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**Critical Heat Flux Performance of Hypervapotrons Proposed
for Use in the ITER Divertor Vertical Target**

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ABSTRACT

Task T-222 of the International Thermonuclear Experimental Reactor (ITER) program addresses the manufacturing and testing of permanent components for use in the ITER divertor. Thermalhydraulic and critical heat flux performance of the heat sinks proposed for use in the divertor vertical target are part of subtask T-222.4. As part of this effort, two single-channel, medium-scale, bare copper alloy, hypervapotron mock-ups were designed by Sandia National Laboratories (SNL) and McDonnell Douglas Aerospace (MDA), fabricated at MDA and tested at Sandia's Plasma Materials Test Facility using the EB-1200 electron beam system. The objectives of our effort were to develop the design and manufacturing procedures required for construction of robust high heat flux (HHF) components, verify thermalhydraulic, thermomechanical and critical heat flux (CHF) performance under ITER relevant conditions, and perform analyses of HHF data to identify design guidelines and failure criteria and possibly modify any applicable CHF correlations. The design, fabrication, and finite element modeling of two types of hypervapotrons are described - a common version already in use at the Joint European Torus (JET) and a new attached-fin design. HHF test data on the attached-fin hypervapotron will be used to compare the CHF performance under uniform heating profiles on long heated lengths with that of localized, highly peaked, off-nominal profiles.

Keywords: hypervapotron, critical heat flux, thermalhydraulics, fusion energy, ITER, high heat flux, electron beam, tokamak, heat sink

1. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is a 1-GW, 1000-s pulse, DT fusion reactor.¹ Particle exhaust and impurity control are performed by a single-null divertor, which is composed of 60 cassettes positioned toroidally around the bottom of the machine. The water-cooled, outboard vertical target is one of the plasma facing components (PFCs) in each of the divertor cassettes shown in Figure 1. The power load to the outboard vertical target during nominal operation is about 210 MW around the entire circumference of the tokamak. Approximately 10% of the total power is dissipated in radiation. The vertical target is designed to spread the heat load over the largest area possible, while providing for optimum particle pumping and recycling. Currently, carbon-fiber composite (CFC) monoblock and tungsten tile armor protect the high-strength, copper alloy heat sink on this PFC. The nominal heat load to the vertical target is 5 MW/m², but it must be designed to survive localized, off-nominal transients as high as 30 MW/m² without burnout of the heat sink. Each channel in the vertical target has a flow length approximately 160 cm long, which is dictated by plumbing inside the cassette.

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Figure 1. A typical ITER divertor cassette contains inner and outer vertical targets, a gas box liner, the wings and the dome.

ITER task T-222 addresses the manufacture and testing of permanent divertor components.² Subtask T-222.4 concentrates on the thermalhydraulic performance of the divertor component heat sinks, including their CHF margin. As part of the task, heat sink materials were evaluated, heat transfer enhancement techniques were selected, mock-ups were designed, and manufacturing processes were developed. The task also included development of nondestructive joint inspection techniques, HHF testing, and analyses of HHF experiments to establish design guidelines and failure criteria. The results of this task will be used as a base for manufacturing armored, medium-scale and full-scale divertor prototypes in Task T232 and as an aid in predicting PFC lifetime performance.

The hypervapotrons are part of four reference design concepts selected by the ITER US Home Team for fabrication and comparison of thermalhydraulic performance. They are shown schematically in Figure 2. The first three designs are scheduled for testing this year. These include (1) one ribbed channel mock-up (URC-1) and (2) two hypervapotron mock-ups manufactured by McDonnell Douglas (UHV-1, UHV-2); (3) three circular channel mock-ups, two of which contain a porous metal coating manufactured by the D.V. Efremov Institute, Russian Federation (RF) (UBC-1, UPC-1, UPC-2), and (4) a swirl-rod insert (SRI) mock-up manufactured by General Atomics (GA).

Figure 2. Heat transfer enhancements are illustrated in the channel cross-section for each mock-up.

2. MOCK-UP FABRICATION

2.1 Manufacturing Techniques

The individual mock-ups represent a one-channel segment of a typical target plate and provide a 33 x 740-mm heated test area. The ribbed channel and hypervapotron were fabricated from the CuNiBe alloy, Hycon 3.³ Those fabricated by the Russian Federation were made of CuCrZr and DS copper (Al-25). Unlike the ITER first wall, the copper alloys used in the divertor provide part of its structural integrity. This makes the physical properties of these alloys, which were obtained by McDonnell Douglas and are shown in Table 1, extremely important. The SRI mock-up included an explosion-bonded, SS316 back plate to add stiffness and to begin developing the necessary procedures for fabricating full-scale hardware. Due to budget constraints, the final fabrication of the SRI mock-up was postponed indefinitely.

The general ribbed channel and hypervapotron cooling channel configuration is shown in Figure 3. The top and base plates of both mock-ups were machined separately and the plates then joined with an e-beam weld to form the cooling channel. Weld features and lengths were standardized on both mock-ups to facilitate manufacturing. The water supply tubes with welded mini-conflat flanges and three pressure taps were brazed to the mock-up using a #604 (60Ag-30Cu-10Sn) braze alloy at 720°C.

