

First Wall Qualification Testing at SNL

T. J. Tanaka^a, Alice Ying^b, Manmeet Narula^b, Michael A. Ulrickson^a

^a Sandia National Laboratory, Albuquerque, USA

^b University of California, Los Angeles, USA

Abstract—The first wall of ITER will be a replaceable sandwich of beryllium tiles, water-cooled copper alloy, and a water-cooled stainless steel backing. The first wall will be subject to approximately 30,000 pulses of surface heating at levels of 0.2–0.5 MW/m² and 5–10 W/cm³ of volumetric nuclear heating. At these low heating levels, the main failure mechanism is predicted to be fatigue, particularly at the interface between the copper alloy and beryllium tile. Six different party teams are proposing to produce the first wall for ITER. To qualify the processes and materials for producing the first wall, small mock-ups will be subject to fatigue testing at Sandia National Laboratories' (SNL) Plasma Materials Test Facility and at a European Union test facility. We propose that the failure of a joining process is determined by an increase of surface temperature over nominal temperatures for a given surface heat flux. If the joint between a Be tile and Cu alloy degrades, the path from the heated surface to the coolant in the copper alloy increases, which should result in a higher surface temperature. This paper will document the test setup and preliminary analysis of the fatigue testing and failure criteria at SNL.

Keywords—ITER, Tokamak, Blanket module, first wall shield.

I. INTRODUCTION

ITER is an international effort of seven parties to build a magnetic fusion reactor. Six of these parties, China, European Union, Japan, Korea, Russian Federation and the United States, are planning to build the first wall that protects the vacuum vessel from heat and radiation. The first wall is a replaceable water-cooled shield that absorbs the plasma surface heating as well as nuclear volumetric heating. Since so many different parties are planning to build this first wall, the ITER International Organization (IO) has required each party to produce a mock-up of the first wall that passes qualification tests prior to issuing a procurement [1]. Specifications for the mock-up include materials, the design, and material strength requirements. Included in these requirements is a thermal fatigue test of the joint between the beryllium tiles and the copper alloy heat sink. The thermal fatigue tests will be performed at two different laboratories, one in the European Union, and one in the United States at Sandia National Laboratories in the Plasma Materials Test Facility.

II. ITER FIRST WALL AND QUALIFICATION FOR MANUFACTURING

A. ITER first wall

The first wall of ITER is a sandwich of three materials: beryllium (S65C), copper alloy (CuCrZr, C18150), and

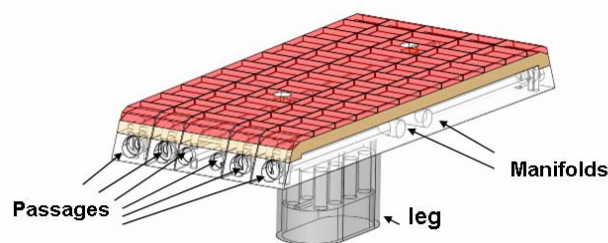


Figure 1. A first wall panel in ITER

stainless steel block to maintain the strength (SS316LN-IG—IG stands for ITER grade). Fig. 1 shows a typical first wall panel. Beryllium tiles that are 10 mm thick provide the first material that is exposed to plasma radiation. Behind the beryllium tiles are water-cooled copper heat sinks. Within the copper alloy are stainless steel tubes that contain the cooling water, flowing at about 3 m/s, 100 °C and 3MPa. The stainless steel tubes prevent the water from contacting the copper alloy directly to reduce corrosion. In the first wall the stainless steel tubes are completely enclosed by the copper alloy until they enter the stainless steel back plate. Coolant water enters the stainless steel back plate, and follows a route up and through the stainless steel tubes and back into the steel back plate. The method of producing this sandwich is Hot Isostatic Pressing (HIP) [2]. The sandwich is subject to high pressure and temperature, which melds the copper to the stainless steel in the first HIP step, and beryllium tile to copper in the second HIP step. The beryllium tile is pre-coated with metal layers that prevent formation of brittle copper/beryllium alloys prior to the second HIP step.

