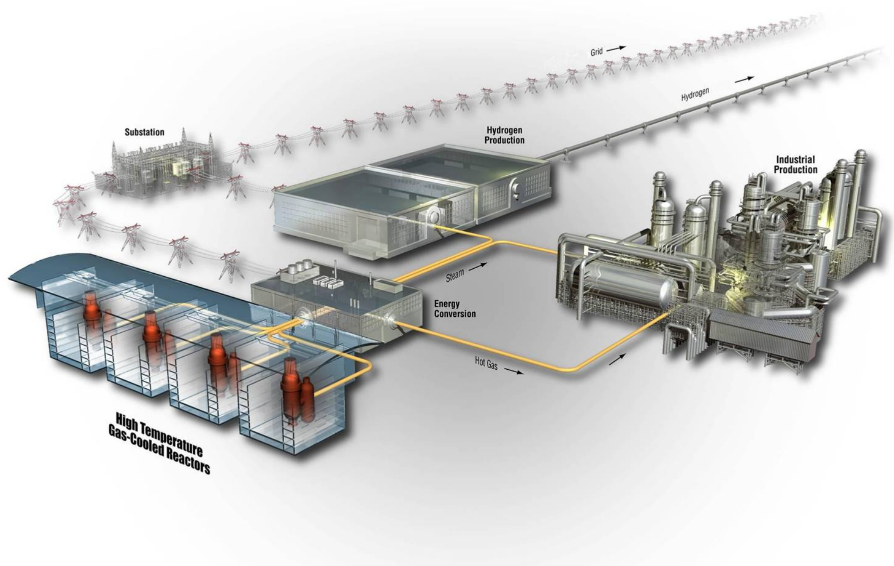
INL/EXT-11-23165

AGC-1 Post-Irradiation Examination Status

W. Swank

September 2011



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Idaho National Laboratory
Next Generation Nuclear Plant Project
Idaho Falls, Idaho 83415

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Next Generation Nuclear Plant Project

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ABSTRACT

The Next Generation Nuclear Plant (NGNP) Graphite Research and Development Program is currently measuring irradiated material property changes in several grades of nuclear graphite for predicting behavior and operating performance within the core of new very high temperature reactor designs. The Advanced Graphite Creep experiment, consisting of six irradiation capsules, will generate the irradiated graphite performance data for NGNP reactor operating conditions. All six capsules in the experiment will be irradiated in the Idaho National Laboratory (INL) Advanced Test Reactor, disassembled in the INL Hot Fuel Examination Facility, and examined at the INL Research Center or Oak Ridge National Laboratory. This is the first in a series of status reports on the progress of the AGC experiment. The first capsule (AGC-1) was irradiated from September 2009 to January 2011 to a maximum dose level of 6 to 7 dpa. The capsule was removed from the Advanced Test Reactor and transferred in April 2011 to the Hot Fuel Examination Facility, where it was disassembled and the test specimens were extracted. The first irradiated samples from AGC-1 were shipped to the IRC in July 2011and initial post-irradiation examination activities were performed on the first 37 samples received; the activities will continue for the remainder of the AGC-1 specimen as other samples are received. This report provides results of the initial PIE and a comparison to preirradiation graphite characterization.

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ACRONYMS

AGC	Advanced Graphite Creep
ATR	Advance Test Reactor
CCL	Carbon Characterization Laboratory
HFEF	Hot Fuel Examination Facility
HOPG	Highly Oriented Pyrolytic Graphite
INL	Idaho National Laboratory
IRC	INL Research Center
MFC	Materials and Fuels Complex
NGNP	Next Generation Nuclear Plant
ORNL	Oak Ridge National Laboratory
PIE	Post-Irradiation Examination

AGC-1 Post-Irradiation Examination Status

1. DESCRIPTION OF AGC EXPERIMENT

The Next Generation Nuclear Plant (NGNP) Graphite Research and Development (R&D) Program is currently measuring irradiated material properties for predicting the behavior and operating performance of new nuclear graphite grades available for use within the cores of new very high temperature reactor designs. The Advanced Graphite Creep (AGC) experiment, consisting of six irradiation capsules, will generate irradiated graphite performance data for NGNP reactor operating conditions. The AGC experiment is designed to determine the changes to specific material properties such as thermal diffusivity, thermal expansion, elastic modulus, mechanical strength, irradiation induced dimensional change rate, and irradiation creep for a wide variety of nuclear grade graphite types over a range of high temperature, and moderate doses. A series of six capsules containing graphite test specimens will be used to expose graphite test samples to a dose range from 1 to 7 dpa at three different temperatures (600, 900, and 1200°C) as described in the Graphite Technology Development Plan.[1] Since irradiation induced creep within graphite components is considered critical to determining the operational life of the graphite core, some of the samples will also be exposed to an applied load to determine the creep rate for each graphite type under both temperature and neutron flux.

All six AGC capsules in the experiment will be irradiated in the Advanced Test Reactor (ATR). AGC-1 and AGC-2 will be irradiated in the south flux trap and AGC-3–AGC-6 will be irradiated in the east flux trap. The change in flux traps is due to NGNP irradiation priorities requiring the AGC experiment to be moved to accommodate Fuel irradiation experiments. After irradiation, all six AGC capsules will be cooled in the ATR Canal, sized for shipment, and shipped to the Materials and Fuels Complex (MFC) where the capsule will be disassembled in the Hot Fuel Examination Facility (HFEF). During disassembly, the metallic capsule will be machined open and the individual samples removed from the interior graphite body containing the samples. Samples removed from the capsule will be loaded in a shipping drum and shipped to the Idaho National Laboratory (INL) Research Center (IRC) for initial post-irradiation examination (PIE) and storage for any future testing at the newly completed Carbon Characterization Laboratory (CCL).

The CCL is located in Labs C-19 and C-20 of the IRC. It was specifically designed to support graphite and ceramic composite R&D activities[2]. The CCL is designed to characterize and test low activated irradiated materials such as high-purity graphite, carbon-carbon composites, and silicon-carbide (SiC) composite materials. The laboratory is fully capable of characterizing material properties for both irradiated and nonirradiated materials. All test specimens from each of the six capsules will be processed through the CCL to visually inspect each sample, perform initial dimensional changes, and repackage the samples for shielded storage in the NGNP irradiated graphite vault located in Lab C-19 as shown in Figures 1 and 2.

Figure 1. CCL glovebox used to visually inspect graphite samples, perform initial dimensional measurement, and repackage samples for storage in the irradiated graphite vault located in Lab C19.

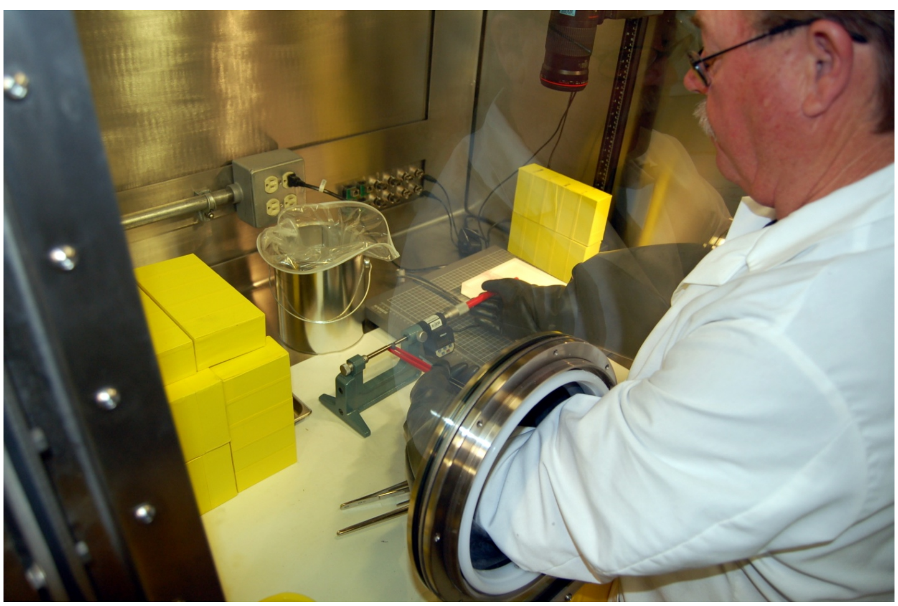

Figure 2. Dimensional measurement and transfer of samples to plastic storage containers.

2. AGC-1 Status

Activities for AGC-1 began in 2006 with the preirradiation testing (Pre-IE) of all graphite samples to be inserted into the AGC-1 capsule. After PIE sample testing was completed, the samples were loaded into the AGC-1 capsule then inserted into the ATR. Capsule irradiation began September 5, 2009. After irradiation, on January 8, 2011, the top and bottom ends of the capsule were sectioned to allow the sample section to be inserted into a GE2000 shipping cask. The capsule was shipped to MFC in April 2011 and disassembly was performed in the HFEF main cell from May through July 2011. Graphite samples were shipped to the IRC in June and July 2011, and PIE activities were initiated in July 2011. PIE of the remaining samples continues in the CCL.

2.1 Preirradiation Examination of AGC-1 Samples

A complete preirradiation testing and characterization program was conducted in fiscal years 2007 and 2008 on all graphite samples inserted into AGC-1 capsule. The properties measured were: bulk density by mensuration, electrical resistivity, and elastic constants, including dynamic Young's modulus (fundamental frequency method); sonic elastic constants, including Young's modulus, shear modulus, and Poisson's ratio; ambient temperature thermal conductivity; and Thermal Expansion (RT-800°C).[3] Samples were inserted in the AGC-1 capsule in the summer of 2009 before irradiation.

2.2 Irradiation of AGC-1 Capsule

The AGC-1 capsule was irradiated in the south flux trap of the ATR from September 5, 2009 to January 8, 2011 spanning seven irradiation cycles (approximately 378 effective full-power days). The irradiation data qualification report summarizes the AGC-1 irradiation history.[4]

After the flux wires have been analyzed and the temperature model finalized through verification and validation, specific data on the temperature, dose, and applied stress levels of the loaded samples will be reported in a future AGC-1 irradiation experiment Engineering Calculation and Analysis Report.

2.3 Disassembly of AGC-1 Capsule

After irradiation, completed on January 8, 2011, the AGC-1 capsule was stored in the ATR Canal for approximately 60 days to allow the activity of the steel pressure tube section of the capsule to decay to lower levels. After radioactive cooling, the ends of the capsule were sectioned to remove the upper pneumatic ram compressive loading components and the lower pressure tube, including the stack stirring pneumatic bellows. The sectioning was performed using a remotely operated band saw in the ATR Dry Transfer Cubicle. The sectioned capsule was shipped to MFC in April 2011 and disassembly was performed in the HFEF main cell from May through July 2011.

The interior of the AGC-1 capsule was constructed of four graphite body sections approximately 2 inches in diameter by 12 inches long (for a total length of approximately 48 inches before irradiation), held together by intricate bayonet joints.[5,6,7,8,9,10] Seven channels were machined axially down the length of the graphite body; 1 central channel and 6 on the outer radius surrounding the central channel. Graphite samples in the 6 radial channels of the upper half of the graphite body were compressively stressed while the graphite samples in the lower half were left unloaded as control samples. The samples in the central channel, upper and lower halves, were unstressed. Twenty-six spacer samples containing flux wires were located in upper, middle, and lower positions within the 6 radial channels to ascertain the accumulated dose in the samples throughout the capsule. The top and bottom halves were separated at the graphite body centerline but pistons between each half transmit the pneumatic force from the stack stirring pneumatic bellows to allow the test samples in each stack to be stirred during reactor shutdown and outages.[11] A center channel running the entire length of the graphite body contained unstressed piggyback samples. SiC temperature indicators were inserted into center holes machined into the middle of the piggyback samples. The SiC monitors are intended to verify the modeled temperature profile is accurate for the first AGC capsule.

