Simulation of ELMS in High Heat Flux Tests of W Rod Armor

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Abstract

With the EB1200 (large electron beam), Sandia researchers are performing high heat flux tests that simulate heat loads from ITER ELMs. Our objective is to find the envelope of ELM heat loads versus operating temperature above which damage occurs by melting or cracking. We are testing with heat loads of 0.5-3.0 GW/m^2 (absorbed) for 0.3 or 0.8 ms repeated at 2 or 5 Hz superimposed on a steady state heat flux that establishes the surface temperature of the rods. The targets are water-cooled mockups armored with 3.2mm dia. tungsten rods embedded in plasma-sprayed CuCrNb and electron-beam welded to a CuCrZr heat sink. A thermal analysis of the behaviors of the mockups and our brief initial experimental observations that confirm our capability to perform these tests are reported in this PSI paper.

JNM Keywords: experimental techniques, melting, surface effects, thermal shock, tungsten
PSI Keywords: divertor materials, ELM, high-Z material, power deposition, tungsten brush
PACs: 44.10.+i, 81.70.Y, 81.40.E

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1. Introduction

During a shot in a magnetic fusion energy device, the confined plasma releases energy from the plasma through radiation and particles that are transported to the wall of the plasma chamber. In evaluating requirements for heat removal via chamber components, this transport is typically viewed as a continuous process. However, in high power devices, large ELMs (Edge Localized Modes) are expected to release energy from the plasma edge in short bursts several times per second. The conditions for ELMs and their rapid release of energy and particles has been an active area of study in JET[1,2] and DIII-D[3], as has the projected characteristics of ELMS in ITER[4,5] (International Thermonuclear Experimental Reactor). In this paper, we are concerned with the thermal response of a tungsten surface to the type of successive rapid heating anticipated from ELMs in ITER.

For a typical ELM in ITER, Loarte[5] estimates the plasma will loose ~12 MJ (12% of the pedestal energy) in ~200 μs. Analyses were done for times from 100-300 μs and deposition areas of 8 and 16m^2. A "nominal ITER ELM" has 300 μs rise time and 300 μs fall with a 5 GW/m^2 peak for 8m^2.

As an ELM reaches the chamber wall, only a fraction of the energy actually heats the surface. Evaporation quickly produces "vapor shielding." Extensive analyses by Hassenein[6-9] suggests that heating and expansion of the vapor cloud can consume much of the transported energy of the ELM and as little as ~5% of the ELM energy reaches the surface; as a function of the duration of the event, the fraction of energy transported to the surface reaches a roughly constant fraction of several percent after an opaque vapor cloud initially forms. Unpublished data from experiments with the MK200 plasma gun also support the vapor shielding effect but with much shorter pulses that simulate plasma disruptions.

The objective of our experiments and analyses is to determine the thermal response of a W rod surface to repeated ELM-like rapid heat pulses. The features of interest are surface melting (J/m^2) or unacceptable cracking or spallation, both just above and below the surface melting threshold. Our experiment was interrupted after some initial observations. The capability of the system to perform the experiment was confirmed but no data were recorded with the diagnostic systems. We anticipate reporting further work at the 2004 Symposium on Fusion Technology. We are also studying the erosion of the surface of the tungsten rods using spectroscopic observation of molecules such as tungsten oxide. This paper describes our experimental approach and then summarizes the results to date of our thermal analyses.

2. Experiment

We simulate the heat load of ELMs using the unique capability of the large electron beam, EB1200, at the Plasma Materials Test Facility at Sandia National Laboratories[10] to hold an intense beam of electrons for sub-millisecond times on a target while also maintaining a second, constant heat flux that simulates the steady state operation of a divertor in ITER. The target is a water-cooled mockup armored with W (tungsten) rods. Thermal analyses are used both to guide the experiment and interpret experimental results.