The first wall will be heated by plasma surface heating and bulk nuclear heating. These heating values are estimated to be about 0.2–0.5 MW/m² on the surface, and about 6 W/cm³ in the bulk [3]. Heating of the first wall is expected to cause thermal stresses because of the different expansion rates of the materials. Bulk properties of stainless steel, copper alloy and beryllium can be used to calculate stresses in this sandwich of materials. Unfortunately, it is difficult to calculate the stresses that will occur at a joint between the materials, particularly at a butt joint as will be created between Be tiles and copper alloy. The bulk material values should not be used because there are metallic layers that will be between the Be and copper, and in calculating such an interface, there is a singularity at the very edge [4]. The best determination of the strength of this

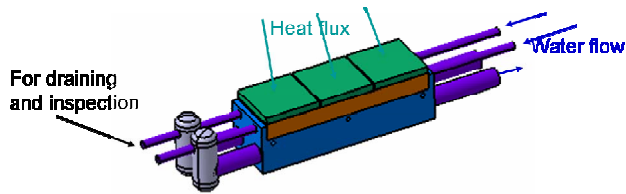


Figure 2. The design for the first wall quality mockup.

interface is to test it. The fatigue test is only one of the steps needed to qualify a party for first wall manufacturing. This paper describes the Sandia National Laboratories' test setup and failure criteria for thermal fatigue testing of ITER first wall manufacturing techniques.

B. Test Object

A typical first wall panel surface is approximately 1 m long by 0.4 m wide. Rather than qualifying an entire panel, the IO has decided to qualify a much smaller section, one that has typical beryllium tile sizes and copper alloy thicknesses comparable to a first wall panel on the inboard of ITER. This piece consists of three beryllium tiles, each 80 x 80 mm² on the plasma facing surface by 10 mm thick, a copper alloy that is 25 mm thick, and a stainless steel back plate that is 49 mm thick. There are two stainless steel tubes in the copper layer, each 10 mm ID and 12 mm OD that carry coolant through the mock-up, and two drilled-hole passages in the stainless steel back plate of 20 mm ID. The mock-up is shown in Fig. 2. Coolant flows through the upper two tubes and is directed downward into the lower stainless steel passages by a manifold tube. There is one thermocouple located in the middle of each Be tile, 8 mm below the top surface.

C. Test conditions

The expected load is outlined in the project integration document [3]. Expected loads are:

- Steady state heat load
 - 10,000 “shots” at 0.25-0.50 MW/m² of surface heat for 400 s or greater
 - 20,000 shots below 0.25 MW/m² of surface heat for 400 s or greater
 - Approx 6 MW/m³ of nuclear heating from the neutrons (exact estimates vary with nuclear analysis and position in ITER)
- MARFE (multifaceted asymmetric radiation from the edge)
 - 1,000 shots between 0.5 and 1.4 MW/m² < 10s long
- VDE (vertical disruption event)
 - 10 shots with < 60 MJ/m², < 0.2 s long

The conditions that are expected in ITER cannot be reproduced in test facilities, in particular, the nuclear heating. To reconstruct similar temperature and stress conditions for a qualification test, the IO slowed the water flow so that the temperature of the overall mock-up would be closer to the first wall with nuclear heating. Rather than subjecting the mock-up

TABLE I. TABLE 1. FIRST WALL QUALIFICATION TEST CONDITIONS IN US

Heat flux on tiles	0.7 MW/m ²
Coolant velocity in tubes	1 m/s
Coolant Temperature	100 °C
Number of cycles	12,000
Cycle time (on and off)	96 s
Absorbed power/cycle	13.4 kW
Temperature rise (coolant)	~20°C

