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The Next Generation Nuclear Plant Graphite Creep Experiment Irradiation in the Advanced Test Reactor

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Abstract – *The United States Department of Energy's Next Generation Nuclear Plant (NGNP) Program will be irradiating six gas reactor graphite creep experiments in the Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL). The ATR has a long history of irradiation testing in support of reactor development and the INL has been designated as the United States Department of Energy's lead laboratory for nuclear energy development. The ATR is one of the world's premiere test reactors for performing long term, high flux, and/or large volume irradiation test programs. These graphite irradiations are being accomplished to support development of the next generation reactors in the United States.*

The graphite experiments will be irradiated over the next six to eight years to support development of a graphite irradiation performance data base on the new nuclear grade graphites now available for use in high temperature gas reactors. The goals of the irradiation experiments are to obtain irradiation performance data, including irradiation creep, at different temperatures and loading conditions to support design of the Next Generation Nuclear Plant (NGNP) Very High Temperature Gas Reactor, as well as other future gas reactors. The experiments will each consist of a single capsule that will contain six stacks of graphite specimens, with half of the graphite specimens in each stack under a compressive load, while the other half of the specimens will not be subjected to a compressive load during irradiation. The six stacks will have differing compressive loads applied to the top half of each pair of specimen stacks, while a seventh stack will not have a compressive load. The specimens will be irradiated in an inert sweep gas atmosphere with on-line temperature and compressive load monitoring and control. There will also be the capability of sampling the sweep gas effluent to determine if any oxidation or off-gassing of the specimens occurs during initial start-up of the experiment.

The first experiment was inserted in the ATR in August 2009 and started its irradiation in September 2009. It is anticipated to complete its irradiation in early calendar 2011. This paper will discuss the design of the experiment including the test train and the temperature and compressive load monitoring, control, and the irradiation experience to date.

I. INTRODUCTION

The United States Department of Energy's Next Generation Nuclear Plant (NGNP) Program will be irradiating six gas reactor graphite creep experiments in the Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL). The ATR has a long history of irradiation testing in support of reactor development and the INL has been designated as the United States Department of Energy's lead laboratory for nuclear energy development. The ATR is one of the world's premiere test reactors for performing long term, high flux, and/or large volume irradiation test programs. The graphite irradiations are being performed over the next six to eight years to support development of the next generation reactors in the United States.

The historical nuclear grade graphites are no longer available due to depletion of the feedstock material used in their manufacture. However, new nuclear grade graphites have been developed to replace the historical graphites for use in the nuclear industry. The goals of the irradiation experiments (designated the Advanced Graphite Capsule [AGC] series) are to obtain irradiation performance data on the new nuclear grade graphites at different temperatures and compressive loading conditions to support design of the Next Generation Nuclear Plant Very High Temperature Gas Reactor (VHTR), as well as other future high temperature gas reactors. The graphite specimens are being irradiated in an inert sweep gas atmosphere with on-line temperature and compressive load monitoring and control. There is also capability for sampling the sweep gas effluent to determine if oxidation or off-gassing of the specimens occurs during initial start-up of the experiment.

The final design for the first experiment (AGC-1) was completed in September 2008. The fabrication and assembly of the experiment test train as well as installation and testing of the control and support systems that will monitor and control the experiment during irradiation were completed in early calendar 2009. The experiment was inserted into the ATR and began irradiation in September 2009. The design of the experiment including the test train and the temperature and compressive load monitoring, control, and data collection systems will be discussed.

II. EXPERIMENT CAPSULE

The experiment test train consists of a capsule, or ATR core section, and an umbilical tube (termed a lead out) extending from the top of the capsule up through the top head of the ATR reactor. A horizontal capsule cross-section at the top of the reactor core is shown in Figure 1.

The capsule portion of the test train is approximately 64 mm (2.5 inches) in diameter and 2.3 m (90 inches) in height, extending from approximately 0.9 meters (32 inches) below the active core to approximately 0.25 meters (9 inches) above the 1.2 meter (48 inch) active core height of ATR. The capsule contains seven separate stacks of graphite specimens. Six of the specimen stacks are arranged around the perimeter of the capsule, and the seventh stack is located in the center. The top half of the six perimeter specimen stacks have a compressive load applied to them during irradiation to determine irradiation creep. The lower half of the perimeter stacks are not subjected to a compressive load in order to provide a benchmark for the loaded specimens. The seventh stack of specimens does not have a compressive load on any of its specimens during irradiation.