In both the testing and the analyses, the presence of the thermal gradient associated with the steady state surface heat load is important. The well known equation, $T = {2q''\sqrt{\kappa t/\Pi}}/{k}$ where q'' is heat flux of 1500 MW/m^2, κ is thermal diffusivity and k is thermal conductivity, gives the rise in temperature for heating of an initially isothermal semi-infinite slab. Fig. 1 compares temperatures from this equation with results from the finite element model with and without the thermal gradient present. The case with the thermal gradient is ~ 500°C cooler.

2.1 Experiment - Approach

EB1200 has electron guns oriented ±30° (horizontal) from the normal of the vertical target. For this experiment, we maintain a steady-state temperature on the target with a 600 kW gun and use a slightly defocused beam (6mm dia., 28.3 mm^2) from a 150 kW gun to provide the rapid ELM-like heat pulses. Two features of EB1200 enable this approach. The first is the digitally controlled restoring system developed by Youchison that specifies the pattern on the target as a sequence of spots; the beam sweeps rapidly from one spot to the next and dwells on each spot for a prescribed period. The second is a rapid sweep. The maximum restoring frequency of the beam-steering coil set is 10 kHz. The minimum time to position the beam on a stationary spot is ~100 μs; 200-300 μs is a reasonable minimum duration to move onto a target spot, hold, and move off again. To simulate the ELMS we switch between two patterns. One sweeps continually over the side shield. The second sweeps the side shield but also has some repeated spots on the target rod for the duration of the exposure, e.g., 300 μs.

For 40 keV electrons, our W targets reflect ~60% of the incident power. The 150 kW gun, with lower power but a smaller beam diameter of ~2 mm, can provide a maximum absorbed power density of ~17 GW/m^2 on a spot smaller than one W rod. For these experiments, a diameter of 5 mm spreads the power peak over the rod. Also, the power onto the edges of surrounding rods is useful for aligning the spot on a target rod.

2.2 Mockup and Test Conditions

Plasma Processes, Inc. of Huntsville, Alabama fabricated eight mockups 32 mm wide with an armored length of 95 mm. Each has CuCrZr heat sinks with two 10 mm dia. cooling channels and twisted tapes with a twist ratio of 2. Other variations are: 4 with Cu rather than CuCrNb rod beds, 6 with the rod bed and heat sink joined by hot isostatic pressing, and 4 with rods held in place for the plasma spray operation with an array of 0.125 mm dia. W wire. The target for this experiment, mockup V2-02-15Q, has armor with 3.2 mm dia. lanthanated W rods 5 mm long, with an additional 2 mm in the truncated conical tips. The rods are embedded in a plasma-sprayed CuCrNb bed that was electron-beam welded to the heat sink.

Typical water flow conditions in the experiment are 1 MPa pressure, 20^{o}C, and 10 m/s flow velocity. Diagnostics include a fast (10μs/frame) infrared pyrometer, two 1-color and two 2-color pyrometers, infrared and video cameras, water calorimetry and 6 thermocouples embedded in the mockup.

2.3 Experiment – Initial Observations

The main objective of our testing is to determine the envelope of absorbed energy density versus surface temperature above which damage occurs to the W rod armor by melting or cracking. In the checkout phase of the experiment, we have confirmed the capability to utilize the fast sweeping system of EB1200 to produce a rapid ELM-like heat pulse on a single tungsten rod. Fig. 2 shows the mockup V2-02-15Q mounted in EB1200 and a video image of a single heated rod. We have also calibrated the fast IR pyrometer. Most of the instrumentation we use determines the absorbed power and surface temperature of the rods from the steady state heat load of the 600 kW gun. The rapid rise and fall in the temperature of the target rod exposed to an ELM-like heat pulse are to be recorded with a fast IR pyrometer. The 30Hz infrared camera may also help discern the significant tail in the thermal signature of the fast heat pulses.