Figure 3. Channel cross-sections show comparison between the ribbed channel and hypervapotron geometries.

The hypervapotron design is derived from the standard JET configuration.⁴ The teeth are 3 mm wide by 4 mm high and cut on 6-mm centers. The open channel is 5 mm high, as indicated. Based on flow testing results discussed later, this open configuration leads to minimal hypervapotron pressure drop penalty compared with a smooth-walled channel. Yet, there appears to be a significant improvement in heat transfer and CHF performance based on recent EU test results.^{5,6} Thermal-structural analyses of the dome and vertical target indicate that hypervapotron fatigue life at ITER-relevant heat fluxes can be enhanced by attaching the hypervapotron teeth to the sidewalls of the channel. JET hypervapotrons were not fabricated in this manner, because they were not being subjected to the high internal pressures (4 MPa) and surface heat fluxes (30 MW/m²) as required in ITER. To investigate the effect that this change has on thermalhydraulic performance, a second hypervapotron was machined with the teeth connected to the sidewalls.

The front plates for both the ribbed channel and hypervapotron plates were machined using high-speed cutting techniques developed at MDA. This allowed the parts to be cut to the desired tolerances in a matter of minutes with minimal distortion. Final dimensional checks over the 1-m long mockups showed that the perimeter mating profiles were all within the 0.125-mm tolerance required for e-beam welding. A photograph of the finished hypervapotron front plates is shown in Figure 4. Fabrication of both hypervapotrons was identical, except the final slitting operation to separate the teeth from the sidewall was not performed on the attached-fin hypervapotron.

Table 1. Physical Properties of Copper Alloys

HYCON 3 - Solutionized, Air Quenched, and Aged - Ready for Design

TEMP (C)	ALPHA (°C) (x 10 ⁶)	SECANT (°C) (x 10 ⁶) Tref = 20°C	HEAT CAPACITY (J/kg-°C)	YIELD STRENGTH (MPa)	ULTIMATE STRENGTH (MPa)	YOUNG'S MODULUS (GPa)	DENSITY (Mg/m ³)	THERMAL CONDUCTIVITY (W/m-°C)	POISSON'S RATIO
20	16.614	16.614	384	667	719	139	8.829	274	0.3
200	17.352	16.983	408	562	613	120	8.749	277	0.3
400	18.172	17.393	426	447	496	98	8.657	276	0.3
600	18.992	17.803	435	331	378	76	8.562	271	0.3
750	19.607	18.111	436	244	290	60	8.488	266	0.3
Equation	0.0041T + 16.532		381 + 0.156T - 1.094E-4T ²	678.17 - 0.5784T	730.35 - 0.5869T	141.48 - 0.1085T	-3.725E ⁻⁸ T ² - 4.382E ⁻⁴ T + 8.838	274 + 0.022T - 4.39E ⁻⁵ T ²	0.3

Mechanical properties above 350°C valid for exposure times less than 8 minutes.

GLIDCOP AL-25 - Annealed - Ready for Design

20	16.842		384	345	429	134	8.860	344	0.3
200	17.320	17.066	408	239	280	121	8.780	318	0.3
400	18.066	17.386	426	142	153	106	8.687	299	0.3
600	19.036	17.781	435	66	68	91	8.592	289	0.3
750	19.911	18.127	436	24	32	79	8.518	288	0.3
Equation	16.8 + 0.00204T + 2.81E ⁻⁶ T ²		381 + 0.156T - 1.094E ⁻⁴ T ²	358 - 0.6479T + 2.698E ⁻⁴ T ²	448 - 0.9443T + 5.196E ⁻⁴ T ²	135 - 0.0696T - 7.41E ⁻⁶ T ²	-3.737E ⁻⁸ T ² - 4.397E ⁻⁴ T + 8.869	347 - 0.168T + 1.19E ⁻⁴ T ²	0.3

JET CuCrZr - Solutionized, Air Quenched, and Aged - Ready for Design

20	16.614	16.614	384	249	397	139	8.829	374	0.3
200	17.352	16.983	408	222	324	120	8.749	364	0.3
400	18.172	17.393	426	192	244	98	8.657	354	0.3
600	18.992	17.803	435	162	163	76	8.562	345	0.3
750	19.607	18.111	436	140	102	60	8.488	339	0.3
Equation	0.0041T + 16.532		381 + 0.156T - 1.094E ⁻⁴ T ²	251.74 - 0.1489T	404.73 - 0.403T	141.48 - 0.1085T	-3.725E ⁻⁸ T ² - 4.382E ⁻⁴ T + 8.838	375 - 0.0596T - 1.59E ⁻⁵ T ²	0.3

Mechanical properties above 300°C valid for exposure times less than 30 minutes.

Extrapolation past 450°C

Figure 4. Completed hypervapotron front plates were manufactured both with and without the vapotron teeth connected to the sidewalls.