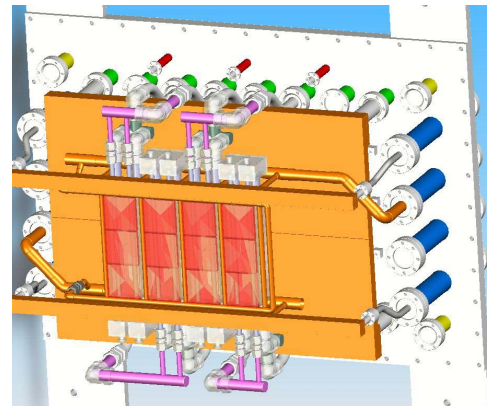


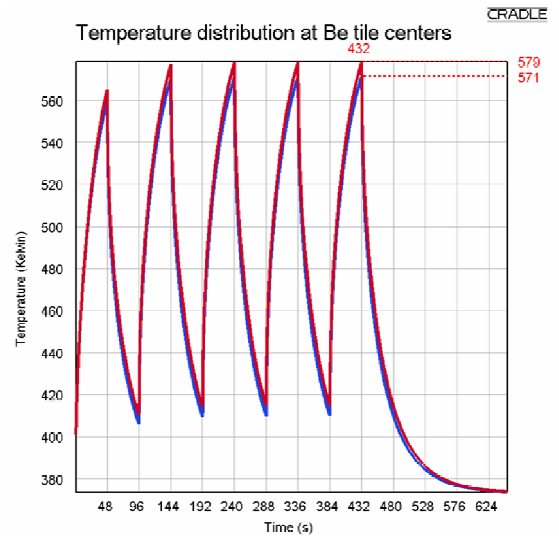
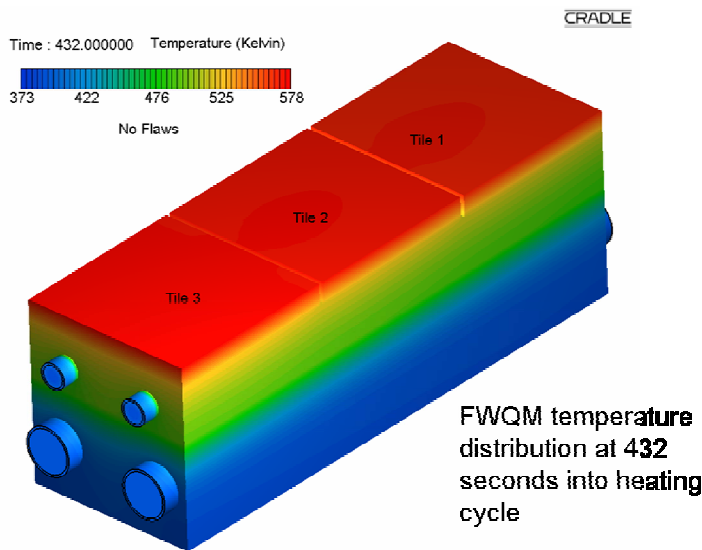
Figure 3. The design for mounting four first wall quality mockups in the EB-1200 vacuum chamber. The stainless steel tubes of the mockups are covered by water cooled end shields to protect them

to 30,000 shots, the IO reduced the number of shots to 12,000 including 10,000 to match the heat over 0.25 MW/m², and 2,000 to make up for the other 20,000 shots with surface heat fluxes below 0.25 MW/m². In addition, the heat flux was increased, and the cycle shortened. The final test conditions are shown in Table 1.

Testing at the Plasma Materials Test Facility will take place in EB-1200. Mock-ups will be mounted on the vacuum chamber door as shown in Fig 3. Four mock-ups will be mounted at one time, and two electron guns will be run simultaneously to heat the surfaces. An electron beam will be rapidly moved across one mock-up for 48 seconds, then a mock-up next to it for 48 seconds while the first mock-up cools. This will simulate the cyclic heating and cooling of the first wall surface. As shown in Figure 4 (calculated by a fluid dynamics code called SC/Tetra [5]), the mock-up temperature will cycle and does not reach a steady state cyclic temperature for two to three cycles. The color image shows the temperature of the mock-up at the end of the fifth heating cycle. The Be-Cu interface is expected to cycle between 235 and 250 °C and the maximum temperature for the top of the beryllium tile should be about 300 °C.

Calculations of the thermal stress as a result of temperature cycling show that high stresses are located near the Be tile-to-Cu interface. These are areas for which calculations using bulk material strengths are inadequate. These are also areas that we

¹ Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000



Tiles subject to 5 heating cycles of 48 seconds each. (48 sec on 48 sec off)

Figure 4. Expected temperature of mock-up

would expect failure of the beryllium/copper bond as it is a high stress area.

