4.6 HIGH-HEAT FLUX TESTING OF LOW-LEVEL IRRADIATED MATERIALS USING PLASMA ARC LAMPS

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OBJECTIVE

The objective of this work is testing of irradiated materials that are candidate of divertor component materials and mock-up divertor components under high-heat flux using Plasma Arc Lamps (PAL).

SUMMARY

In this reporting period high-heat flux testing of six samples, which were supplied by the Japanese collaborators in the PHENIX program, was conducted at ORNL in collaboration with Dr. Kazutoshi Tokunaga of Kyushu University, Japan. As part of the joint US/Japan PHENIX program, Dr. Tokunaga was on assignment at ORNL for four weeks. During this high-heat flux testing, several fixtures for specimen clamping were evaluated for their performance.

PROGRESS AND STATUS

Effort was conducted on three main areas: (a) enhancing the measurement accuracy of the sample temperature, (b) conducting high-heat flux testing with non-irradiated specimens for the joint US/Japan PHENIX program, and (c) enhancing the radiation safety during testing of irradiated specimens.

Temperature measurement and specimen clamping

The current efforts for enhancing the temperature measurement during testing of irradiated specimens included: (a) fabrication of fixtures that would enable specimen onto the substrate and (b) clamping or bolting the thermocouples that would be in direct contact with the specimen. In this reporting period, several attempts were made to fabricate such fixtures for the high-heat flux testing that was conducted in January/February 2014 at ORNL in collaboration with Dr. Kazutoshi Tokunaga for the PHENIX program (Figures 1 and 2).

Clamping the specimen onto the substrate is the best option for high-heat flux testing as the specimen will be pushed onto the substrate, ensuring (a) consistent sample contact with the cooling surface for different specimens and (b) a good contact to the thermocouple for estimating the sample temperature. However, due to the large area covered by the incident heat flux from the plasma-arc lamp, the design of the clamping fixtures is not trivial as the clamping fixtures would be heated directly by the PAL during testing, while on the other hand, the clamping fixtures would not be directly cooled. Moreover, due to different thermal expansion of specimen holder and specimen itself, the clamping fixture cannot be bolted to both sample and cooling rod, resulting in lack of disk clamping for cooling. Thus, the design of the clamping fixtures had to strike an appropriate energy balance between the thermal radiation heating and limited cooling available.

In Figure 1, the drawing of a fixture for specimen clamping is shown. The following features can be pointed out for this design:

- Springs allow the control of the clamping force, for fixed clamping, the springs can be removed
- Springs were placed in low temperature regions for durability and performance
- Top disk may still absorb more energy that it can dissipate by thermal radiation
- The top surface includes a conical area to reduce energy absorption
- Disk cutouts will further minimize energy absorption

The Gen 4 washer clamp fixture, which is sketched in Figure 2, would allow higher-sample temperature at high clamping load, similar to that used for e-beam testing. The Gen 4 of Mo holder is based on clamping the specimen using a washer, allowing high clamping loads, similar to that used for e-beam testing, and

high sample temperatures. The Gen 5 of Mo holder is based on clamping the specimen using a scalloped disk and springs, allowing the control of the clamping loads. It is expected that higher heat fluxes would be used for Gen 4 than for Gen 5 Mo holders as the clamping disk used in Gen 4 Mo holder is directly cooled unlike the scalloped disk used in Gen 5 Mo holder. One Gen 3 of Cu rod (7mm diameter of the thread) was fabricated for use with both Mo holders (Figure 1 and 2).