All samples (1-inch long creep and ¼-inch long piggyback), spacers, flux wire spacers, and SiC temperature monitors were extracted from the AGC-1 capsule. All samples, spacers, and SiC monitors were shipped to the IRC for initial PIE, visual inspection, repackaging, and storage in the irradiated graphite vault in Lab C-19. The flux wires and graphite body will be held at the MFC for analysis and eventual disposition.

2.3.1 AGC-1 Capsule Disassembly Activities

The AGC-1 capsule was placed in the HFEF main hot cell because the 4-ft-thick walls provide shielding from the high energy of the cobalt-60 contained in the steel pressure tube and other metal components. The main cell has 15 shielded windows with remote master slave manipulators to allow mechanical tasks, such as separating small pieces from larger ones, to be performed.

The disassembly task sequence was planned as follows:

1. Remove the graphite body containing the samples from the heavy steel pressure boundary tube.
2. Remove the gas lines that actuated the lower section stack upset bellow.
3. Remove the 12 thermocouples that penetrated to each elevation in the graphite body.
4. Push out the continuous stack of 0.25-inch-thick piggyback samples from the center position of the graphite body.
5. Separate the upper and lower sections of the experiment at the middle joint by milling into the graphite bayonet joint that held them together.
6. Push the individual radial position creep samples into a sorting station for visual identification by sample number.
7. Separate the spacers containing the flux wires from the test samples for individual analysis.
8. Push each radial section of samples into a Lexan tube to protect the samples from contamination in the HFEF and against damage during transport to the CCL.

Because of uncertainties regarding the condition of the irradiated graphite and its changes in relation to the pressure tube components, several approaches were developed to remove the graphite from the steel. The experiment section was installed on a custom-built fixture with adjustable clamp units to hold the tube or the graphite body. They are actuated by lead screws that can move one clamp longitudinally with respect to the other, or the entire unit relative to a milling cutter as shown in Figure 3. The initial approach was to push on the lower section samples through the radial pushrod holes in the bottom plate of the steel pressure tube. This would transmit force to the samples and the graphite body, pushing the entire unit out as one piece. Alternatively, the experiment tube would be mounted in the 3-axis mill, and the steel tube cut open circumferentially or longitudinally, as the circumstance dictated.

Because the tube was cut with a band saw, there was a concern that the burr created by the cut would hook the steel shim stock heat shield, causing it to crumple, thus preventing the graphite body from being easily pushed out. Initial positioning of the experiment section on the clamping fixture was therefore followed by deburring the upper cut end prior to engaging the push rods in the ratchet flapper to try complete extrusion as the first option.

After deburring, a catch tray was attached to the pressure tube to receive the section being pushed out. The rods were positioned in the pushrod guides, aligned in the bottom plate holes. By manually driving the lead screw, the clamp carriages holding the experiment were pushed toward the stationary pushrods as shown in Figure 4.

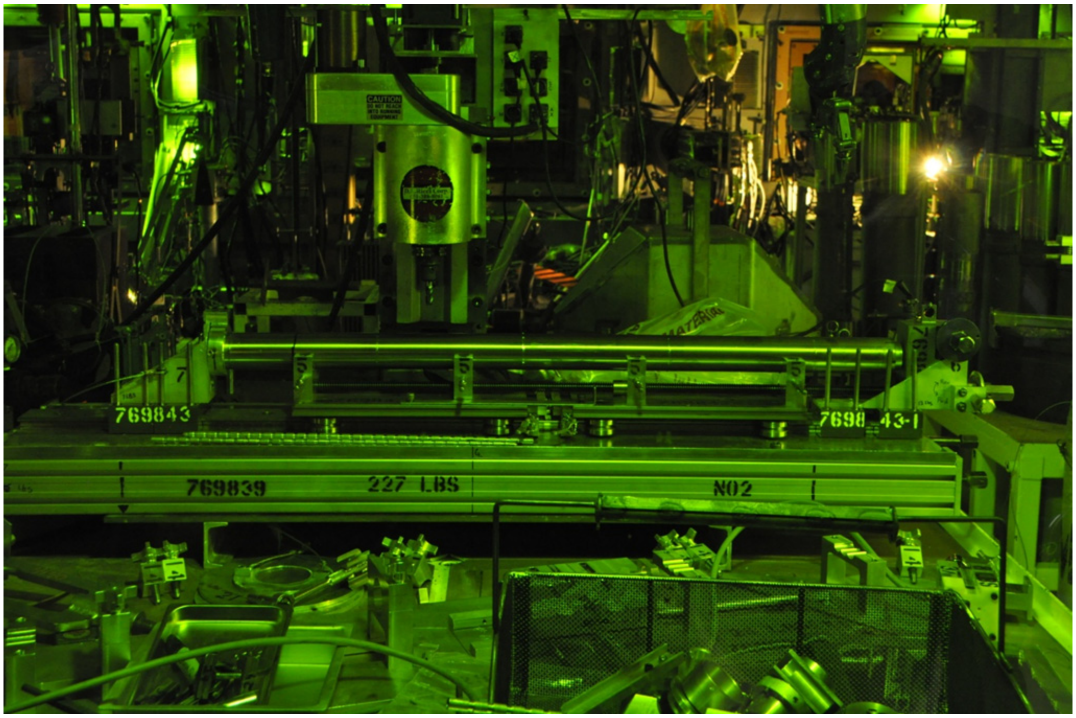

Figure 3. Test train installed on the mill fixture with the deburring fixture installed on the left side (denoted by item number 7, above 769843).

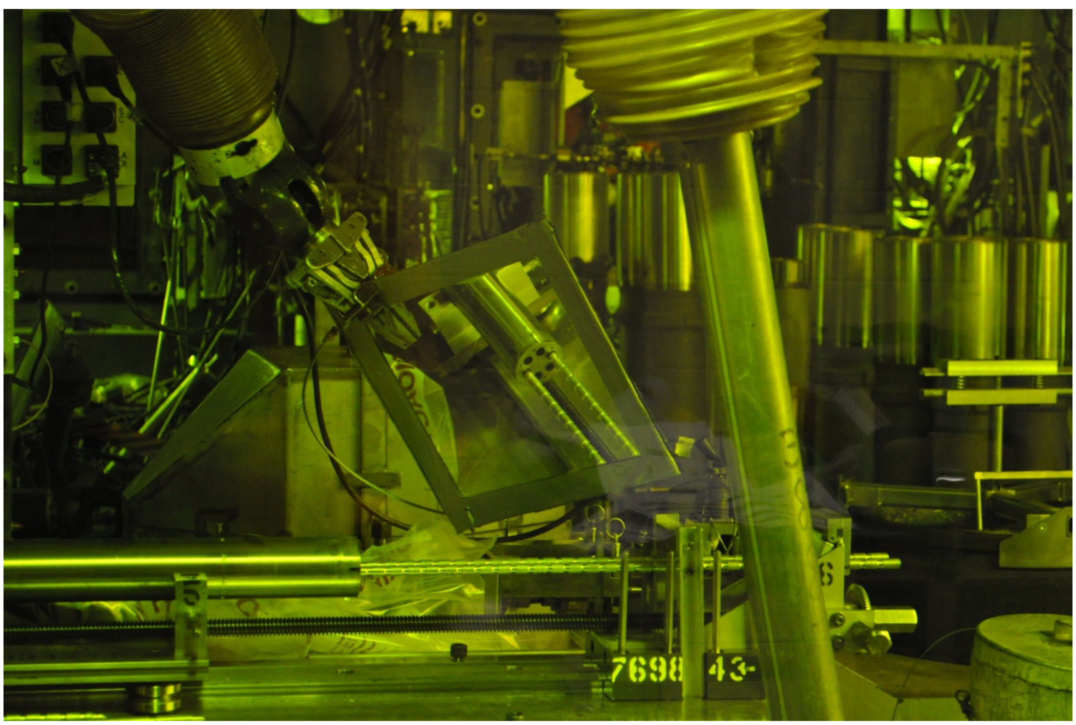

Figure 4. Pushrods installed in the guides, inserted into base plate holes for Channels 3 and 6 as seen in the mirror held above the tube.

The lead screw is driven by a 10:1 reduction gear that moves the clamp carriages, driving the test train section towards the stationary pushrods. Some resistance was initially encountered when moving the test train section toward the pushrods but the resistance was brief and not excessive, resulting in a smooth movement of the carriages for the rest of the extraction. Approximately 30 inches of the graphite body were pushed out from the pressure tube. The lifting fixture end covers were installed on this 30-inch section, which was then moved to the manual sorting tray fixture clamps.

Before moving the extracted 30-inch section, it was noted that the ends of the extraction pushrods were visible at the base of the steel pressure vessel section as shown in Figure 5. This indicated that the bottom section, approximately 12 inches of graphite, had broken away from the top 30 inches of graphite body and was stuck in the steel pressure tube. Further inspections of the exposed end of the graphite body showed evidence of failure of the graphite bayonet joint "fingers" under tension when the pushrods caused the joint to separate from the main section during the initial extraction effort as shown in Figure 6.

It was assumed that the graphite body and samples from the last 12-inch section remained inside the steel pressure vessel tube. The mill cutter was used to make a circumferential cut approximately 3 inches above the bottom end plate to determine at what level the lower graphite section was stuck and to recover the samples from this section of the capsule as shown in Figure 7.

This circumferential cut was successfully performed, and the tube was moved horizontally in the clamps separating the bottom cap, still containing the stuck graphite body, from the steel pressure tube as shown in Figure 8. The lowest 12-inch section of the graphite body remained stuck in the end cap.

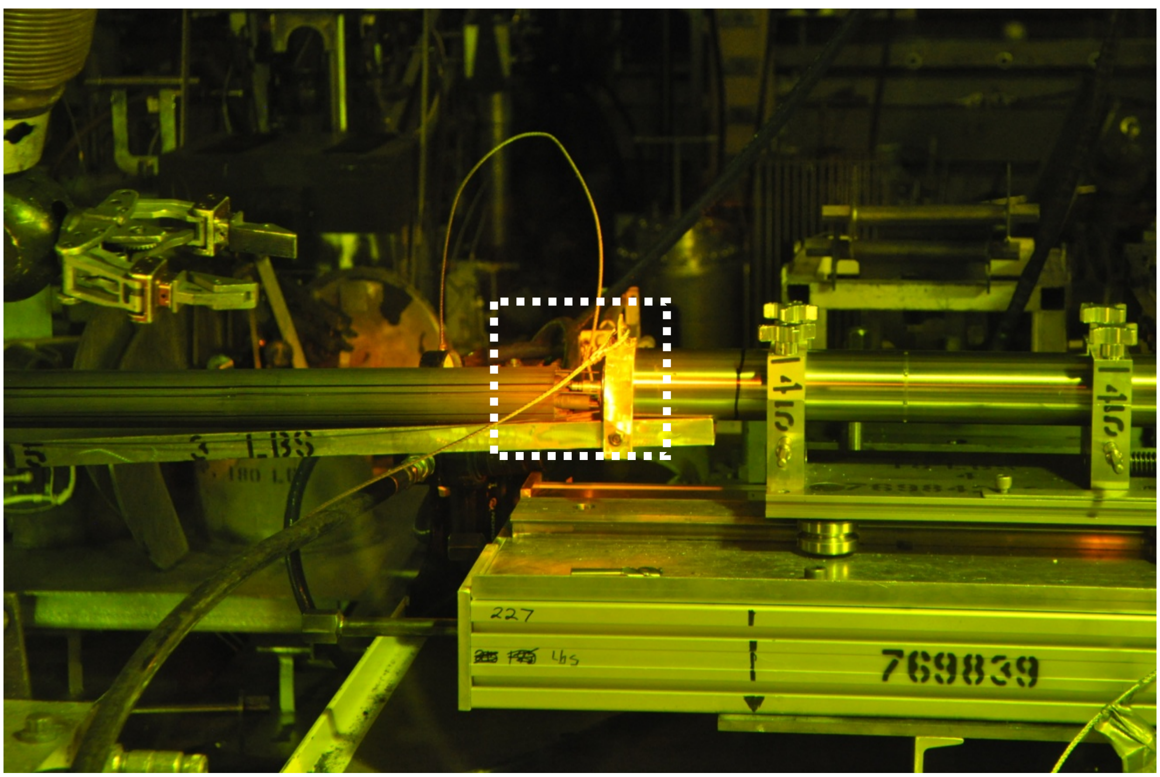

Figure 5. Graphite body in catch tray (3 lbs label visible) with end of pushrod showing at the center of picture (shiny pointed end protruding just below the cable bail).