Based on perimeter and tube stub weld development, it was decided to have the front plates in the fully hard temper and the back plates in the solution annealed and quenched temper for welding. The parts were cleaned and chemically etched

prior to welding. After welding, the parts were aged at 450°C between 1 and 3 hr to fully harden the weld and the back plates. Sample, full-sized front and back plates were welded together to verify the beam parameters for the perimeter weld. The sample part passed ambient temperature, 7 MPa proof pressure and He leak checks.

2.2. Analyses

2.2.1. CFD Modeling

Computational fluid dynamics finite-element (FE) modeling was undertaken to determine the optimum fin height for single-phase, forced-convection cooling. The 2-D model contained 10 teeth in the axial direction with over 430,000 node points. Results of the study indicated that a fin height of 1.5 mm was optimum for a 10 m/s flow at 4 MPa. Changes in fin spacing were not investigated. The model used an incompressible gas at 90 °C and 15.2 MPa that produced fluid properties similar to water at 4 MPa as the coolant. This optimum geometry had the highest flow velocity near the boundary layer of 7 m/s, evenly distributed in the troughs and fin tops. This is in contrast to our current hypervapotron geometry, which has a flow velocity of 7 m/s at the fin tops, but only 3 m/s in the troughs. Velocity vectors and streamlines for the optimum case are shown in Figure 5. Another hypervapotron with this optimized geometry will be fabricated and tested next year. Note that these results are not valid for two-phase flow in the boiling regime and beyond, but are applicable for single-phase flow.

Figure 5. Shorter hypervapotron teeth produce the highest flow velocities at the film boundary.

2.2.2 FEA Modeling

The finite-element analyses for the MDA hypervapotron were performed using a geometric mesh that contains 1564 elements and 4977 nodes. This mesh structure results in a density of 8 nodes per millimeter, which should capture all the subtleties of heat conduction within the hypervapotron. Three individual analysis scenarios were considered:

1. nominal {uniform beam profile} incident heating with the hypervapotron assumed to have the cooling efficiency of a bare tube,
2. nominal {uniform beam profile} incident heating with the hypervapotron assumed to have the cooling efficiency of a tube with a swirl tape insert that has a twist ratio of 2,
3. off-nominal {peaked beam profile} incident heating with the hypervapotron assumed to have the cooling efficient of a tube with a swirl tape insert with a twist ratio of 2.

A uniform surface heating profile was used during “normal” or “nominal incident heating” while a nonuniform surface heat profile was used during “off-nominal” peaked heating in the ABAQUS finite-element analysis (FEA) calculations.⁷ The off-nominal incident heating was simulated by dividing the heated surface of the geometric mesh into three equivalent sections. Since the heated lengths of each section are equal, it is possible to proportion the total heat flux across the sections and still conserve the total amount of added heat. Table 2 shows the heat flux applied to the various sections for the off-nominal heating calculations.

The bare tube was chosen as a baseline for comparison, while the tube with the swirl tape insert was chosen as a consequence of recent European experimental data⁸ that suggest the hypervapotron has lower surface temperatures at equivalent incident heat fluxes and a higher measurable CHF than a similar swirl tape tube.

The determination of the heat transfer coefficients for the hypervapotron is highly speculative at this point. Therefore, we decided to apply the heat transfer coefficient correlations traditionally used in fusion, at least until such time that the experimental data prove these to be insufficient. Table 3 presents the correlations used in the FEA.

Table 2. Partitioning of Heat Flux during Off-Nominal Incident Heating Calculations (W/cm²)

Total Heat	Section 1	Section 2	Section 3
100	5	80	15
500	25	400	75
1000	50	800	150
1500	75	1200	225
2000	100	1600	300
2500	125	2000	375
3000	150	2400	450
3500	175	2800	525

Table 3. Heat Transfer Coefficient and CHF Correlations Used in FEA Calculations

Regime	Correlation
Single Phase	Seider-Tate ⁹
Two Phase	Araki ¹⁰
Local CHF	Tong-75 ¹¹

If the hypervapotron possesses the cooling efficiency of a swirl tape tube, then its surface temperature will be 45 °C lower (335 °C vs. 380 °C) than the baseline case of the bare tube, as indicated in Figure 6. This temperature difference is also present at the hypervapotron wall, as presented in Figure 8. Again, the hypervapotron wall should be 50 °C colder (232 °C vs. 282 °C) than the baseline case.

Figure 6. FEA compares performance of hypervapotron (swirl tape with twist ratio, $y=2$) with a bare tube.

Figure 7. FEA was performed on hypervapotrons using both nominal and off-nominal heat flux profiles.

The off-nominal heating case results in lower surface and wall temperatures since the heat being supplied to the center section is less than in the nominal scenario. Figure 7 shows that the peak surface temperature in the off-nominal heating case at an incident heat flux of 10 MW/m² is 81 °C colder (254 °C vs. 335 °C) than the normal heating case. Although the surface temperature in the off-nominal heating case is considerably colder than in the normal heating case, this large temperature difference does not translate to the wall conditions, as shown in Figure 8. The off-nominal heating case has a peaked wall temperature that is only 42 °C colder (190 °C vs. 232 °C) than the normal heating case.