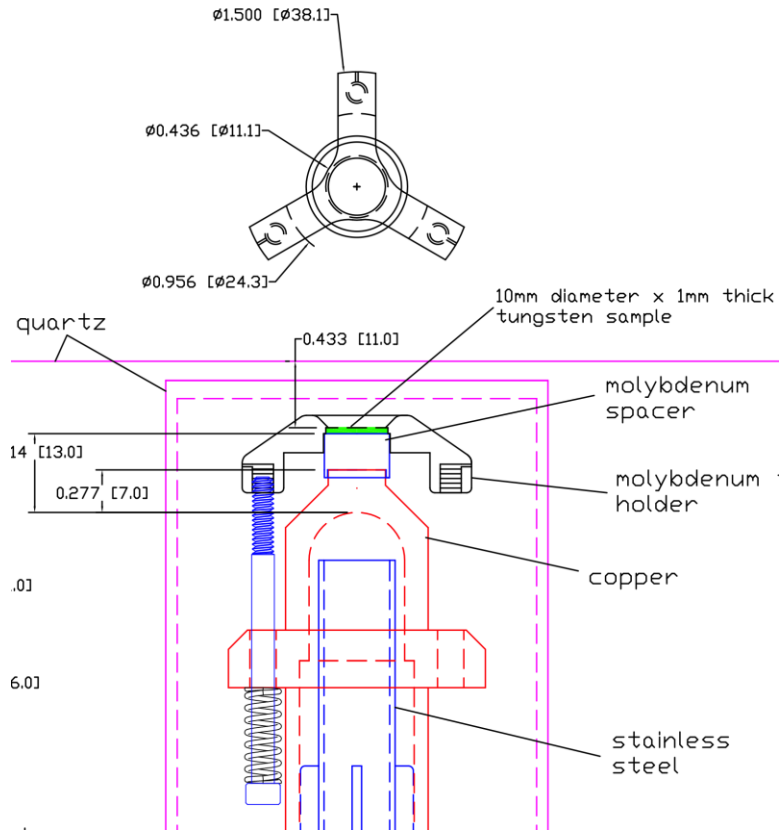


Figure 1. Drawing of a scalloped disk clamp fixture (Gen 5 Mo holder).

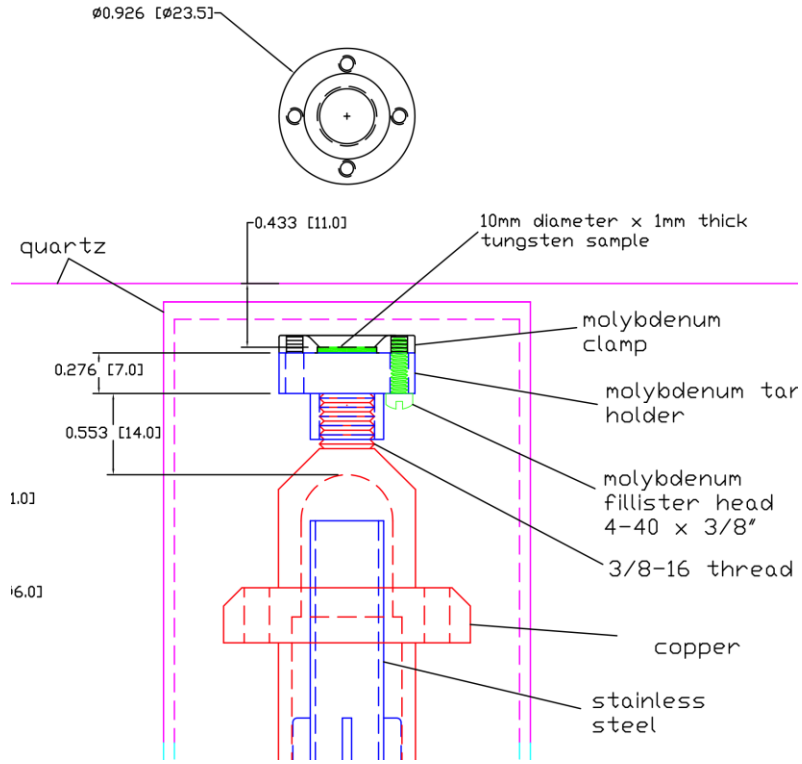


Figure 2. Drawing of a disk clamp fixture bolted from the top (Gen 4 Mo holder).

High-heat flux experiments

In this reporting period, the several high-heat flux experiments were conducted during the visit of Dr. Kazutoshi Tokunaga of Kyushu University, Japan as part of the joint US/Japan PHENIX program. Six samples, which were supplied by the Japanese collaborators in the PHENIX program, were exposed high-heat fluxes at ORNL (Table 1). Each sample was exposed to corresponding high-heat fluxes that would limit the sample temperatures to allowable maximum temperatures for each sample type.

Table 1. Specimens exposed to high-heat flux testing.