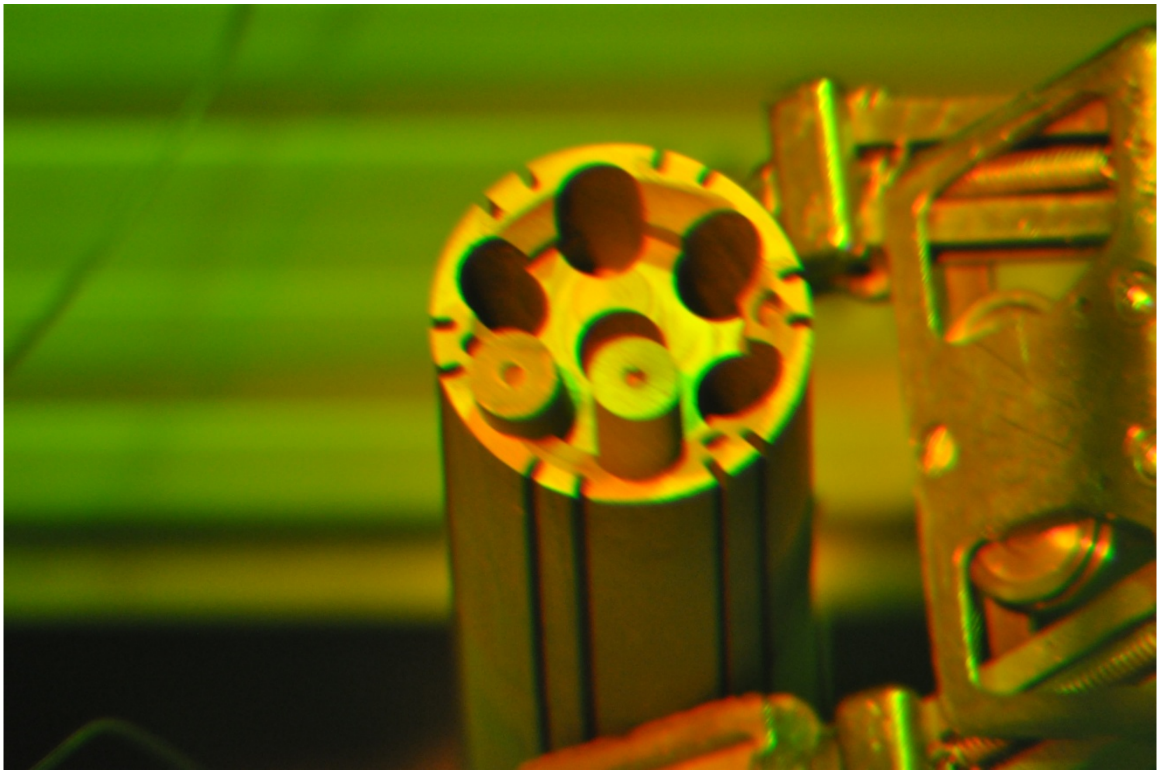

Figure 6. End of graphite body with samples, with sheared-off bayonet joint fingers visible.

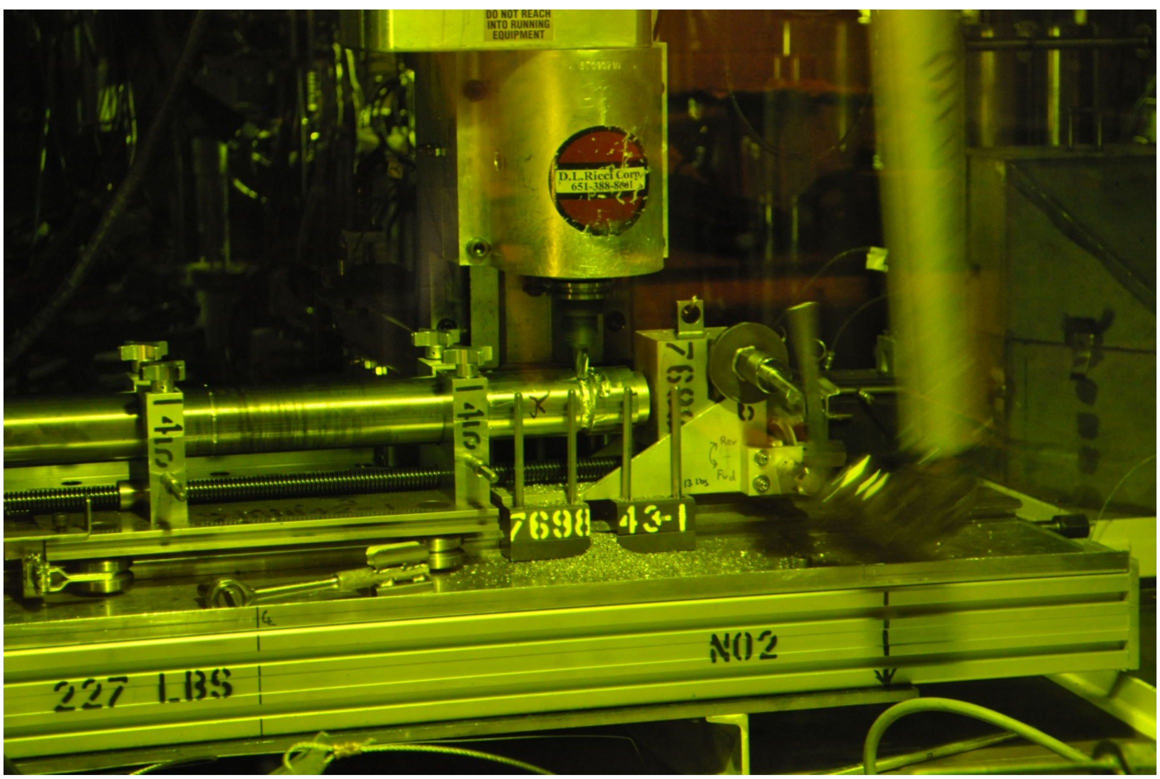

Figure 7. Milling circumferentially to separate the main tube from the end cap. (The rotation of the tube is accomplished by a gear box manually driven with a remote manipulator).

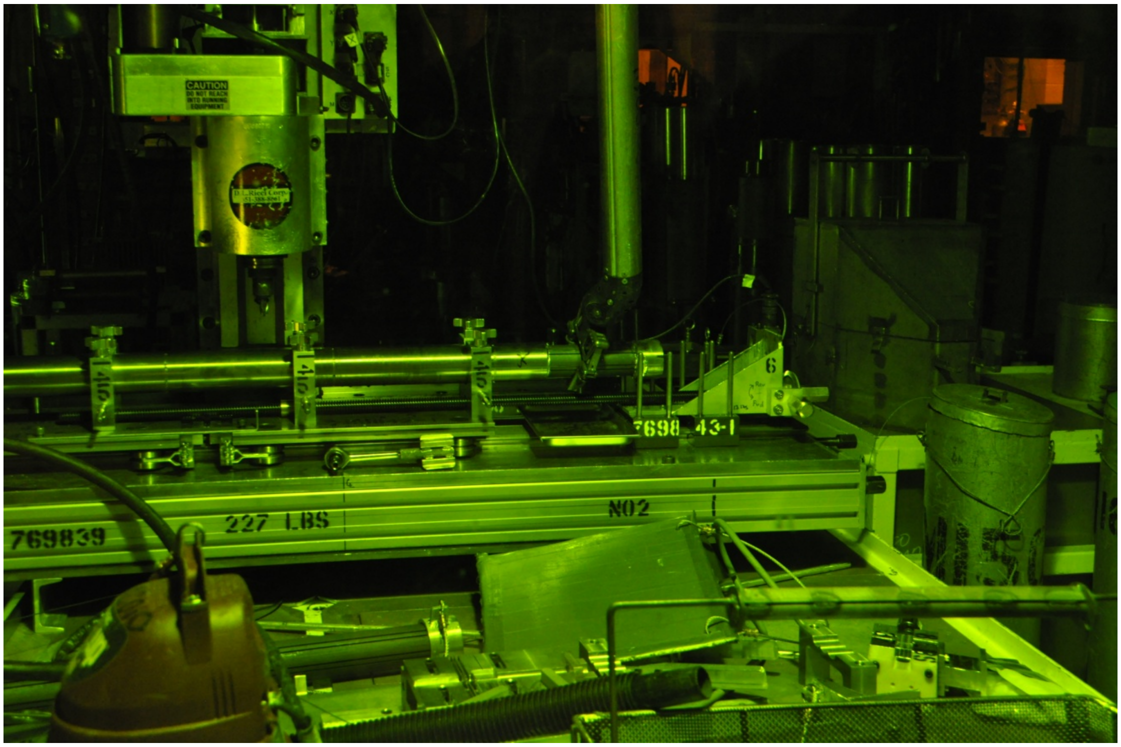

Figure 8. Bottom graphite section (with steel end cap) being removed from the main tube body.

Once the steel pressure tube was sectioned from the end cap and removed from the graphite body, samples from Channels 3 and 6 that were pushed out of the graphite body during extraction, were seen lying inside the empty steel pressure boundary tube as shown in Figure 9. In addition, the heat shield tube had been cut during sectioning and was still intact and in position inside the tube, cleanly separated from the graphite body as shown in Figure 10. The heat shield had not crumpled or bound up during extraction.

After milling, the outer steel pressure tube was removed from the mill clamps and discarded. The large 30-inch section of the graphite body was repositioned in the mill section and the lower sections of the (adjustable V) clamps were tightened to secure the smaller diameter graphite body in the milling fixture. The original plan was to push center stack samples out of the graphite body into a short transfer tube so that a small section could be made available for the first shipment to the CCL as a trial for shipping, handling, and PIE activities. The short tube receiver was attached to the graphite and the pushrod was aligned in the center hole with the ratchet flapper. An attempt was then made to push the center stack samples from the 30-inch graphite body segment.

The push rod was advanced into the center position by manually driving the lead screw. Approximately 2 inches of progress was observed, at which point the joint between the top section and the middle two sections began to separate because the two clamp carriages were not linked together. The sections were pushed back together to confirm that there was generally free movement. The clamp carriages were latched together and the push continued until the ratchet flapper that secures the pushrod on the fixed end drive buttress began to slip, indicating that resistance was greater than the pushrod ratchet could accept. The short sample tube (TUB-AGC-1- 001) was removed from the graphite body and visibly inspected for evidence of graphite samples. A nominal dipstick test was performed, and it appeared that approximately 3 inches of sample material had been pushed into the tube. The tube was capped and set aside for future shipment.