Figure 8. FEA temperature contours for 30 MW/m², 150°C, 15 m/s, 4 MPa, (1 = 185°C, 2 = 212°C, 3 = 240°C, 4 = 267°C, 5 = 295°C, 6 = 322°C, 7 = 350°C, 8 = 377°C, 9 = 405°C, 10 = 432°C) illustrate a peaked temperature distribution.

The boundary conditions and assumptions used in the pre-experiment FEA modeling have an enormous effect on the results. The following assumptions were used:

- cooling channel has an equivalent hydraulic diameter of 8.28 mm,
- vortices in the coolant flow patterns are not included in the FEA analyses,
- the Hycon hypervapotron is assumed to have a minimum cooling efficiency of a copper tube with swirl tape insert of twist ratio 2.

3. HIGH HEAT FLUX TESTING

3.1. Objectives

The primary objectives of the mock-up testing, in order of importance, are:

1. Obtain critical heat flux data under ITER-relevant flow and coolant conditions for ITER HHF component configurations.
2. Verify that the test mock-up can withstand the ITER off-nominal peaked profiles ($\sim 15, 20, 30$, and 40 MW/m^2 peak heat flux, for at least 10 s) at the water pressure, flow velocity and temperature conditions planned for the ITER divertor. The tests are designed to find the performance margin over these heat flux values.
3. To verify heat transfer coefficients/correlations currently in use by comparing finite-element calculations with measured temperatures.
4. Verify FE model predictions of mock-up deflections and distortions.
5. A secondary objective will be to collect enough data on temperature distribution in the test module so that future calculation of heat transfer coefficients by inverse conduction analysis is possible.

The divertor HHF medium-scale mock-up designs were developed to establish performance characteristics relative to the ITER nominal power profile with a surface heat load of 5 MW/m^2 . They also must have the capability to remove up to 15 MW/m^2 (peak) at special locations (plasma striking points and the baffles points) for subpulses of 10 s (a few times during each 1000-s pulse at nominal parameters).

3.2. Testing in the EB-1200

A schematic of the EB-1200 system appears in Figure 9, while Table 4 shows its broad operating range.¹² During the CHF testing campaign, three mock-ups are inserted side-by-side for testing in the EB-1200.¹³ The outer two mock-ups form a close-fitting heat shield around the center mock-up to allow uniform heating across the full center mock-up width during the tests. The mock-ups are not mechanically linked to allow for free expansion/deflection of one mock-up relative to the others. The EB-1200 beam spot size is approximately 15 mm at full width half-maximum (FWHM) and is rastered over the heated area using a pattern repetition rate of 500 Hz. The electron beam raster pattern is enlarged to cover about half the width of each edge mock-up. Higher water flow velocities are provided to the two edge mock-ups to ensure higher CHF margins than the center mock-up.

The mock-up heated surface forms a large portion of the total surface (888-mm length). The maximum heated length available is about 740 mm (centered on either side of the centerline). The heated surface length is constrained by the mock-up support structure. The heated width is ~ 33 mm (single mock-up width) with beam spillage to the two edge mock-ups for a total combined width approaching 70 mm.

The general mock-up mounting arrangement is illustrated in Figure 10. This figure also shows the interfaces with the EB-1200. The mock-ups attach to the vacuum chamber door mount through two support struts and bracket hardware that can position the mock-up front plate at the focal plane of the two electron beams in a repeatable fashion. Coolant is supplied through four separate supply/return lines that penetrate the door. The facility coolant lines contain a flexible bellows interface that permits the 4-MPa lines to adjust to the mock-up flanges if necessary. This eases the alignment requirements on the mock-up coolant lines and ensures that there are no residual stresses in the joints after attachment to the door. The interface is designed so that the bellows are only subjected to atmospheric pressure, not the 4 MPa coolant pressure. Water-cooled shields are used to protect end fittings, thermocouples, and the gaps between mock-ups from beam spillage and secondary electron bombardment.

Figure 9. The EB-1200 is currently the most powerful electron beam HHF test facility in the world.

Table 4. EB-1200 Operating Ranges

gun power (kW)	0.1-1200
sweep frequency (kHz)	x: 10 kHz, y: 500 Hz
shot pulse length (s)	> 0.1s
beam spot size (diameter - mm)	15
pressure (MPa)	0.5-7
flow rate (l/s)	11
inlet temperature (°C)	20-230
vacuum pressure (Pa)	$< 1 \times 10^{-4}$
maximum number of thermocouples	48
maximum sweep length (cm)	37
maximum sample length (cm)	90

All components received the following proof tests prior to delivery to SNL by McDonnell Douglas. Certifications provided along with the mock-ups included:

- Proof pressure to 7 MPa at room temperature.
- Cold helium leak check at 300°C, $< 10^{-9}$ Pa-m³/s or lowest measurable.
- Dimension and tolerance report and quality assurance/quality control inspections before and after delivery.