Specimen	Materials	Diameter [mm]	Thickness [mm]	Target Max. Temp. [^{o}C]	No. Cycles	Cycle duration [s]	Comments
1	[1]W	6	1	1,200	8		Sample heavily oxidized due to loss of vacuum
2	W	6	1	1,200	61	20-25	Gen 3 cooling rod
3	[2]W/F82H		2	550	76	25	Gen 3 cooling rod
4	[2]W/F82H	10	2	550	75	20-25	Gen 2 cooling rod
5	[2]W/F82H	6	2	550	203	25	Gen 2 cooling rod
6	W	6	1	1,200	42	25	Gen 2 cooling rod

[1] – ITER grade
[2] –Thickness W and F82H steel was 1 mm, respectively.

The temperature results, which were obtained for the first PHENIX sample and are shown in Figure 3, indicate that the accurate data was measured by the bolted thermocouple as it showed the expected temperature range while the unbolted thermocouples indicate similar lower temperatures as before. Both

the specimen and Mo holders were oxidized during this preliminary run. However, the rate of heat removal by the Gen 3 cooling rod is lower than that of the Gen 1 cooling rod as the heat exchange area between the Mo holder and Cu rood was limited to that of a disk of 7mm diameter. These temperature results obtained with Gen 3 cooling rod indicate an inefficient cooling of the specimen holder and specimen, as the specimen holder makes good contact only over a 7mm diameter disk. Thus, the Gen 2 cooling rod was used in subsequent runs. It has to be noted that a coolant flow rate of 5 GPM, which is approximately 10 times larger than that for the Gen 1 cooling rod, was attained for both Gen2 and Gen3 cooling rods. The contact surface between the Gen 2 cooling rod and specimen holder was the same as that for the Gen 1 cooling rod, which was previously used in the project.

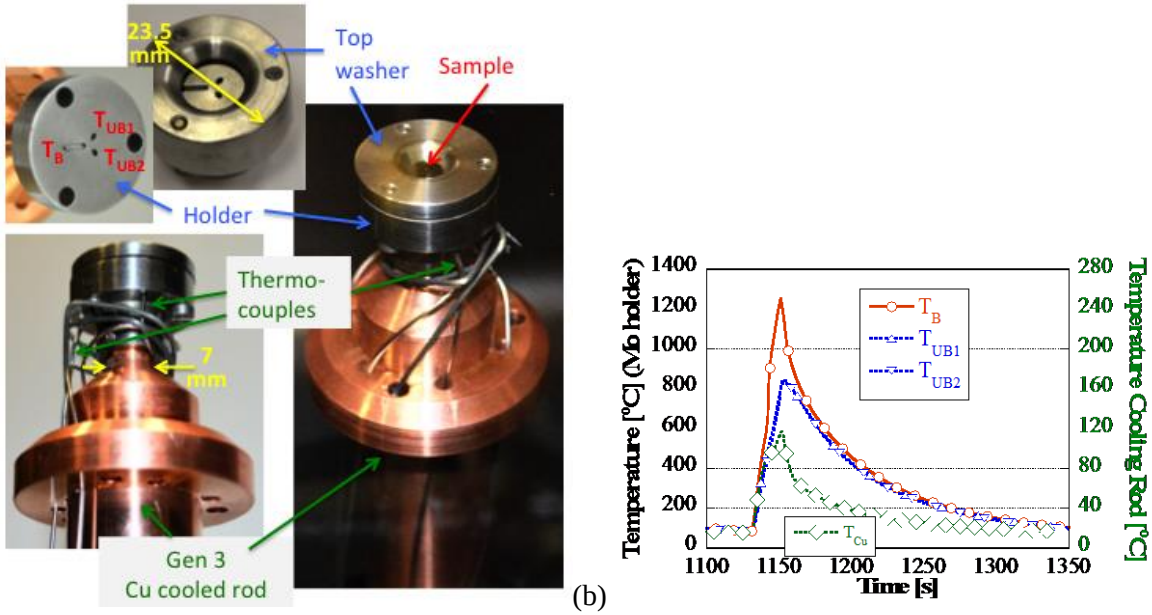
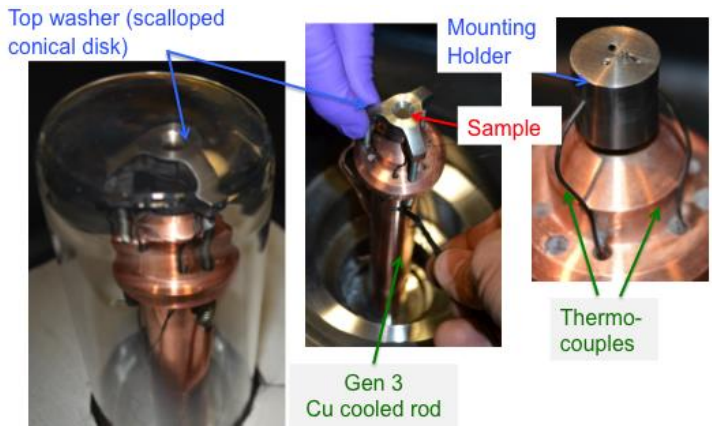
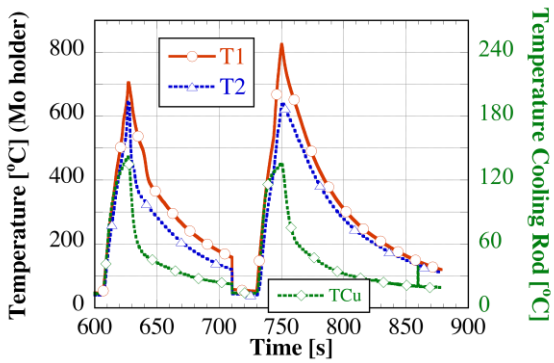