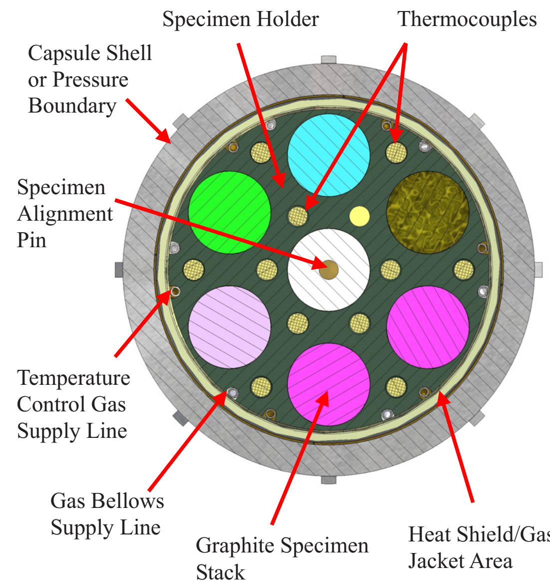

Fig. 1: AGC-1 Capsule Horizontal Cross-Section

A graphite specimen holder surrounds and separates the seven specimen stacks and has features machined to accommodate the temperature control and compressive load control gas lines as well as the thermocouples for measuring temperature within the capsule. The graphite holder also provides the inner most boundary of two adjacent insulating gas jackets used for temperature control of the specimens during irradiation. In order to maintain the same temperature in the specimens throughout the height of the core, the combined width of the two gas jackets range from approximately 0.40 mm (0.016 inches) at core center to a maximum of 1.70 mm (0.067 inches) at the top of the core. The variation in width is necessary due to the ATR neutron and gamma axial flux profile, which has the shape of a chopped cosine curve with the peak maintained at the vertical center of the core. The variation in the (total) gas jacket width is accomplished by varying the outside diameter of the specimen holder throughout its height. This feature required very rigorous and closely integrated reactor physics and thermal analyses to develop the required diametrical variations. The graphite was also carefully analyzed to ensure shrinkage and changes in its thermal properties during irradiation would not adversely impact the specimens or temperature control of the capsule.

An inert sweep gas atmosphere surrounding the specimens during irradiation is used in conjunction with the gas jackets to maintain the desired temperatures in the specimens. The sweep gas is provided by an on-line temperature monitoring and control system that will be discussed in a separate later section of this paper. Inside of the capsule the sweep gas is provided by six temperature control gas lines. Four of the gas lines provide sweep gas to the graphite specimens and the specimen holder located inside of a radiation heat shield. The other two gas lines provide sweep gas to the gas jacket between the radiation heat shield and the capsule pressure boundary. The flow from the six lines is distributed and directed to the appropriate section of the capsule by a graphite insulator located at the bottom of the specimen holder. The insulator also supports and horizontally centers the specimen holder and radiation heat shield at the bottom of the capsule to maintain the appropriate gas jackets. In addition it insulates the holder from the capsule pressure boundary bottom support that is in radial contact with the relatively cold reactor primary coolant. The top of the specimen holder and radiation heat shield are centered by a machinable ceramic insulator. Unfortunately, this type of ceramic insulator could not be used at the bottom of the capsule due its density (gamma heating capacity) and materials in the insulator that resulted in neutron reaction heating. However, it could be located far enough from the core at the top of the holder to overcome these issues. In addition to the six temperature control gas lines, there are also six compressive load control gas lines to supply gas to a series of gas bellows located at the bottom of the test train.