The top surfaces of the mock-ups were grit blasted with 25 μ m Al₂O₃ beads at 4.1 - 5.5 MPa for approximately 15 s. The mock-ups were then baked in air at 300°C for 2 hr and placed in a relative humidity of 100% at 70°C for 3 days. This procedure creates a uniform layer of oxidation that increases the copper surface emissivity from < 0.1 to approximately 0.4. The increased emissivity of the heated surface area correspondingly increases the efficiency of the low-wavelength pyrometer, and makes a more uniformly emitting surface for the infrared camera. After baking, the mock-ups were cleaned in isopropanol.

Figure 10. Mock-up support and cooling interfaces for the EB-1200 system were designed and manufactured simultaneously with the mock-ups.

3.3. Instrumentation

A complete set of diagnostics supported the HHF tests and provided the information needed for comparison with numerical analyses. The following instrumentation was used for each mock-up.

- Turbine flow meter to measure flow rate in each mock-up channel located on the exit line with an accuracy of $\pm 1\%$.
- Inlet water temperature.
- Outlet water temperature.
- Absolute pressure transducers located at the inlet, outlet and predicted CHF location (1-3 in Table 5).
- Two differential pressure transducers as listed in Table 5.
- Ungrounded, 0.5-mm diameter, SS-sheathed, Type K target thermocouples (TC) mounted in each test mock-up:
 - The TC distribution is optimized to the HHF profile (see Figure 12).
 - The maximum number of TCs for each test mock-up is 35 for ribbed channel, 39 for the conventional hypervapotron, and 43 for the attached-fin hypervapotron.
- Surface temperature in the heated area:
 - Low-wavelength optical pyrometer, 150-550°C range.
 - Calibrated spot temperatures from the IR camera, 50-1500°C range.
 - One-color low-range optical pyrometer, 300-850°C range.
- Surface temperature distribution from calibrated IR thermography.
- Voltage-current (V-I) measurement of emitted electron gun power.
- Line-scan mode for IR camera near anticipated burnout location.
- Platinum resistance temperature device (RTD) water calorimetry for each channel.
- Linear Variable Differential Transmitters (LVDTs) to measure deflection near the inlet, outlet and CHF location: - 26.5 cm, 7 cm, 26.5 cm.

All thermocouples were Type K, 0.5-mm diameter, electrically isolated and sheathed. Thermocouples and their leads are shielded from direct and reflected beam power by installing them in holes and/or grooves cut into the mock-ups as indicated in Figure 11. Since the CHF location for the ITER profiles cannot be accurately predicted, mock-ups will contain more thermocouples than will typically be monitored in realtime during testing. Although as many as 48 thermocouples can be recorded, only 16 can be monitored in realtime. The 16 monitored thermocouples should be adequate to detect the onset of CHF at critical locations along the mock-ups. If necessary, alternative thermocouples can be selected for monitoring or else the pattern position can be adjusted to position the CHF location coincident with the thermocouples. Figure 12 indicates the typical location and labeling of the thermocouples in the divertor medium-scale mock-ups. Pressure transducer locations are summarized in Table 5. In all cases, beam power was terminated if the surface temperature at any pyrometer spot location exceeded 800°C. Finite-element modeling was used to provide an estimate of maximum expected surface temperature as a function of heat flux for the planned test conditions.

(Transducers were located along channel backside centerline, $Y=0$.)

Pressure Differential	Identifier :
PT-1 - PT-2	PD-1/2
PT-1 - PT-3	PD-1/3

The CHF tests began with uniform heat flux profiles over long heated lengths to ensure that axial conduction effects were minimal. The heat flux was then varied with length as indicated in Figure 13 to conserve total absorbed power and keep exit temperature and pressure constant. CHF tests with localized, peaked profiles, as predicted for the ITER vertical target during off-nominal transients, were also performed to verify the increase in CHF margins first observed at the EB-200 facility in France.⁶

Inlet Pressure:	3 , 4, and 5 MPa (At inlet pressure transducer)
Inlet Velocity:	5, 10, and 15 m/s (Based on measured mass flow rate and mock-up channel nominal flow area)
Inlet Temperature:	100,125 and 150°C (At mock-up inlet)
Heat Flux Level:	5 MW/m ² to 25 MW/m ²
ICHF Step Total Heat Load:	0.12 MW (Uniform step heat flux)
Heated Length with Uniform Heat Flux:	100 - 400 mm uniform step profile
Heated Length with ITER Off-nominal Profile:	< 400 mm “double-Gaussian” profile

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Figure 1 is a schematic diagram of the test facility, showing three views: Back Face View, Right Side View, and Front Face View.

Back Face View: This view shows the back of the test facility. It features a horizontal tube with a centerline. Thermocouples (TC) are located at TC-38, TC-40, TC-41, TC-42, and TC-43. The left side is labeled "LEFT SIDE" and the right side is labeled "RIGHT SIDE".

Right Side View: This view shows the right side of the test facility. It features a horizontal tube with a centerline. Coolant inlet and outlet ports are shown. Pressure transducers (PT) are located at PT-1, PT-2, and PT-3. The back face is labeled "BACK FACE" and the front face is labeled "FRONT FACE".