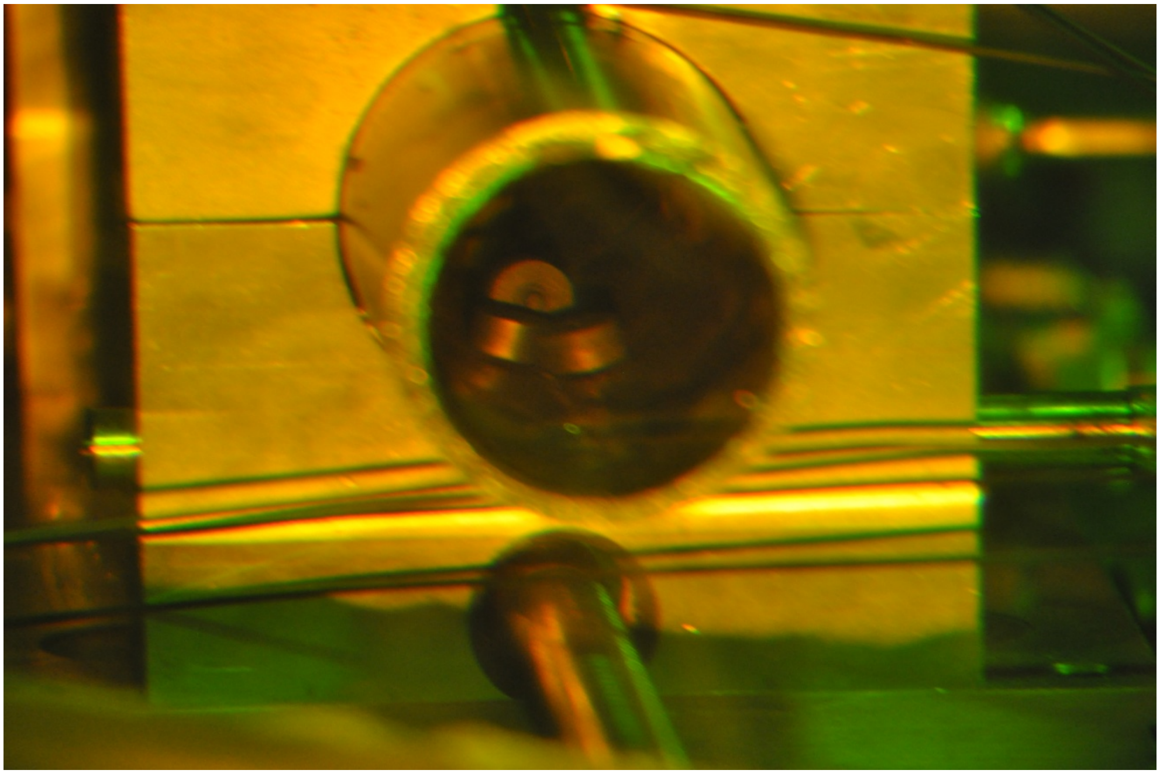

Figure 9. Graphite samples visible inside the empty steel pressure boundary tube.

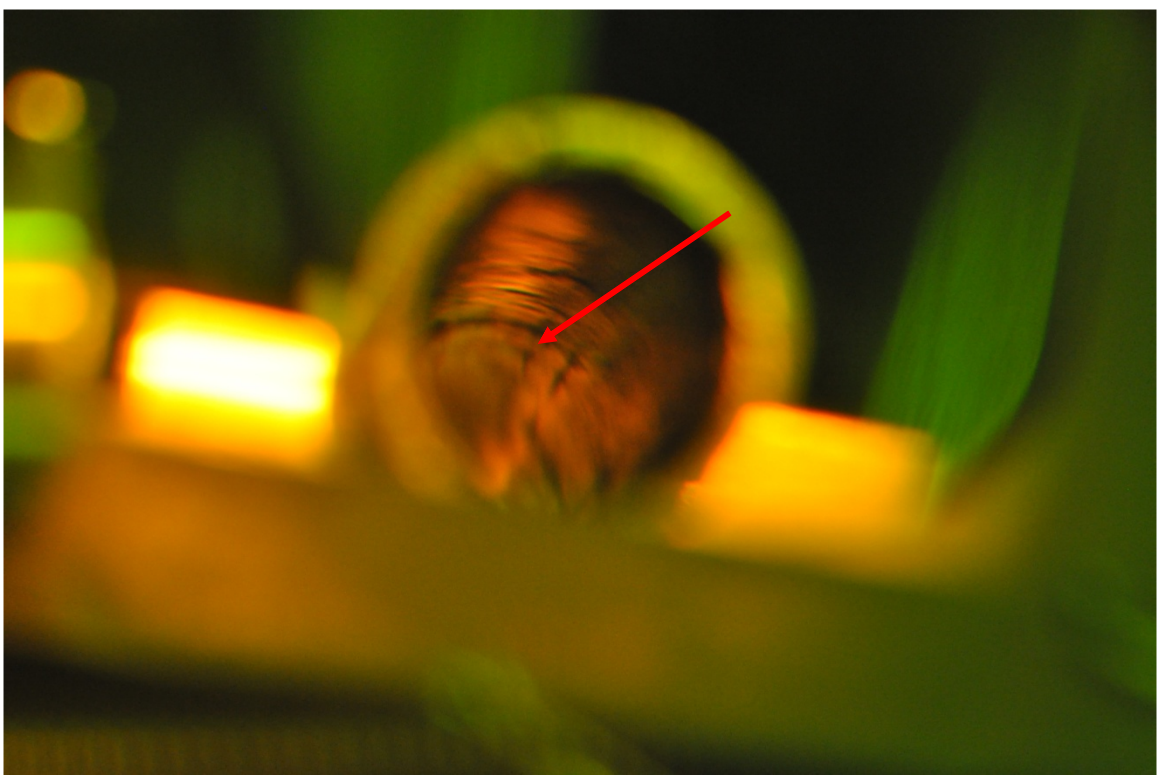

Figure 10. Interior of steel tube with ripples of the heat shield visible.

During this extraction step it was noted that the 9-inch upper section had broken at the bayonet assembly joint as shown in Figure 11. This 9-inch section was removed from the mill clamp and moved to the sorting table. Approximately six, one-quarter-inch pieces (spacers and piggybacks) fell out of the graphite body as a result of the separation. In addition, one of the silicon carbide temperature indicators was seen protruding from the center stack samples as shown in Figure 12.

To avoid breaking the SiC temperature indicator during recovery and extraction of the samples into the transfer tube, the indicator was manually removed from the stack. This activity is normally performed during PIE activities at the CCL. The temperature indicator was removed, along with the four piggyback samples that originally housed the indicator. This entire assembly was placed on the sorting tray and the sample numbers identified on the piggyback samples as shown in Figure 13. Since the SiC temperature indicators do not have individual identification numbers they are identified by the piggyback samples that originally housed them as shown in Figure 14.

After the initial three transfer tubes of center piggyback samples were removed from the top graphite body section, identified, packaged, and shipped, four 1-inch long creep samples were packaged in a 5-inch tube to provide additional material, if space within a small shipping container allowed. The initial short, 5-inch long, transfer tubes were shipped inside a Type 8500 shielded shipping package for this initial small scale shipment.

A bag containing transfer tubes TUB-01, 02, and 05 and BOT-01 was moved from the main HFEF argon cell to the decontamination cell for surface decontamination of the tubes and radiation dose measurement. Surface contamination was approximately 90,000 dpm/100cm^2 following initial decontamination. The tubes were moved to the Hot Repair Area for final decontamination in preparation for shipping. The Hot Repair Area contamination and activity levels are lower than the decontamination cell, and the manual cleaning task can be performed through a glove wall rather than with manipulators.

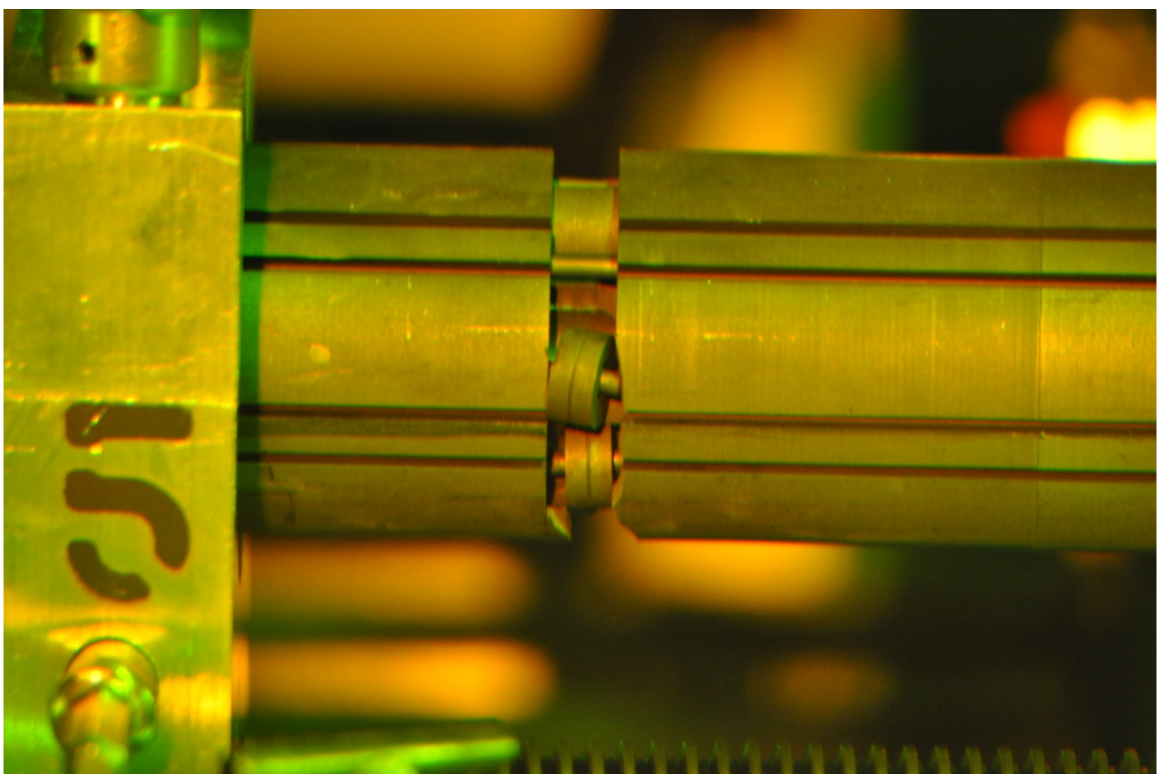

Figure 11. Break of upper 9-inch section (on left side of break) from the original 30-inch section when extracting center channel samples.