Figure 3. Use of Gen 4 sample holder and gen 3 cooling rod and sample 1 and sample 2: (a) thermocouple location and clamped specimen, and (b) temperature results obtained for sample 1 using bolted thermocouple (T_B) and unbolted thermocouples (T_{UB1}, T_{UB2}), and temperature in the cooling rod.

The temperature results for the second PHENIX sample, which are shown in Figure 4, are lower than those for sample 1 (Figure 3), indicating that a the thermocouples were not in good contact with the specimen. This poor contact noticed for the Gen 5 of specimen holder was due to two factors: (1) the Mo holder – below the disk – was too narrow to allow a horizontal groove to be machined and (2) the Inconel set screws partially melted and the scalloped disk did not clamp the specimen for the entire test duration (i.e., maintain a good contact with the specimen).



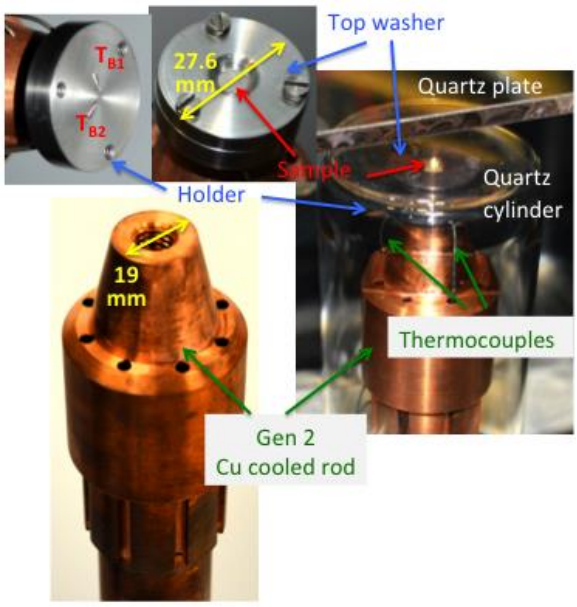
(a)



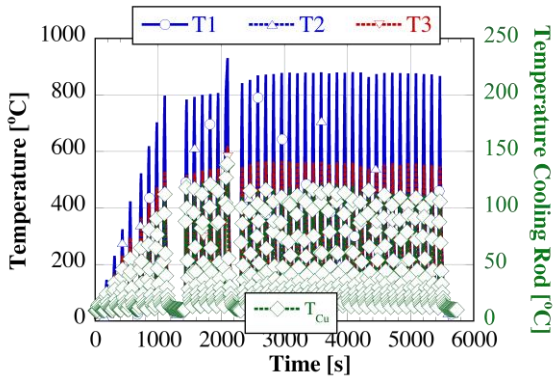
(b)

Figure 4. Use of scalloped disk fixture (Gen 5 Mo holder) with Gen 2 cooling rod for sample 2: (a) experimental setup and thermocouple location, and (b) temperature results obtained for sample 2 using un-bolted thermocouples (T_1, T_2), and temperature in the cooling rod.

The temperature results for the sixth PHENIX sample are shown in Figure 5. For this specimen, the disk was bolted from the Mo holder (Gen 4b of specimen holder, similar to the Gen 4 of specimen holder, which was bolted from the top disk, as shown in Figure 2 and 4). The Gen 2 cooling rod was also used in order to provide a larger contact cooling area to the Mo holder than that of the Gen 3 cooling rod that was used for Specimen 1 and 2. The temperature results indicate that maximum temperature reached was approximately 900 ^{o}C.