3. Thermal Analysis

The primary thermal excursion from the ELM-like heat pulses is brief and occurs very close to the heated surface of the tungsten rod. Predicting the threshold of the heat load and duration for a given starting temperature to melt the surface layer of a W rod is one objective of the thermal analysis. Another is to evaluate the thermal response during repeated ELM-like heat pulses. The initial "thermal spike" contains appreciable enthalpy and a diffuse but still significant thermal tail persists as the heat pulse diminishes via thermal diffusion into the rod.

We created several thermal finite element models using ABAQUS as the solver and PATRAN to create the geometry and mesh. The models include radiation from the surface of the rod and melting when the temperature exceeds 3377°C. Temperature-dependent properties were used for tungsten[11] along with a value of 255.4 J/g (61 cal/g) for the latent heat[12], an interval required by the model to define melting of 3377 to 3380°C, and a total hemispherical emissivity of 0.33.[13] Plasma Processes, Inc. provided data on thermal conductivity for the plasma-sprayed CuCrNb.

A previous 3-D model (Fig. 3) for a US ITER divertor design with 10-mm-tall rods was modified by adding a progressively denser mesh in the top layers. Fig. 4 shows an early result for the same heat pulse modeled without the latent heat of melting. The two "plateaus" indicate melting of discrete layers and that the mesh was too coarse; however, the result illustrates the arresting of the surface temperature during melting or solidification and the slight initial delay in the decline of the surface temperature due to solidification. We are using this model to investigate thermal stresses in W rod armor and in the region where the rods are joined to the bed and heat sink. However, these results are not reported here. For the smaller mesh sizes and time steps, e.g., a 0.5 nanosecond first step, needed in this analysis, we are using a 2-D model of a narrower slice of the 10-mm rod.

3.1 Thermal Analysis – Approach

For our parametric thermal analysis, the ELM-like heat loads varied from 500 to 3000 MW/m^2 with durations of 300 or 800 μs. For the repetitive ELM simulations, the ELM frequencies were 2 or 5 Hz. Steady state heat loads were set to give several "operating" temperatures at the surface of the W rod in the range from 1000-2000°C.

In our cases, the heat absorbed from an ELM can be a significant fraction of the nominal steady state heat load and we use a heating sequence illustrated in the following example. First, a nominal heat load of 10 MW/m^2 absorbed for 60 s establishes the steady-state temperature distribution in the W rod and heat sink. The ELM cycles begin with a pulse of 2000 MW/m^2 for 300 μs followed by a second "normalizing" heat load. Two such ELMs per second add an equivalent average power of 1.2 MW/m^2. The remaining 8.8 MW/m^2, to give an average absorbed heat load of 10 MW/m^2, comes from two 8.8053 MW/m^2 normalizing pulses during the 0.4997 seconds after each ELM. (If one simply added ELMs onto the nominal heat load, then the temperature would ratchet up to some new equilibrium value.)

3.2 Thermal Analysis – Results

Fig. 5 shows results from the 2-D model for the 1st and 20th cycles with 300-μs ELM-like heat pulses at 2 Hz and a 10MW/m^2 average heat load. In this case, the top of the rod melts. The inset in this figure shows the shape of the peaks. As noted for previous Fig. 3, the changes from a smooth slope before and after the peak are due to melting and solidification of the surface layer. The 1st and 20th cycles are essentially identical. The slight drift downward in the temperature of 10-15°C is likely due to steady state radiation losses that were ignored in setting the normalizing heat load mentioned previously. The radiated power losses during the short time of the ELMs are negligible even though the temperature is much higher then.

Table 1 gives a summary of a series of cases with 300-μs, ELM-like heat pulses at 2 Hz and 10MW/m^2 steady state with heat loads and an equilibrium surface temperature of ~1100°C. The temperature rise is roughly linear with the ELM heat load to ~2100 MW/m^2, above which melting of the rods begins. Above this value, the temperature rise is again roughly linear with increasing power, but with a lower slope as more of the absorbed power is stored in the enthalpy of melting.