Front Face View: This view shows the front of the test facility. It features a horizontal tube with a centerline. Thermocouples (TC) are located at TC-1, TC-2, TC-3, TC-4, TC-5, TC-6, TC-7, TC-8, TC-9, TC-10, TC-11, TC-12, TC-13, TC-14, TC-15, TC-16, TC-17, TC-18, TC-19, TC-20, TC-21, TC-22, TC-23, TC-24, TC-25, TC-26, TC-27, and TC-28. Pressure transducers (PT) are located at PT-1, PT-2, and PT-3. The left side is labeled "LEFT SIDE" and the right side is labeled "RIGHT SIDE".

Legend:

- TC - THERMOCOUPLE
- PT - PRESSURE TRANSDUCER

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Uniform HHF Profiles

The purpose of this classical CHF test was to obtain a general correlation of critical heat flux for the selected geometry. The reference critical heat flux correlation is Tong'75 as used by the ITER JCT. Mock-up-specific correlation coefficients and parameter exponents will be developed as the result of these tests to tailor the Tong'75 correlation. For the CHF tests, a uniform heat flux was imposed over a specified length, for fixed inlet condition of: (1) pressure, (2) temperature, and (3) flow velocity.

The following strategy was used for the uniform heat flux profiles. First, a curve of surface temperature versus absorbed heat flux, known as a "thermal response" curve, was generated for each mock-up by adhering to the following procedures. A uniform heat flux was applied until steady state was reached. Steady state was assumed when the mock-up coolant channel thermocouple readings and RTD signals at the exit location were observed to be essentially unchanged over a one-minute period. Starting with a heat flux level that is about 10% of the calculated CHF value for the given coolant conditions, the heat flux level was increased until CHF occurred. A total of 0.12 MW will be applied to the mock-up for each CHF test. The heat flux level was increased by the reduction of heated length to maintain total heat load (e-gun power is constant). For each shot, the step heating profile ended at a selected location where the instrumentation was concentrated. Figure 13 shows the uniform profiles used for CHF testing. As indicated in Table 6, this process was repeated as required, increasing heat flux by reducing heated length, for several heat fluxes until CHF was reached. When the incident CHF (ICHF) is exceeded, a temporal inflection in the steady state surface temperature may occur. As a safety precaution, the beam power was electronically terminated any time the mock-up surface temperature exceeded 800°C as measured by any of the pyrometers, or any thermocouple near the surface produced readings exceeding 600°C.

After a complete scan with one parameter, e.g. velocity, another complete thermal response curve was generated for the Hycon mock-ups to investigate any possible changes in thermal conductivity of the alloy as were found for CuCrZr in the EU.⁷

The strategy outlined in the test matrix found in Table 6 starts with the least aggressive cooling, i.e., high inlet temperature (150 °C), low pressure (3 MPa), and low flow velocity (5 m/s), and proceeds to the most aggressive cooling by increasing the flow velocity, increasing the pressure, and reducing the inlet temperature for each scan. This is done to obtain as much critical data as possible within a minimum amount of time. The full thermal response curves are shorter and require less time to compile for the least aggressive cooling. Therefore, we started with the lowest CHF value and worked toward the highest.

Figure 13. Typical CHF step profiles that demonstrate the methodology. Between 10 and 20 profiles are performed for each set of flow conditions.

Table 6. Uniform Profile Critical Heat Flux Test Matrix

Run #	Temp (°C)	Inlet Pressure (MPa)	Flow rate (m/s)	Shot Duration* (s)	Profile	Peak Heat Flux (MW/m ²)	Heated Length (mm)	Req'd Pyro Trip (°C)
1-2	150	3	10	300	Uniform	10, 15	360, 240	800
3-5	150	5	10	300	Uniform	10, 15, 20	360, 240, 180	800
6-7	150	4	5	300	Uniform	10,15	360, 240	800
8-10	150	4	10	300	Uniform	10, 15, 20	360, 240, 180	800
11-14	150	4	15	300	Uniform	10, 15, 20,25	360, 240, 180, 144	800
15-17	125	4	5	300	Uniform	10, 15, 20,	360, 240, 180,	800
18-20	125	4	10	300	Uniform	10, 15, 20	360, 240, 180	800
21-24	125	4	15	300	Uniform	10, 15, 20, 25	360, 240, 180, 144	800
25-27	100	4	5	300	Uniform	10, 15, 20,	360, 240, 180, 144	800
28-31	100	4	10	300	Uniform	10, 15, 20, 25	360, 240, 180, 144	800
32-35	100	4	15	300	Uniform	10, 15, 20, 25	360, 240, 180	800

* Shot duration is 300 s or until steady state is achieved.

Off-Nominal, Highly Peaked HHF Profiles

Typical ITER off-nominal heat flux profiles used for the HHF testing are shown in Figure 14. The separatrix maps to the 100-mm location on the x-axis. Positive x values correspond to moving upward along the vertical target plate. The profiles conserve total power to the mock-up to more realistically simulate the plasma-induced conditions. All profiles are positioned axially so that the probable critical heat flux location aligns with a cluster of thermocouples and a pressure transducer. The figure illustrates the capability of the EB-1200 facility to reproduce the ITER profiles in the form of 15-mm wide histograms.