(a)



(b)

Figure 5. Use of clamped disk fixture (Gen 4b sample holder), bolted on the Mo support, with Gen 2 cooling rod for sample 6: (a) thermocouple location and clamped specimen, and (b) temperature results obtained for sample 6 for 42 cycles using bolted thermocouple (T_1, T_2) and unbolted thermocouples (T_3), and temperature in the cooling rod.

The microstructure of top surface of specimen 6 is shown in Figure 6. At higher magnifications (bottom row of pictures), several nano-size particles are evident (white dots) after HHFT (bottom right-hand-side picture).

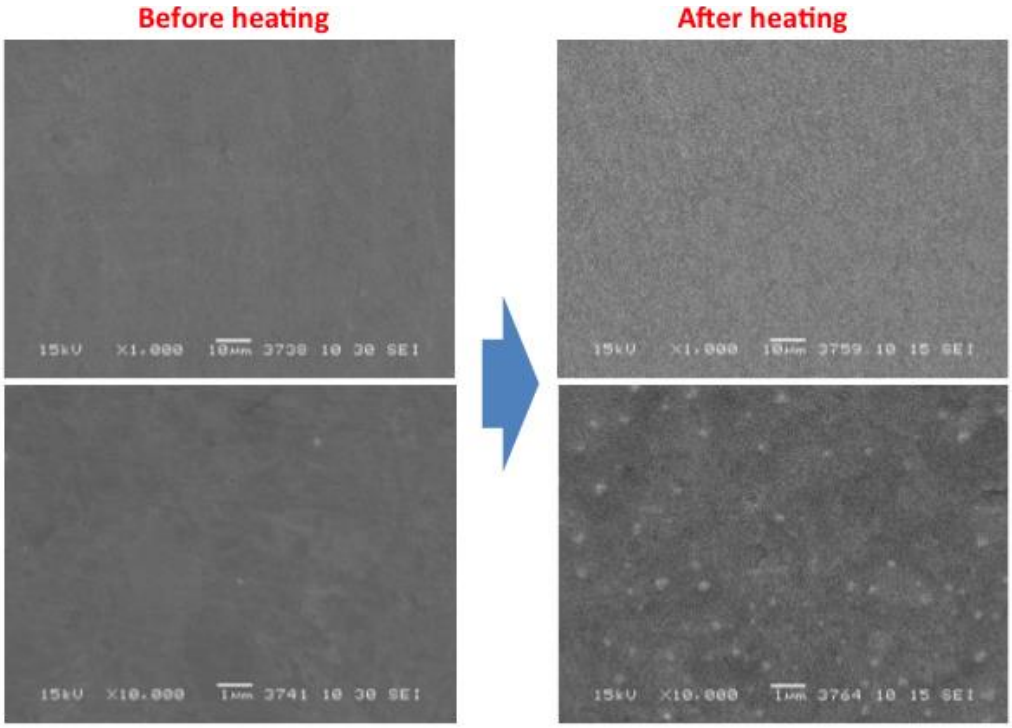


Figure 6. SEM images showing the microstructure of top surface of specimen 6 (provided by Dr. Tokunaga). Different magnifications were used. The left-hand-side pictures were taken before the high-heat flux exposure while the right-hand-side pictures were taken after the high-heat flux exposure.

The sample was clamped as shown in Figure 5. Sample 5 was exposed to a total of 203 cycles. W top surface was not oxidized while the Mo washer was slightly oxidized. These temperature results indicate that the accurate data was measured by the bolted thermocouples as it showed the expected temperature range while the unbolted thermocouple indicate similar lower temperatures consistent with the data recorded previously (Figure 1b and Figure 2). The microstructure analysis of the specimens exposed to high-heat fluxes is ongoing and will be reported in the next reporting periods.