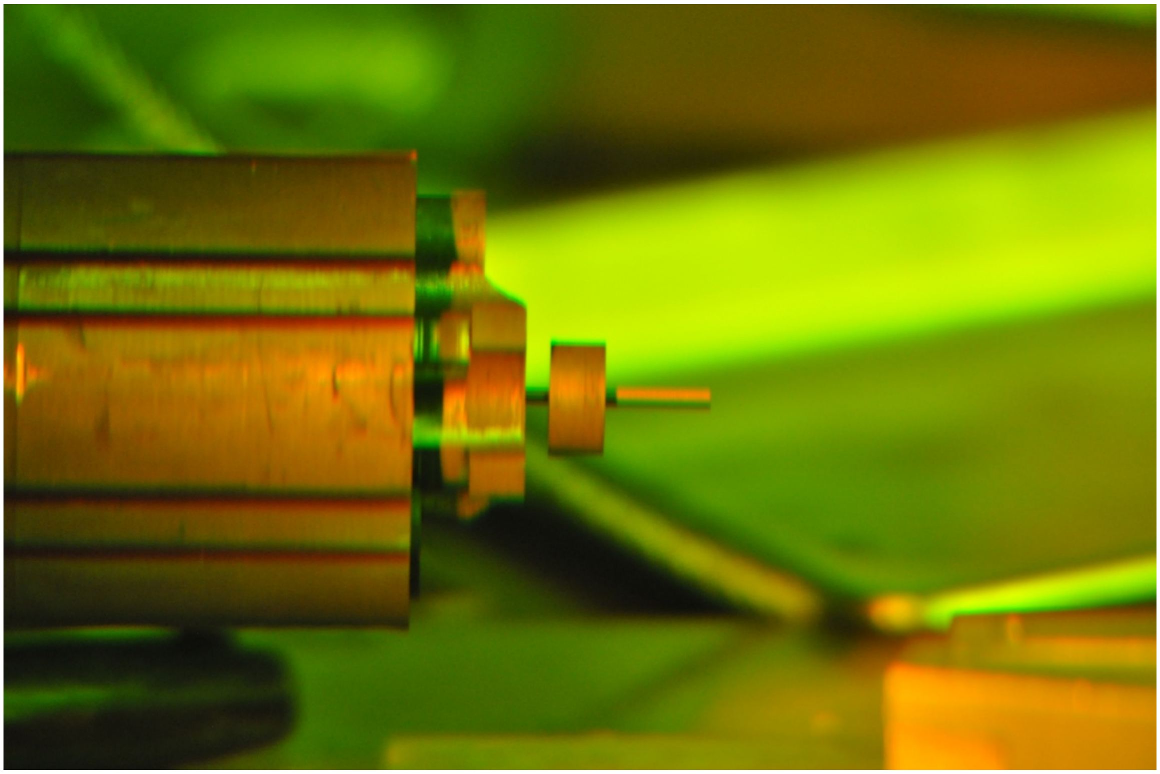

Figure 12. Exposed SiC temperature indicator exposed after graphite body break. One of four piggyback samples that housed the temperature indicator is still attached.

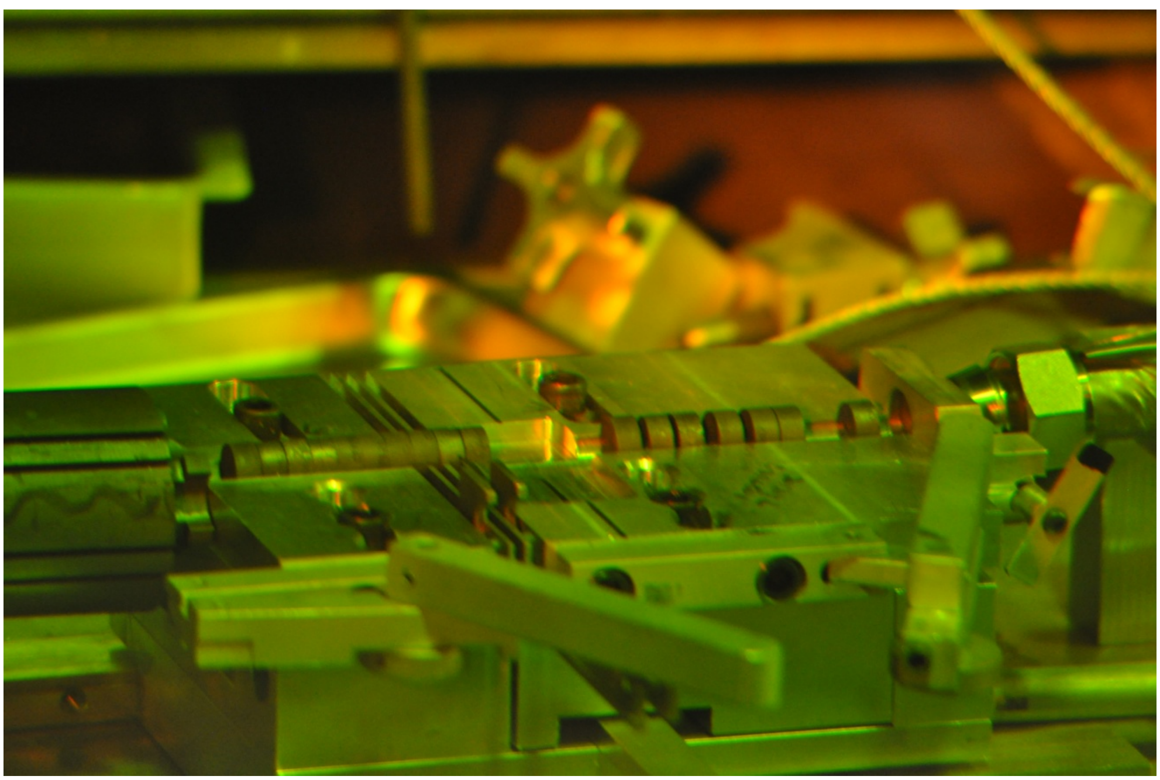

Figure 13. Piggyback samples after extraction sitting in sorting tray before insertion into the transfer tube.

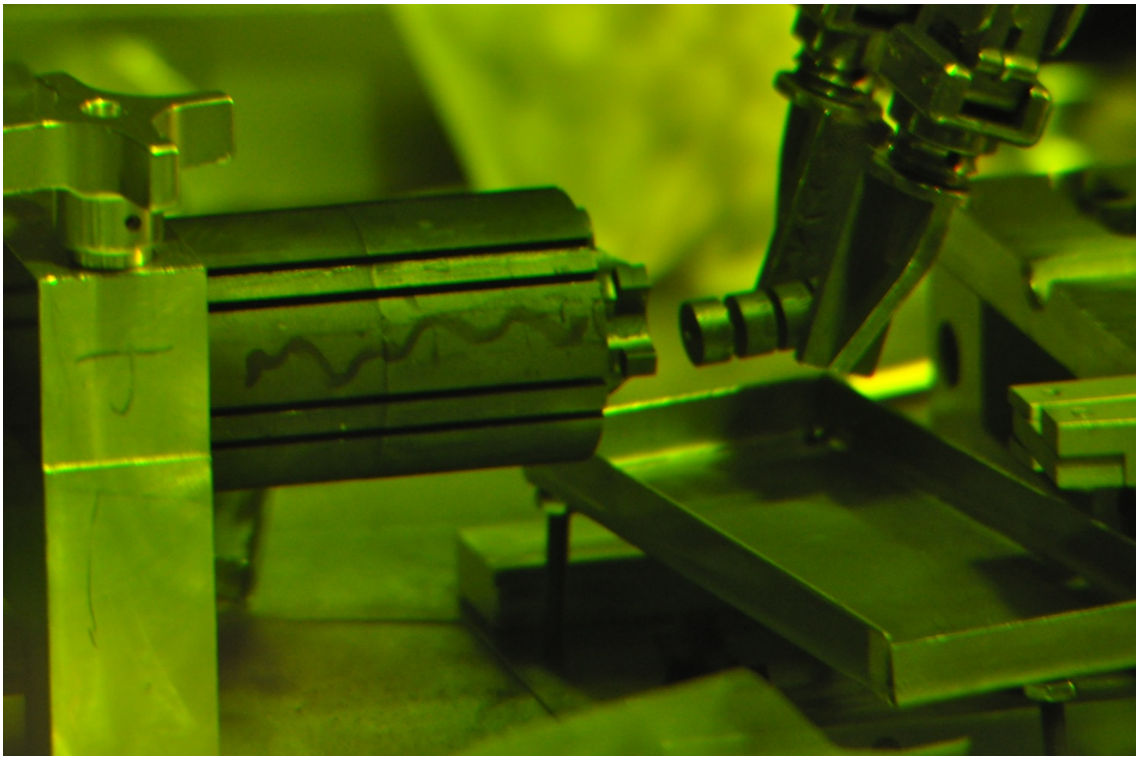

Figure 14. The four piggyback samples that housed the SiC temperature monitor were taken out of the center hole together with the temperature indicator shown in Figure 15.

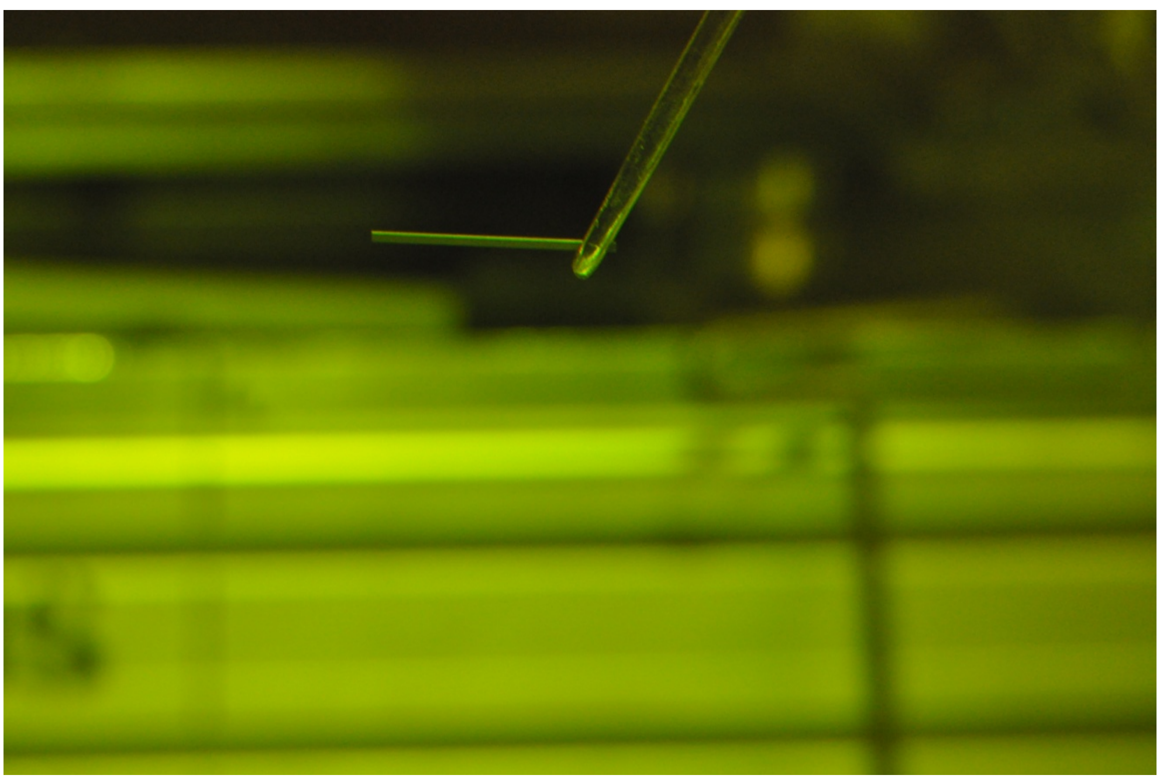

Figure 15. SiC Temperature Indicator.

Ultimately, it was determined that only two tubes would fit into the Type 8500 shipping package, and the tubes containing the 17 and 20 center piggyback samples were sent to the IRC C-19 laboratory. The other tube and the bottle containing the single SiC temperature indicator were put into a second 8500 package until shipping could be arranged at a later date.

An attempt was made to separate the steel cap and gas line components from the bottom section of the graphite body. Two longitudinal cuts were made at approximately 180 degrees from each other. Although the cuts were made to the complete depth of the steel, when the graphite body was pulled on to see if it had been loosened, the bottom graphite section separated from the bottom cap at the bayonet joint. That left the bottom cap with the remainder of the gas lines and the steel end cap, for which it was determined, did not require further separation. The newly freed bottom 12-inch section of the graphite body was moved to the manual sorting tray fixture clamps for sample extraction and sorting.