4. Conclusion and Future Work

Our initial checkout of the experimental approach and equipment indicates that we can perform the simulation of heat loads due to ELMs with heat pulses in the range of 300-800 μs, or greater, and apply repeated ELM-like heat loads to observe their effect on the surface of the W rod armor on our water-cooled mockups. These conditions are relevant for ITER and we will be able to observe melting when it occurs and damage of the surface from cracking.

Our modeling indicates that the thermal history of the surface of the rods will show a thermal tail that persists with a still significant slope of ~400-500°C/s even after a tenth of a second. From this information, we expect to obtain useful information on the thermal signature from the infrared camera as well as our fast infrared pyrometer. We will extend the thermal modeling for cyclic ELM-like heat loads at 2 and 5 Hz to cover a wider range of starting temperatures with specific material configurations for the individual mockups we test. We anticipate completing the first campaign of experiments and related thermal modeling by the fall of 2004.

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Table 1. Temperature vs. heat load

q"-ELM	Tstart	Tpeak	Trise
MW/m^2	C	C	C
1800	1104	3021	1917
2000	1100	3237	2137
2200	1096	3390	2294
2400	1092	3497	2405
2600	1088	3637	2549
2800	1085	3739	2654

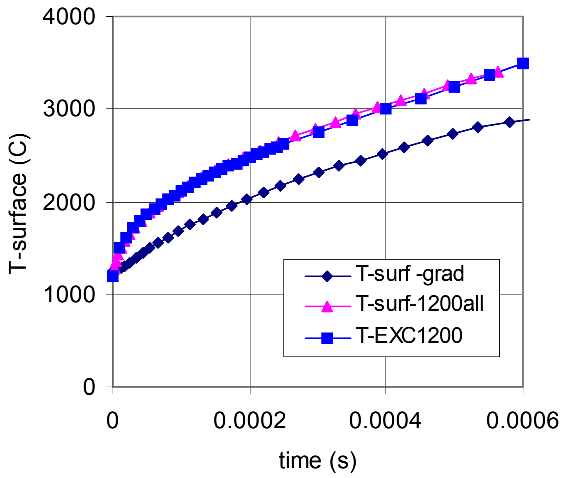

Fig. 1. Surface temperature of a W rod exposed to 1500 MW/m^2 as calculated by (a) finite element model with thermal gradient present, (b) finite element model with rod beginning as isothermal and (c) spreadsheet calculation with 1-D equation and temperature–dependent properties.

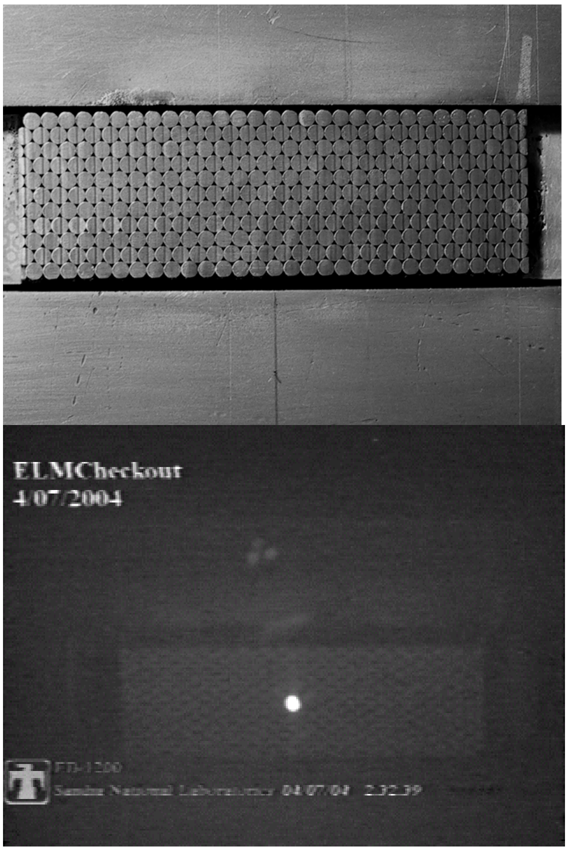

Fig. 2. Mockup in EB1200 between heat shields above and below.(top) IR camera view of hot target rod in low power check of spot focus and alignment.(bottom)