Comparisons of the recent EU test results with the hypervapotron ICHF correlation developed by Baxi based on past JET testing show that the EU results are significantly higher (by a factor of 1.6) than predicted by Baxi's correlation.¹⁴ Higher flat profile heat flux levels were added to the US test plan to validate this performance regime. After our uniform profile CHF tests were completed, a series of CHF tests were run on each mock-up with the highly peaked ITER off-nominal profiles. Axial conduction effects for the peaked profiles cause an ICHF enhancement. Recent test results on the EU's FE-200 system at Le Creusot, France indicate that ICHF may be enhanced by a factor of 2.5 over the Baxi correlation for these peaked profiles.

The purpose of this procedure is to ascertain how longitudinal conduction losses or short length/diameter (L/D) effects might allow the mock-up to reach CHF with higher peak heat flux levels than would be possible under uniform heat loading. The ITER off-nominal "double Gaussian" profile used for testing is shown in Figure 14. The smooth curves were developed by assuming a constant Gaussian shape for the power decay with a different decay length for each peak power level. The ITER plasma separatrix maps to the zero location on the x-axis and positive x values correspond to moving upward along the vertical target plate. Figure 14 also illustrates the capability of the EB-1200 facility to reproduce the ITER profiles in the form of histogram curves. These histograms are derived by conserving power to the surface over 15-mm long bands or sections along the heated length of the mock-up. In all cases, the total power to the mock-up surface is conserved.

Since it is extremely time consuming to re-adjust the dwell times for each section of the EB-1200 pattern and verify the accuracy of the absorbed heat flux profile, it was decided to increase the peak heat flux by simply decreasing the heated length. No effort was made to readjust the heat flux profile from the original 15 MW/m² peaked profile. Nor was it possible to measure and verify the absorbed heat flux profile for each decrement in heated length. The programmed beam dwell time in each section and the total absorbed power were conserved throughout. Testing was performed only at the ITER divertor reference flow conditions (150 °C inlet, 4 MPa, 10 m/s) using the matrix in Table 7.

Figure 14. ITER off-nominal operating conditions produce peaked heat flux profiles. The overlaid histograms depict the EB-1200 simulation of the ITER off-nominal profiles.

Table 7. ITER Off-Nominal Profile Test Matrix

Run #	Temp. (°C)	Inlet Pressure (MPa)	Flow rate (m/s)	Shot Duration* (s)	Profile	Peak Heat Flux (MW/m ²)	Req'd Pyro Trip (°C)
1	150	4	10	300	Gaussian	15.0	800
2	150	4	10	300	Gaussian	17.5	800
3	150	4	10	300	Gaussian	20.0	800
4	150	4	10	300	Gaussian	22.5	800
5	150	4	10	300	Gaussian	25.0	800
6	150	4	10	300	Gaussian	27.5	800
7	150	4	10	300	Gaussian	30.0	800

- Shot duration is 300 s or until steady state is achieved.

Hypervapotron ICHF performance has previously been assessed and published by the EU. Our hypervapotron medium-scale mock-ups have a geometry similar to the EU test element (HV1) and the performance results are comparable. The predicted ICHF capability using a factor for a uniform heating profile based on EU test results and an absolute pressure of 4 MPa ranges from 21 MW/m² at 10 m/s and a subcooling of 100 °C to 32.5 MW/m² at 15 m/s and a subcooling of 150 °C. The ICHF performance for an off-nominal test profile was predicted to be about 50% greater.

Pressure Drops

Figure 15 shows a summary of hypervapotron pressure drop data as a function of free flow channel height and Reynolds number. These data were obtained at the University of Illinois on an adjustable-channel-height, rapid-prototype model of the hypervapotron developed by MDA. The figure illustrates the typical quality and consistency of the available data. The data are compared against the pressure drop correlation of Baxi¹⁴ and that of a classic correlation for a smooth tube.

Figure 15. The friction factor for the hypervapotron is significantly less than predicted.

The results indicate that the hypervapotron pressure drop is significantly lower than previously predicted based on the Baxi correlation. It appears that more extensive testing is required to develop a statistically robust hypervapotron pressure drop correlation. As expected, the data show a clear pressure drop dependence on channel height, but it was much stronger than anticipated. The friction factor appears to asymptotically approach the classical smooth channel correlation as channel height increases. Further testing is planned at larger channel heights to better establish the asymptotic height dependence of the friction factor correlation. Testing at these larger channel heights should also permit the database to be extended to higher Re numbers.

4. FUTURE MOCK-UPS

Two porous coated mock-ups fabricated by the Russian Federation and the ribbed channel mock-up developed by MDA will be tested later this year. Also, as part of our exchange program with the ITER EU Home Team, a swirl tape mock-up of a design identical to one already tested on the FE-200 system in Le Creusot will be tested in the EB-1200. This will be a validation test of the EU results using a different technique. In the FE-200, CHF is reached by increasing total power to the mock-up; whereas, in the EB-1200 CHF will be reached by decreasing the heated length under constant incident power.