Once the center piggyback samples had been extracted from the graphite body, the samples from the radial channels were extracted into full length 24-inch transfer tubes, starting with Channel 6. While the center channel has SiC temperature monitors, the outer radial channels have 25 spacers containing flux wire indicators to accurately determine the dose received at different locations in the capsule as shown in Figure 16. During sample extraction, the flux wire spacers were identified, removed, and put into separate containers for shipping and analysis. Because of the original tool design for extracting the flux wire spacers, it was difficult to handle the spacers and flux wires as shown in Figure 17. Extra effort was spent recovering a flux wire dropped during the second day of this activity. To eliminate dropping any more flux wires, a new design with cups to cover the open ends of the spacer, preventing the wire from falling out of the end of spacer, was developed and fabricated as shown in Figure 18.

Figure 16. Flux wire protruding from flux wire spacer in transfer can.

Figure 17. Initial design in use - Flux wire spacer trapped in separation hooks on the sorting table.

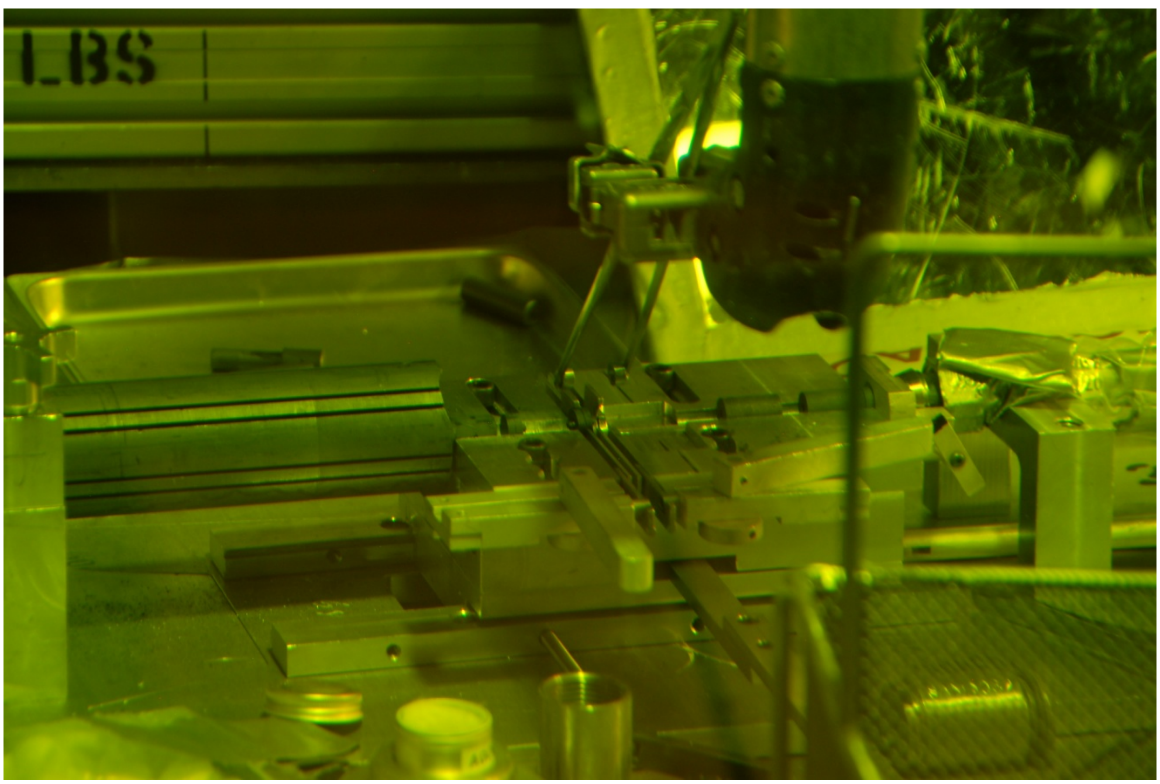

Figure 18. Modified spacer handling design with end cups.

When all samples were removed from the top graphite body section, the samples in the bottom section were separated and packaged. The focus then returned to the larger middle graphite body sections that remained joined together. The first action was to push the center stack piggyback samples from the middle two sections. The pushrods were put into place and the receiver was attached to the graphite body. Very little progress was made, so an effort was made to separate the sections by locking the left clamp carriage in place and using the lead screw to pull the bayonet joint apart. The left carriage brake did not hold securely, so it was not possible to achieve separation. The left manipulator, a heavy duty Central Research Laboratories System 50, was then used to twist the upper section to see if the joint could be disengaged. Because of the presence of the pistons between sections, this was not successful. Inadvertent twisting along the long axis, however, did cause the bayonet joint fingers to break loose, allowing the two sections to be separated. This separation caused a section of the graphite body to break out of one of the radial positions as shown in Figure 19.

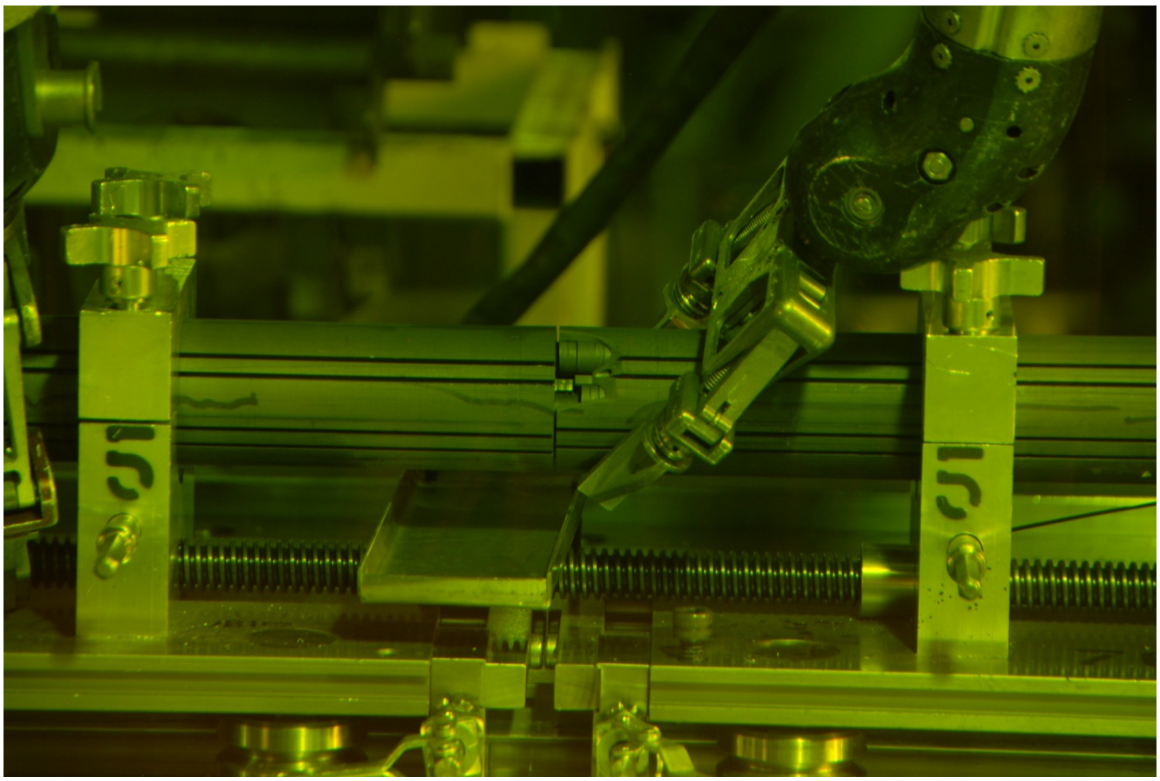

Figure 19. Midpoint joint separation with crack in radial graphite body.

Following this separation, the center stack and radial samples from the midsection of the graphite body were successfully transferred to sample tubes. During extraction, three channel positions required a moderate amount of force to move the samples. Radial Channel 5, the upper midsection, and the center stack required more than 60 lb indicated force to move the samples. Channel 5 in the bottom midsection required 38 pounds of force to move the samples as shown in Figure 20.

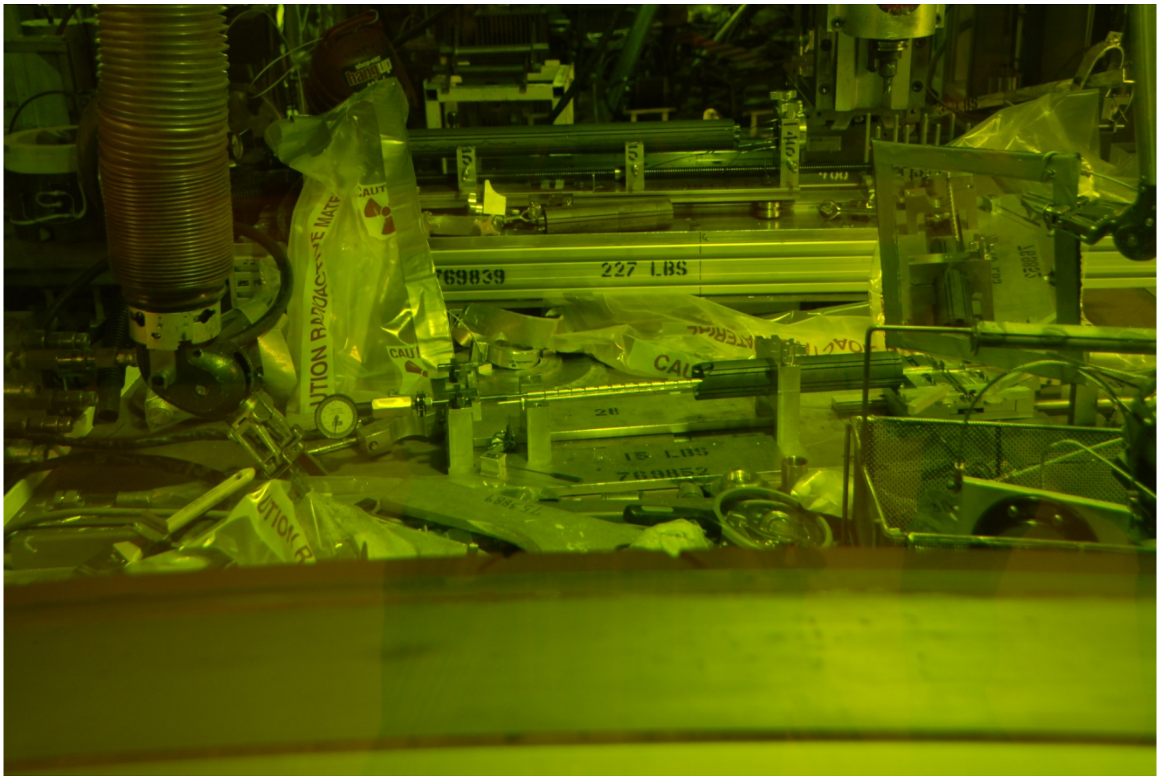

Figure 20. Force gage and pushrod being applied to the bottom section Channel 5.

Once the graphite body sections were emptied, the individual sections were measured for overall section length, and outside diameter on both ends of each section. The overall length was measured with a tape measure and the diameters were measured with a large micrometer. The reported data are shown in Table 1.

Table 1. Measurements of individual graphite body sections.

