat transfer coefficient, h, was between 5000 and 7000 $W/m^2 \cdot °C$.

Long term plans for helium cooling capabilities at the PMTF include the design, procurement and commissioning of a separate, much larger helium loop for the EB-1200 system. Operating pressures of 20 MPa and mass flow rates near 200 g/s are proposed. The new loop would be used for high heat flux testing of medium-scale helium-cooled divertor mock-ups.

BERYLLIUM HIGH HEAT FLUX TESTING AT THE PMTF

Since the HPHT coolant loop at the PMTF can control inlet temperatures to the sample while maintaining high working pressures, it is an ideal choice for the fatigue testing of beryllium components for the ITER program. Inlet temperatures as high as 280 °C can easily be maintained. Currently, the EBTS is a Sandia/Department of Energy Environment, Safety and Health (ES&H) approved beryllium handling facility. By the middle of 1995, the EB-1200 will also be an approved beryllium handling facility using the existing hardware and safety procedures now in place for the EBTS.

Thermal response and thermal fatigue tests of four 5 mm thick beryllium tiles on a Russian divertor mock-up were completed in the EBTS (Youchison et al., 1994). Each tile was 1 cm x 2 cm in area. The TGP-56 beryllium tiles were diffusion-bonded onto an OFHC copper saddleblock and a DSCu (MAGT) tube containing a porous coating. Thermal response tests were performed on the tiles to an absorbed heat flux of 5 MW/m^2 and surface temperatures near 300 °C using 1.4 MPa water at 5.0 m/s flow velocity and an inlet temperature of 8-15 °C. The electron beam was rastered over four tiles simultaneously. Following this test, the beam was rastered over each individual tile. One tile was exposed to incrementally increasing heat fluxes up to 9.5 MW/m^2 and surface temperatures up to 690 °C before debonding at 10 MW/m^2. A third tile debonded after 9200 thermal fatigue cycles at 5 MW/m^2, while another debonded after 6800 cycles. In all cases, fatigue failure occurred in the inter metallic layers between the beryllium and copper. No fatigue cracking of the bulk beryllium was observed.

A Brush Wellman diffusion-bonded, beryllium monoblock mock-up was also tested. This mock-up was an Brush Wellman S65 beryllium block with a 1.0 cm ID, 1.2 cm OD OFHC copper tube centered along the longitudinal axis of the block. The block dimensions were 1.84 cm x 1.85 cm x 5.02 cm. The smallest distance from the Be surface to the copper tube was 3 mm orthogonal to the tube. To relieve thermal stresses, a stress riser grid was machined into the top surface. The grid consisted of 2 mm deep grooves, 0.4 mm wide, which were wire cut into the top surface producing castellations approximately 5.5 mm x 5.5 mm square.

The monoblock was tested in a manner similar to the Russian flat tile mock-up using identical flow conditions. The electron beam was rastered over the entire 9.3 cm^2 surface area of the monoblock. Electron beam shot durations of 60 s were used to ensure steady state conditions in the water. During this test series, absorbed heat fluxes ranging from 1 MW/m^2 to 7.6 MW/m^2 were measured by water calorimetry. The surface temperature increased throughout the series, eventually reaching 526 °C at an absorbed heat flux of 8 MW/m^2. At this heat flux, the monoblock began to debond on one end, then the other. As additional shots were taken near 8 MW/m^2, the debonding slowly moved toward the center of the monoblock. No evidence of cracking or excessive sublimation of the beryllium was noticed.

Testing of medium-scale beryllium divertor modules is anticipated for 1995 on the EB-1200 system. ITER divertor-like power densities as high as 5 MW/m^2 over a 74 cm heated length can easily be applied for 10^4 cycles with 30 s durations. Using the HPHT loop, surface temperatures of beryllium between shots can be maintained above 150 °C which is necessary to maintain beryllium above its ductile-to-brittle transition temperature.

PMTF COMPUTER SYSTEM

The PMTF Computer System is used in three areas of high heat flux research: theoretical modeling and analysis, experimental control and data acquisition and post-test data reduction and analysis. The system consists of a heterogeneous network of computing resources. VMS and UNIX workstations, IBM and Macintosh PCs, data and file storage units and other peripherals are used for building models, graphically displaying theoretical analyses, design/drafting of mockup units, and for control and data acquisition during testing on the EBTS and EB-1200 systems. Connections to international networks provide increased electronic communications and file exchange.

The PMTF Data Acquisition and Control System, although connected to the facility computer network, operates independently. The PMTF data acquisition system is currently being upgraded to handle the data acquisition and control demands of the EB-1200 system. The topology is being upgraded to a star-hub configuration for both the EBTS and EB-1200 based upon CAMAC Ethernet crate controllers. The DEC Alpha AXP Open VMS™ and Vsystem™ software package increases flexibility to changes in experimental plans, provides a window based graphical user interface, and distributes control and data processes across multiple workstations, while preserving previous investments in CAMAC hardware and in-house software development. Each of the two electron beam data acquisition systems is configured with the following hardware and software.

Supervisory Control and Data Acquisition:

- 1 Alpha AXP™ Workstation
  - 175 MHz clock speed
  - 64 MB Memory
  - 100 MB/s I/O bandwidth
  - Secondary Ethernet
  - 2d Graphics Accelerator

Operator Interface and Analysis:

- 2 Pentium™-based personal computers
  - 90 MHz clock speed
  - 16 MB Memory
  - 1.6 MB/s ISA, 33 MB/s EISA I/O bandwidth
  - SVGA Graphics Accelerator

Communication Equipment:

- Thick/Thin/Fiber Ethernet
- Terminal servers and repeaters
- DEChub 90™ and DECrepeater 90FL™
- Cisco router
- Alpha open VMS™

Software:

- Vsystem™ suite of software
- Windows NT™ and Motif™ interfaces
- C, C++ and FORTRAN

Hardcopy devices:

- B/W, gray scale and color laser printers and plotters

Communication Protocols:

- DECnet, TCP/IP

In this arrangement, the DEC Alpha™ computer is supplemented with two Pentium™ PC's which provide a Windows™ graphical user interface for beam operation and run-time data analysis, while the Alpha™ computer provides for high-speed data acquisition and control using Vista Control Systems (VSystem™) software.

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