III. FAILURE CONDITIONS

We expect that failures are most likely to occur by beryllium tiles de-bonding from the copper. Localized quarter circle regions on the Be-Cu interface were assigned zero interface conductances so no heat can pass through these “flawed” regions. Fig 5 shows the result after 5 heat cycles. If a tile does not have good thermal contact with the copper heat sink, the temperature of the tile increases because of the poor connection to the copper heat sink. We have proposed that a failure criteria for mock-ups tested in the US be determined by an increase in a surface temperature. The PMTF uses infra-red

cameras to measure surface temperature during testing. The ITER international organization has adopted this criterion for the US test facility.

Failure criterion: If at any time, the average temperature on any 100 mm² local area minus the average temperature on the whole Be top surface is greater than 50 °C, the mock-up has failed.

Failure detection with the IR camera should be quite evident. If the FWQM behaves as expected, the surface temperature will be 300 °C and an area that is 100 mm² that is 50 °C higher is significantly higher. The IR camera should be able to resolve about 1mm² in area and 5 °C in temperature. By these criteria we hope to prevent vaporizing beryllium in the EB-1200 vacuum chamber, as 350 °C is significantly lower than the melting temperature of beryllium of 1287 °C.

Fig 6 is another view of the temperature profile on the top surface, where the temperature scale has been changed to show in red temperatures above 350 °C. A flaw at a corner of a tile

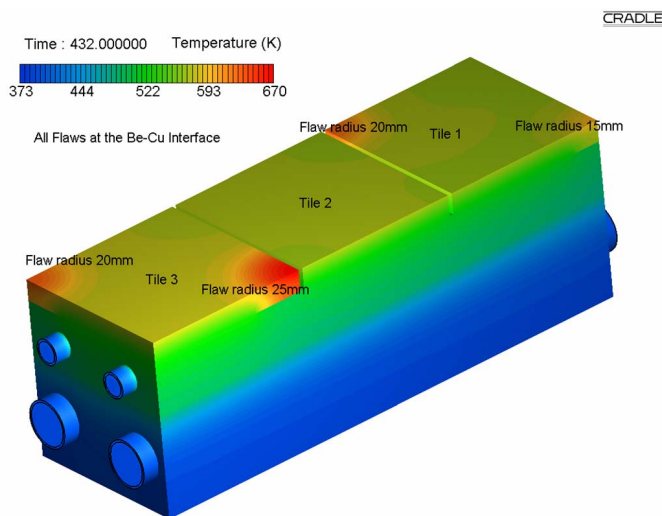


Figure 5. Surface temperatures at the end of 5 cycles of heating

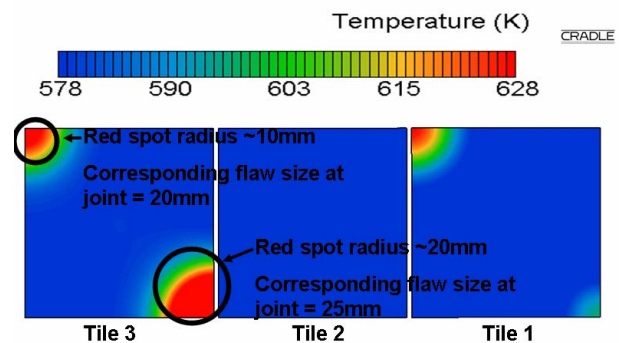


Figure 6. Hot spots that are over 50 °C and 100 mm² are created by quarter circle flaws of about 20 mm in radius.

with a quarter circle of radius slightly greater than 20mm will cause surface temperatures to reach the failure criterion. The hot spot is localized and temperatures at the thermocouple location increase approximately 0.5 degrees for these conditions. We do not believe we can detect this flaw size with the thermocouple.

IV. SUMMARY

The first wall quality mock-up test is necessary to qualify a party for manufacturing the ITER first wall. Testing is important because so many different parties are planning to make the first wall. Testing will be performed in the EU and in the US at the PMTF. We will use electron beams for cyclic fatigue testing of the FWQM. Failure of the mock-up is determined by measuring the surface temperature of the mock-up with infra-red cameras. An increase in surface temperature by 50 °C over normal for an area of 100 mm² is considered a failure.

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