Graphite Body Section	Dimensions	OD left (upper end)	OD right (lower end)	Length at OD
Bottom section, no end cap	inch	2.07	2.04	11.75
	inch	2.07	2.04	
	inch	2.07	2.04	
Lower middle section	inch	2.07	2.06	11.19
	inch	2.07	2.06	
	inch	2.07	2.06	
Upper middle section	inch	2.06	2.06	12.56
	inch	2.06	2.06	
	inch	2.06	2.06	
Top section	inch	2.01	2.05	8.81
	inch	2.01	2.06	
	inch	2.02	2.07	

2.3.2 Lessons Learned

Observations and lessons learned:

1. The bayonet assembly joints fail in a way such that minimal damage is incurred when tension is applied. This action will be considered for future disassembly activities.
2. In anticipation of a joint failure, it is useful to have a tray to catch any wayward samples that are released when two sections are separated.
3. Unless the center stack is perfectly aligned, there is no indication that it will push out as a unit.
4. Flux wire spacers need to be handled with special care to prevent loss.
5. Highly Oriented Pyrolytic Graphite (HOPG) cup-cap samples are challenging to keep in the stack and more challenging to retrieve piecewise.
6. The clamp on the sorting table needs to have the adjustable V-bottom design to compensate for the various graphite body diameters and the fact that the body shrinks in outer diameter because of irradiation dimensional change. The clamp was left loose to allow the channels to be lined up for push-out. This is a particular problem for center stack samples because the AGC-1 arrangement contained eight samples that contained a SiC temperature indicator followed by a flat loose sample and a HOPG, both of which frequently fell out on some sections.

2.4 Initial PIE of AGC-1 Samples

After disassembly in the HFEF, 37 piggyback samples were shipped to the CCL for initial visual inspection, PIE, repackaging into individual storage containers, and storage in the CCL's irradiated graphite vault. The 37 samples were shipped to the IRC on June 2, 2011 in the short transfer tubes TUB-01 and TUB-02. The initial samples, with a limited inventory of irradiated material, were intended primarily as a trial to determine if there were any issues related to shipping the samples from MFC to IRC, handling the samples at IRC, or any other problems that were not anticipated during the planning of PIE activities. No significant issues were identified at any step and the samples were successfully examined and stored in the CCL's irradiated graphite vault on July 11-12 2011.

2.4.1 Post-irradiation Dimensional Measurements of Initial Samples

Thirty-seven irradiated graphite piggyback samples and three SiC temperature indicators were shipped from the HFEF to the CCL for initial PIE on June 2, 2011. All samples and temperature indicators were contained within TUB-01 and TUB-02. TUB-01 contained samples CPB-21 thru CPB-37 and a SiC temperature indicator associated with sample CPB-24. TUB-02 contained samples CPB-1 thru CPB-20 and two SiC temperature indicators associated with samples CPB-1 thru 10 and samples CPB-11 thru 20 respectively. Each SiC temperature monitor was visually inspected, repackaged for storage, given a unique identification number (SiC-01, SiC-02, and SiC-03, etc.) and will be shipped to Oak Ridge National Laboratory (ORNL) for further analysis.

After receiving the samples from HFEF, IRC personnel unloaded the two transfer tubes from the Type 8500 shielded shipping package. The samples were unloaded from the transfer tubes and visually inspected. Each sample was identified and visually inspected before further testing was performed. Visual inspection consisted of taking photographs of the sides of each sample taken at 90-degree intervals. Photographs of the top and bottom of the sample were then taken, noting any chips, cracks, breakage, or damage to the sample.

Representative images of two visually inspected samples are shown in Figure 21. No significant damage to the initial samples was observed during visual inspection. When comparing the images to preirradiation visual inspection images, many of the samples were observed to have additional surface markings as shown in Figure 22. The marks appeared to be superficial, most likely resulting from handling during disassembly and sorting. More detailed inspection of the marks will be performed if further testing indicates a significant flaw. Many samples also appeared to have a rougher surface after irradiation. This increased surface roughness may arise from the significant dimensional changes of the individual crystallites at the surface. Due to the random crystal orientation in the near isotropic graphite grades some of the crystallites will shrink under irradiation while some will expand away from the original surface plane, creating a rougher surface. These samples will be analyzed further in the future. All digital photographs will be stored along with the results from thermal, mechanical, and physical testing, becoming part of the permanent record for each individual sample.

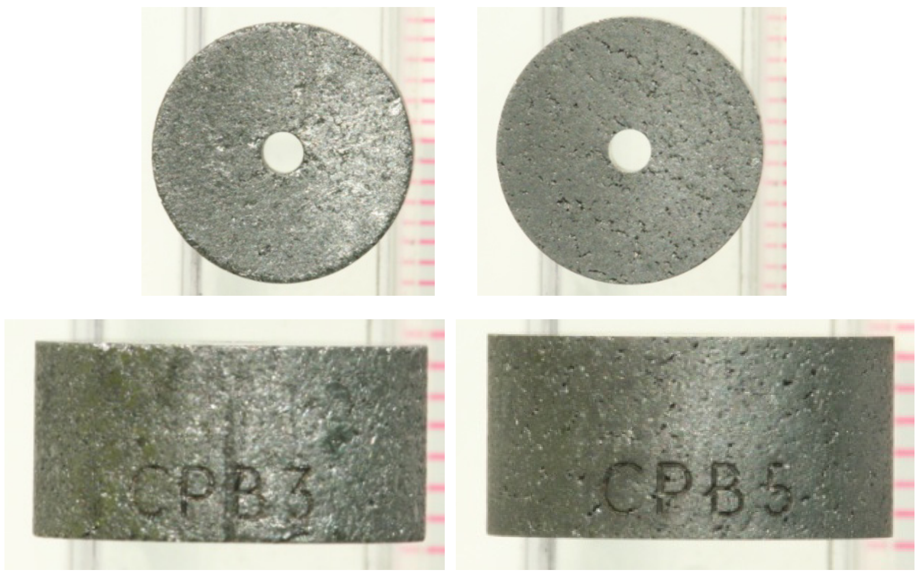

Figure 21. Post-irradiation visual inspection images for CPB3 and CPB5.

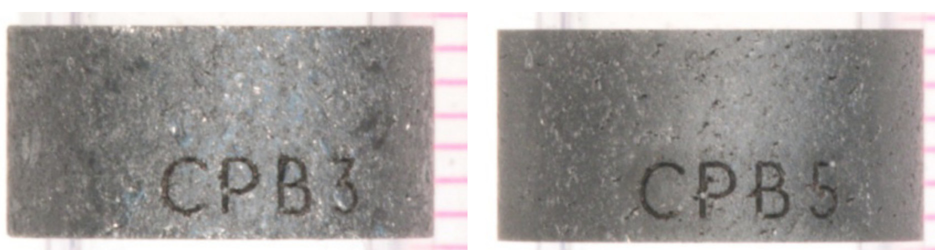

Figure 22. Preirradiation visual inspection images for samples CPB3 and CPB5.

After sample identification and visual inspection, the physical dimensions of each sample were measured using ASTM standard C559-10,[12] which is the same method used to measure the samples before irradiation.[3] Comparing the pre- and post-irradiation dimensional measurements will provide the irradiation induced dimensional change for each type of graphite. By comparing the dimensional change differences between stressed and unstressed samples exposed to similar temperatures and doses, the irradiation induced creep for each graphite type can be quantitatively determined. Determining the irradiation creep is critically important to determining the eventual operational lifetime of graphite components.

For this initial activity, only the unstressed irradiation induced dimensional change was recorded for the 37 initial samples because piggyback samples do not have both stressed and unstressed samples in the

AGC capsules. Only creep samples have matching stressed and unstressed sample pairs. Based on calculations from the design of AGC-1 capsule,[5] the temperature measurements during irradiation,[4] and the position of the samples,[10,11] a rough estimate of the operating dose and temperature for the samples is given in Table 2. The values are purely rough estimates at this time. A more refined and accurate determination of the dose and temperature, as a function of position within the capsule, will be available after the flux wires have been analyzed and the temperature model, based on the measured values from the thermocouple readouts, has been finalized. Final dose, temperature, and stress values will be included in the report to be generated once AGC-1 PIE activities are complete.

Table 2. Estimates of dose and temperature for -21-inch to -12-inch of centerline of capsule.

Sample	Position (inch)	Dose (dpa)	Temperature (°C)
CPB37	-12	3.39	550–625°C (TC09)
CPB33	13	3.25	—
CPB29	-14	3.14	—
CPB25	-15	2.99	—
CPB21	-16	2.85	—
CPB17	-17	2.65	—
CPB13	-18	2.47	500–550°C (TC10)
CPB9	-19	2.25	—
CPB5	-20	2.03	—
CPB1	-21	1.82	450–500°C (TC12)

Pre- and post-irradiation dimensions for each sample are summarized in Figures 23 and 24 (length and diameter measurements respectively). As seen, the dimensional length change is approximately 0.8% and the diameter change is nominally about 1% for all samples. It should be noted that samples CPB2, CPB12, CPB22, and CPB32 are actually the A3 fuel matrix material and are not considered nuclear graphite. It can be seen that the irradiation performance of A3 material is not nearly as stable as nuclear graphite. In addition, CPB1, CPB11, CPB21, and CPB31 are HOPG sample holders and are not plotted with the graphite samples.

Because the AGC experiment is designed to test multiple grades of graphite, the dimensional length changes for individual types of graphite are shown in Figures 25 and 26 (length change only). In general, even over this relatively narrow dose and temperature range (1.8–3.4 dpa and 450–550°C respectively), a larger dimensional change was observed for samples that received higher dose levels at higher temperature (CPB37) as expected. No conclusions concerning the magnitude of the irradiation dimensional change for each graphite type will be made from this limited sample population representing only a fraction of the dose and temperature experienced in AGC-1 irradiations. Further analysis will occur when the full sample population has been characterized.