Next year, as suggested by the CFD analysis, a third attached-fin hypervapotron with shorter vapotron teeth and larger channel height will be tested on the EB-1200. We also plan to begin testing beryllium and tungsten armored mock-ups of similar size by using our successful joining techniques for beryllium and tungsten developed in task T221 and the hypervapotron heat sink.

5. CONCLUSIONS

This paper outlines the design, manufacturing, HHF testing and analyses of medium-scale hypervapotron mock-ups. This represents a tremendous effort by a large group of people confronted with handling the power dissipation of a 1-GW fusion reactor. Careful selection of mock-up materials, economic manufacturing procedures, including proof tests, nondestructive evaluation and quality assurance, attention to extensive instrumentation and mounting requirements for the HHF testing, and the predictive results from finite-element modeling were all part of this effort.

Initial testing of the attached-fin hypervapotron may indicate that a significant enhancement in ICHF can be obtained for highly localized, peaked heat flux profiles. Axial conduction losses result in higher ICHF values. This is very important, since it will allow the ITER vertical target to withstand a localized transient greater than 30 MW/m² before burnout, which may occur during off-nominal, "connected plasma" operation or during a plasma disruption. This provides a sufficient CHF margin for a successful design of the ITER vertical target from an otherwise intractable thermalhydraulics problem.

CHF testing is still under way on the EB-1200. Enough data will soon be available to compare the performance of the attached-fin hypervapotron and the conventional hypervapotron.

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REFERENCES

1. "General Design Requirements Document (GDRD)," ITER Report S10 GDRD 1 95-02-10, W1.2, ITER Joint Central Team, Garching, Germany (1995).
2. G. Janeschitz, "Design Description Document (DDD) Divertor (WBS1.7)," ITER Report G17DDD 1 94-12-2W 00-AB, ITER Joint Central Team, Garching, Germany (1994).
3. Hycon 3 is a CuNiBe alloy manufactured by Brush Wellman, Inc., ASTM B534, Copper Development Association Alloy # C17510
4. H.D. Falter and E. Thompson, "Performance of Hypervapotron Beam Stopping Elements at JET," *Fusion Technol.* **29**, 584 (1996). And H.D. Falter, et al., "Vapotron as Heat Sink for Flat High-Conductivity Unidirectional Carbon-Fiber-Composite Tiles," *Fusion Technol.* **29**, 571 (1996).
5. J. Schlosser, "Manufacture and Testing of Permanent Components - Optimization of Cooling System Complementation of Critical Heat Flux Thermalhydraulics for Swirl and Vapotron," Task T222.4 *Intermediate Report 1*, PCO/95-10, Direction des Sciences de la Matiere, Dept. de Recherche sur la Fusion Controlee, Association Euratom - CEA, Cadarache, France (October, 1995).
6. J. Schlosser, "Manufacture and Testing of Permanent Components - Optimization of Cooling System Complementation of Critical Heat Flux Thermalhydraulics for Swirl and Vapotron," Task T222.4 *Intermediate Report 2*, PCO/95-11, Direction des Sciences de la Matiere, Dept. de Recherche sur la Fusion Controlee, Association Euratom - CEA, Cadarache, France (November, 1995).
7. "ABAQUS User Manual," Version 5.6, Hibbitt, Karlsson and Sorenson, Pawtucket, RI (1996).
8. F. Escorbiac, J. Schlosser, G. Vieider, I. Smid, "Preliminary Results from Thermalhydraulics Tests at CEA Cadarache (T222)," ITER Divertor Project L5 Meeting (T232), St. Louis, MO (June 1996).
9. E.N. Sieder and G.E. Tate, "Heat Transfer and Pressure Drop of Liquids in Tubes," *Ind. Eng. Chem.* **28**, 12 (1936).
10. M. Araki, M. Ogawa, T. Kunugi, S. Ikeda, K. Satoh, and S. Suzuki, "Experiment on Heat Transfer of the Smooth and the Swirl Tubes Under One-Sided Heating Conditions," *JASME*, August 1996.
11. L.S. Tong, "A Phenomenological Study of Critical Heat Flux," *ASME* 75-HT-68 (1975).
12. D.L. Youchison, J.M. McDonald, L.S. Wold, "High Heat Flux Testing Capabilities at Sandia National Laboratories - New Mexico," 1994 Winter Annual Meeting of the ASME, *Heat Transfer in High Heat Flux Systems*, HTD-Vol. **301**, ASME Book No. G00956-1994, p. 31.
13. D. Driemeyer, "T222.4 Design Guidelines Document," ITER Report ITER/US/96/IV-DV-04, ITER U.S. Home Team, San Diego, CA (1996).
14. C.B. Baxi, "Comparison of Swirl Tape and Hypervapotron for Cooling of ITER Divertor," 16th IEEE/NPSS Symposium on Fusion Engineering, Univ. of Illinois, 1995, pp. 186-189.

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