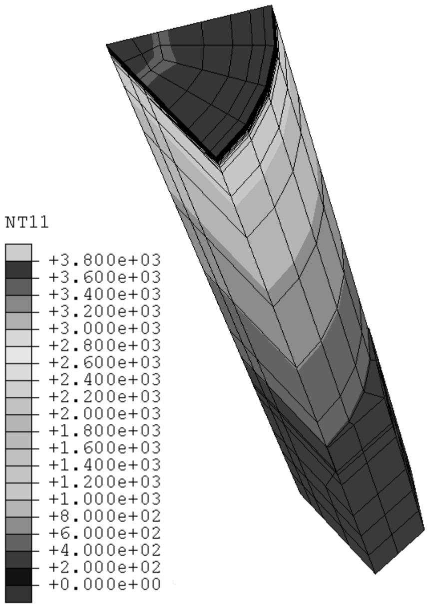

Fig. 3. 3-D PATRAN/ABAQUS model, 60° sector of 10-mm-high W rod with bed and water-cooled heat sink. The model has been adapted with a dense mesh near the surface. The case shown is the temperature distribution after a heat pulse of 2200MW/m^2 for 800 μs with the rod previously under a heat load of 10MW/m^2.

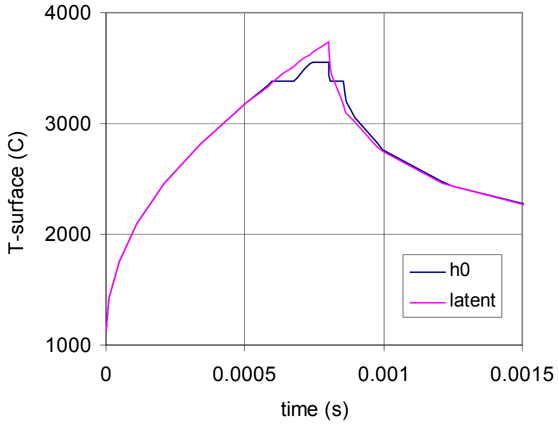

Fig. 4 Comparison of cases with and without latent heat of melting included in the 3-D model for 10 mm length W rods with 10 MW/m^2 heat load and a 1500MW/m^2 heat pulse for 800 μs.

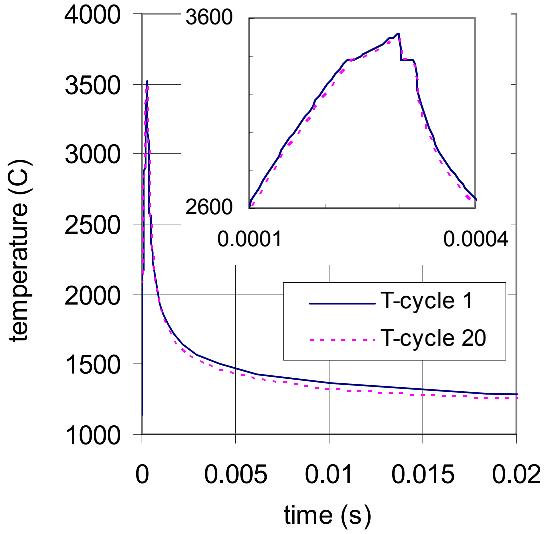

Fig. 5. 1st and 20th cycles for 2-D case with 2400 MW/m^2, 300 μs, 2 Hz; inset shows expanded peaks with changes in slope that denote melting.