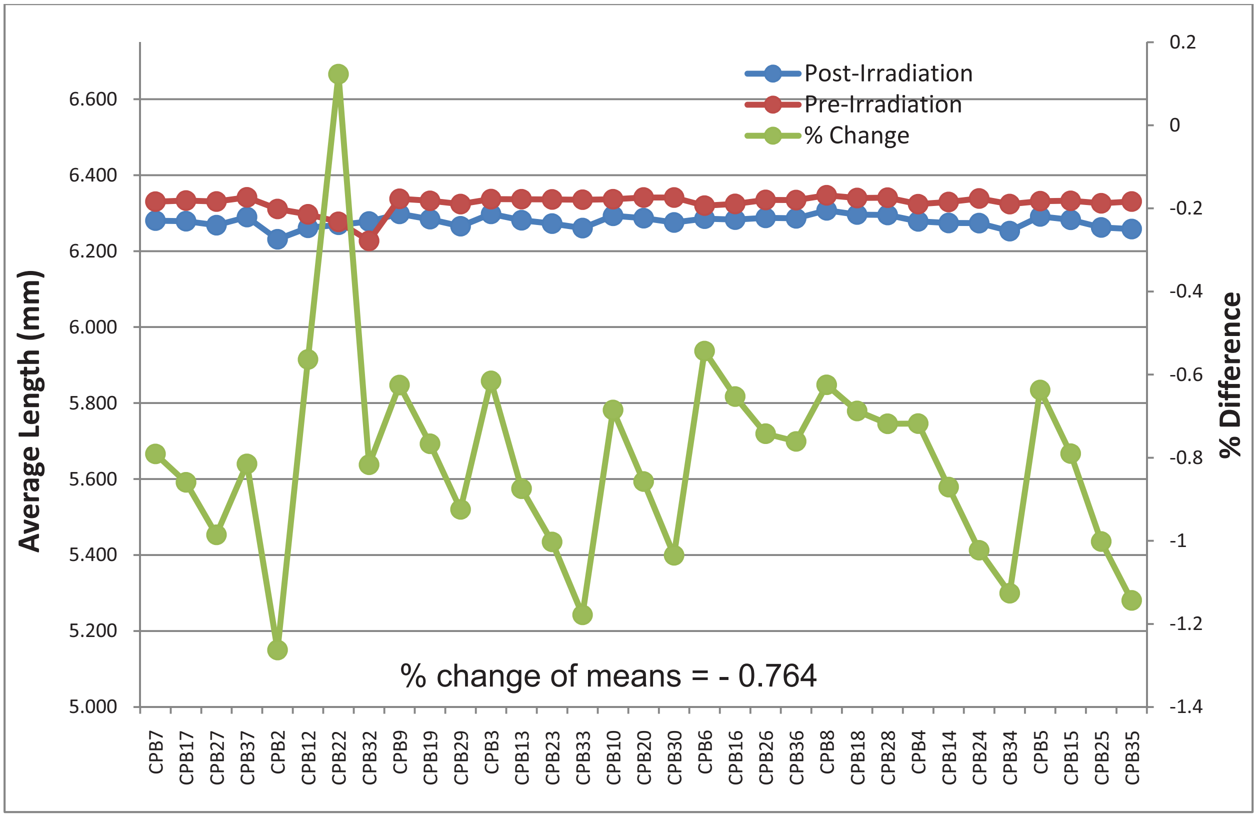

Figure 23. Sample length measurements

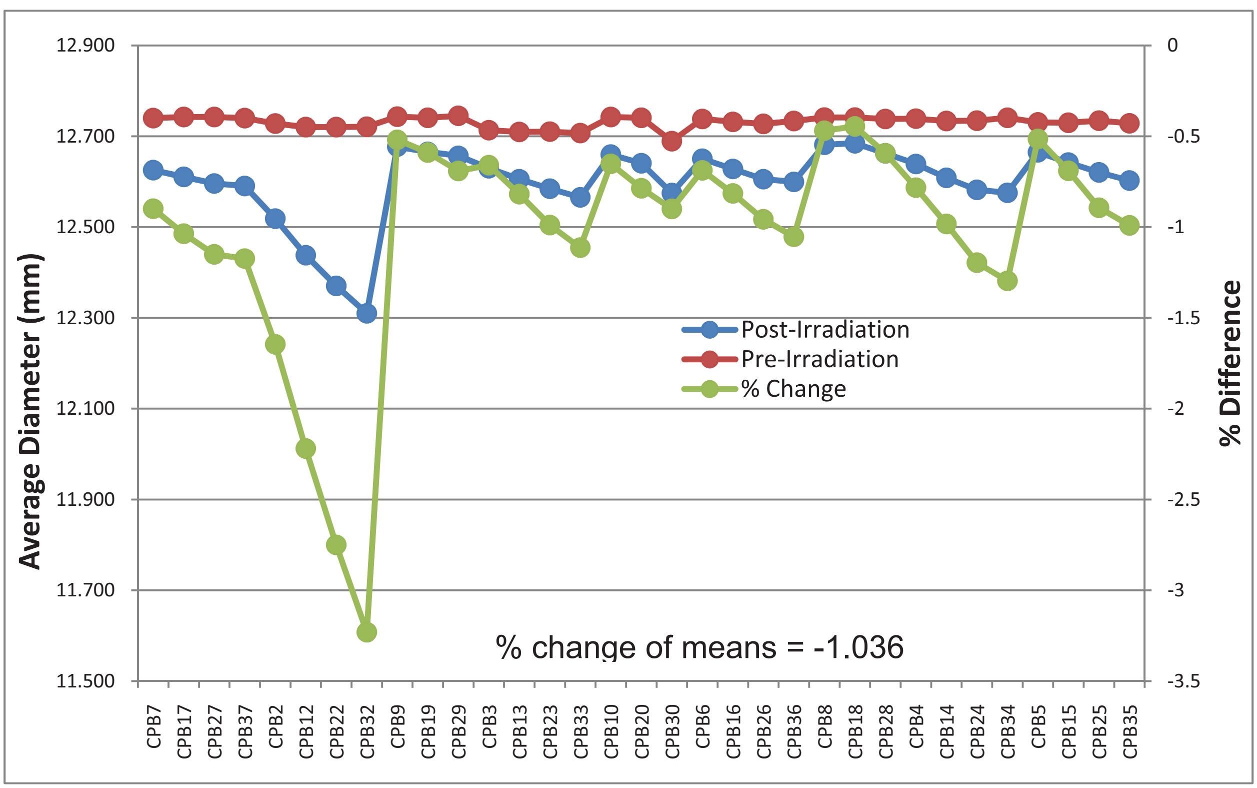

Figure 24. Sample diameter measurements.

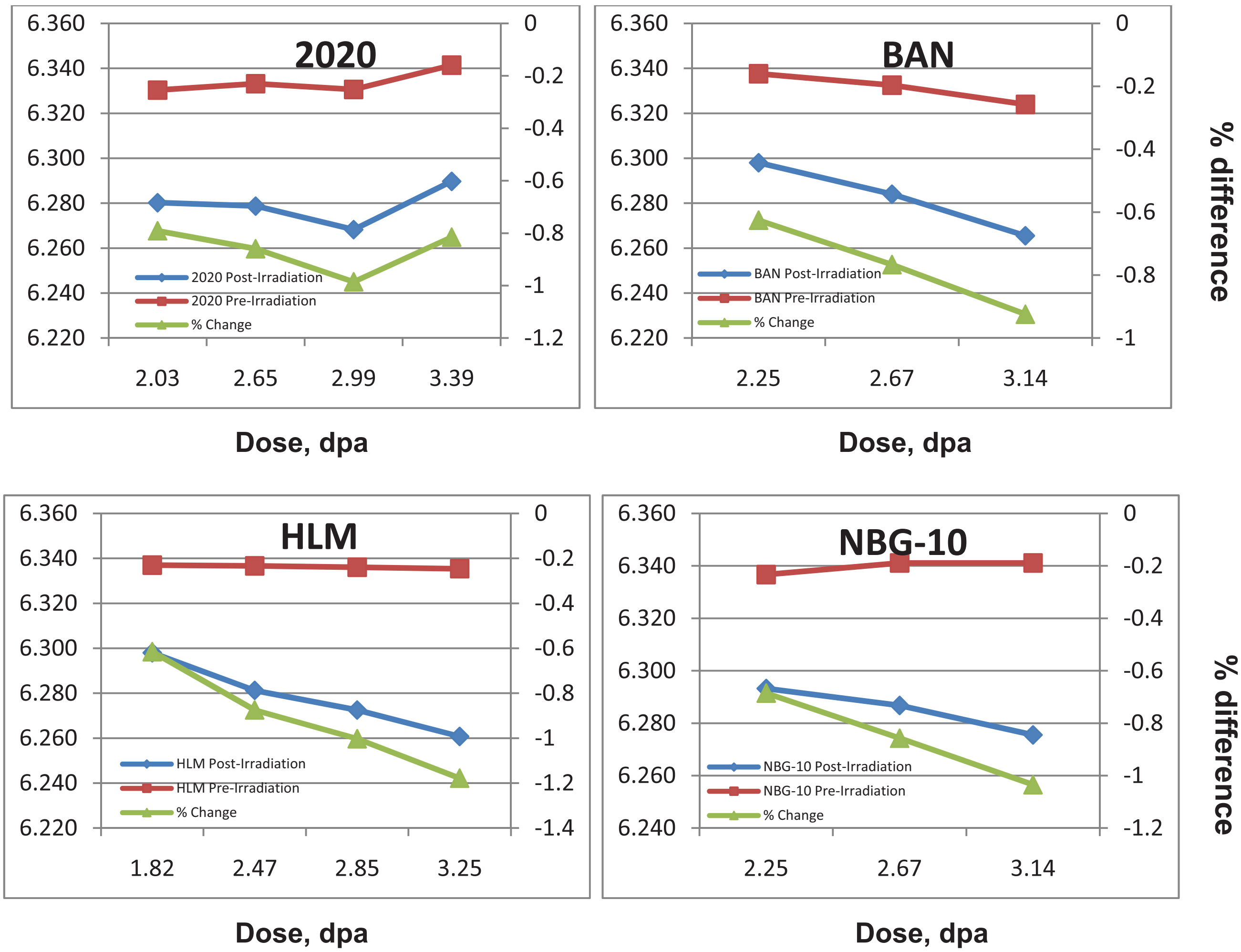

Figure 25. Dimensional changes to 2020, BAN, HLM, and NBG-10 graphite types.

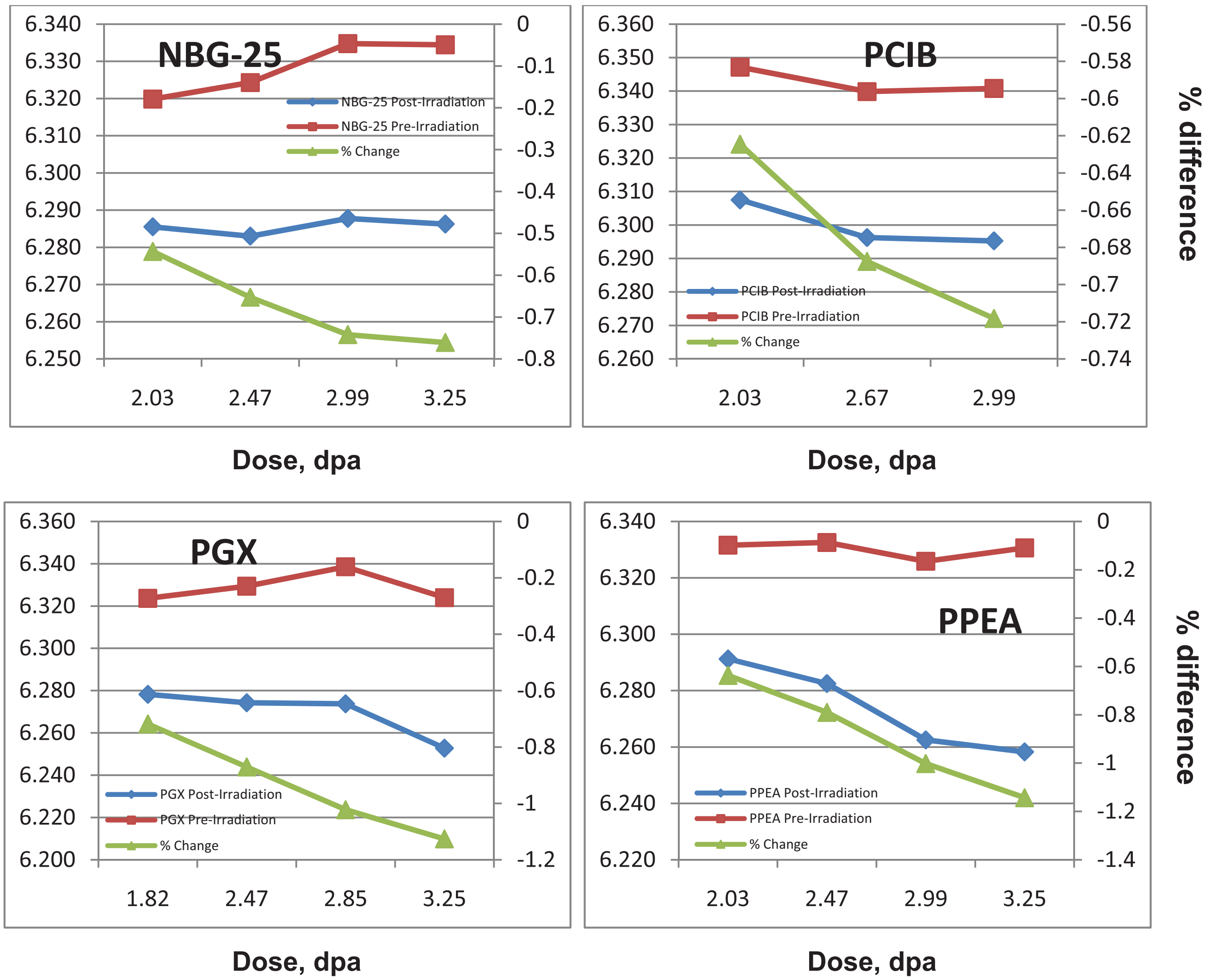

Figure 26. Dimensional changes to NBG-25, PCIB, PGX, and PPEA graphite types

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