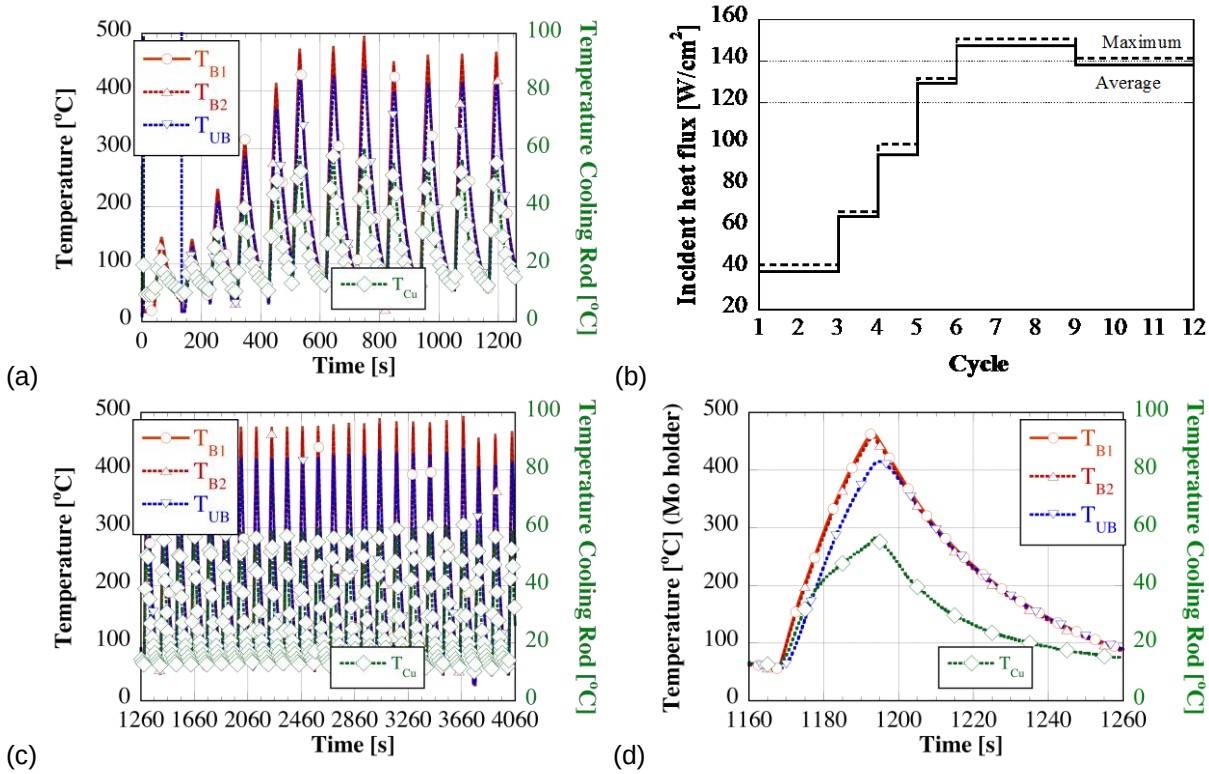


Figure 7. Temperature results obtained specimen 5 (W/F82H, 6mm diameter): using bolted thermocouples (T_{B1}, T_{B2}) and unbolted thermocouple (T_{UB}), and temperature in the cooling rod. (a) cycles 1-12, (b) incident heat fluxes for the first 12 cycles, (b) cycles 13-36, and (c) 12-th cycle considered representative ((525A lamp current, and incident heat flux of 1.4 MW/m^2).

The microstructure of top surface of specimen 5 is shown in Figure 8. After HHFT there is slight change in the microstructure, such as smoothing out of the edges but no cracking was observed. Several considerations have to be made concerning the lack of surface damage at 1.4 MW/m^2: (a) PAL used for the HHFT provides a relatively uniform high-heat flux over the specimen surface, more uniform even than those offered by the neutral beam facilities (e.g., GLADIS), (b) surface damage under more uniform heat sources (e.g. GLADIS) were found to induce surface damage at higher heat fluxes than those by the e-beam. Therefore, for the surface damage for PAL HHFT is expected to occur at larger heat fluxes than those by the e-beam.

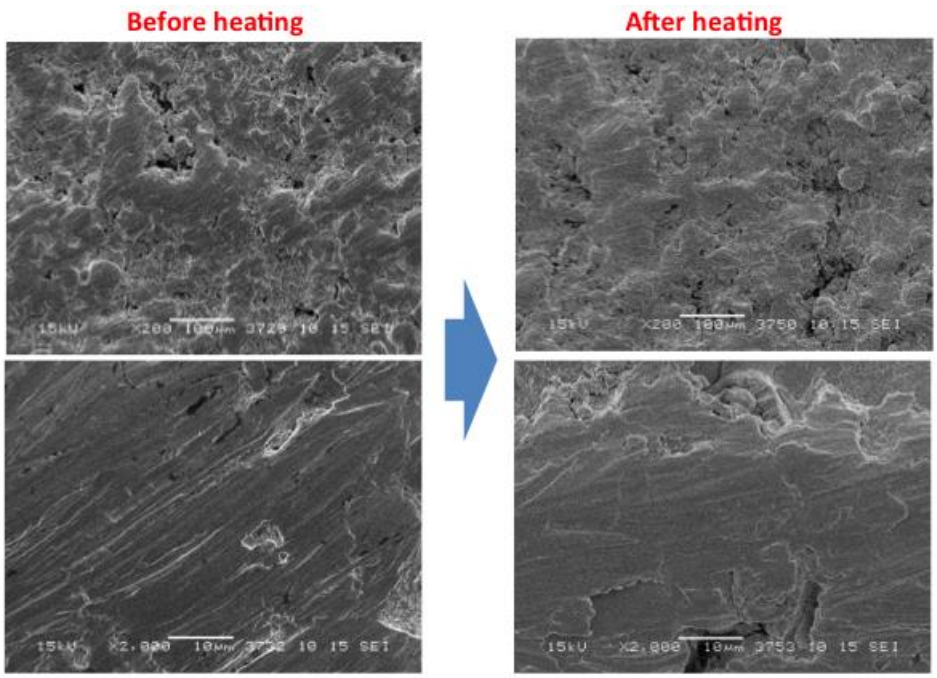


Figure 8. SEM images showing the microstructure of top surface of specimen 5 (provided by Dr. Tokunaga). Different magnifications were used. The left-hand-side pictures were taken before the high-heat flux exposure while the right-hand-side pictures were taken after the high-heat flux exposure.

Enhancing the radiation safety during high-heat flux testing of irradiated specimens

Efforts for enhancing the radiation safety during testing of irradiated specimens include:

- Design of an additional sealed chamber enclosing the cooling rod, specimen holder, and irradiated specimen
- Fabrication of the sealed chamber enclosing the specimen holder and irradiated specimen.

The main test chamber will NOT be contaminated, lowering the maintenance and operational costs. The color legend for the sub-components that comprises the sealed chamber in Figure 9, are as follows:

1. magenta – indicate capped quartz tube surrounding the top region of the cooling rod,
2. light blue – graded quartz to glass region,
3. green – glass region; the glass is fused on the bottom to a steel flange to insure vacuum tight conditions,

The Gen 2 cooling rod that will enable a 3X increase in the coolant flow rate is also shown.

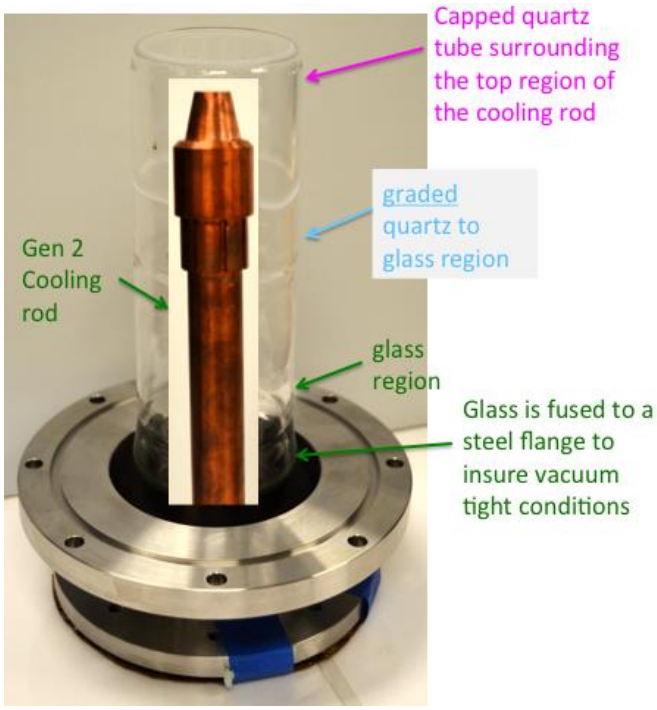


Figure 9. Drawing of the additional sealed chamber to confine contamination to the quartz-glass cylinder surrounding the cooling rod.

Acknowledgments

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