Twelve thermocouples are distributed across the graphite specimen holder cross section and throughout its height to provide well characterized temperature indication of the holder. The temperature data from the holder is then used in the thermal analysis model to determine the temperatures in the graphite specimens. This approach is being used primarily due to the graphite specimens relative movement during irradiation (e.g. irradiation damage, creep strain, etc.) that could possibly result in loss of contact between the graphite specimens and the thermocouples. However, it also avoided having to dedicate some of the specimens to temperature measurement. Since conduction is more easily controlled than other forms of heat transfer, actions were taken in the design to limit heat transfer inside the capsule to conduction as much as possible. A radiation heat shield was placed between the specimen holder and the capsule shell, and the sweep gas pressure and flow rate are maintained at very low values to effectively eliminate convective heat transfer. Temperature control of the capsule is then accomplished by adjusting the mixture of two gases with differing thermal conductivities to control the heat transfer across the two insulating gas jackets between the heat source (gamma heating of the specimens and capsule materials) and the relatively cold ATR primary coolant (52 ºC). Helium is used as the high (thermally) conductive gas and argon is used as the insulating gas. As indicated earlier the six temperature control gas lines deliver the incoming gas to the bottom of the capsule, where it is directed to its assigned vertical pathway up through the capsule and into the lead-out. Inside the lead-out, the gas continues its upward path and exits the test train at the top of the lead-out just above the reactor top head into the temperature control system exhaust line.

There are two different sizes of graphite specimens. The large specimens are 12.3 mm (0.5 inch) in diameter and 25 mm (1.0 inch) long, and the short specimens are also 12.3 mm (0.5 inch) in diameter but only 6.4 mm (.25 inch) long. The six perimeter stacks each contain 15 large compressively loaded specimens above core centerline and a combination of 14 large and 10 small specimens below core center that do not have a compressive load. The center stack contains 172 small specimens, all without a compressive load imposed upon them during irradiation. Vertical alignment of the specimen stacks is maintained by small pins extending from graphite spacers placed between the specimens to a nominal depth of 3 mm (0.110 inch) into the end of the two adjacent specimens. Encapsulated neutron flux measurement wires are installed inside the alignment pins of certain strategically located graphite spacers to measure the specimen thermal and fast neutron fluences. The data from these wires will be used as a verification of the as-run reactor physics analysis. The experiment contains a selection of the new nuclear grade graphites for use in both prismatic and pebble bed gas reactors as well as archive samples of historical graphites to provide a link to the historical graphite database.

A vertical section of the test train in Figure 2 shows the smaller diameter capsule portion of the test train leading up to the larger diameter lead-out that composes the upper section of the test train. One of the primary functions of the lead-out portion of the test train is to house and protect the gas lines and thermocouple leads between the experiment capsule(s) and the reactor pressure vessel penetration.

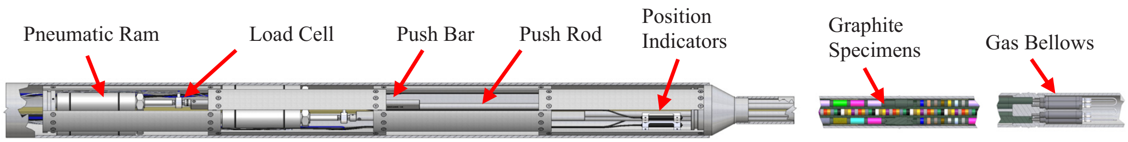

Fig. 2: AGC-1 Test Train Vertical Section

At the reactor vessel penetration, the gas lines and thermocouple leads are connected to their facility counterparts in the monitoring, control and data collection systems. In the graphite creep experiments, the lead-out also houses a major portion of the test train compressive load control system components (e.g. pneumatic rams, load cells, push bars, etc.). As indicated earlier, the compressive force on the upper graphite specimens in the perimeter stacks is provided by the pneumatic rams located in the lead-out portion of the test train. A piston located at the vertical center of the ATR core in each specimen stack rests on a ledge in the graphite specimen holder to resist the force from the rams and therefore place the specimens under a compressive load. A more detailed discussion of the compressive load control components shown in the test train and their functions is included in the compressive load control section of this paper.

The last major function of the lead-out is to vertically locate the experiment in the irradiation position within the ATR core, which is the south flux trap for AGC-1 and AGC-2 but will be the east flux trap for the later experiments. These positions are shown in Figure 3. The south flux trap position (66 mm or 2.6 inch diameter) was chosen for the AGC-1 and AGC-2 irradiations due to the size (permitting a large number of graphite specimens in a single experiment) and the relatively fast neutron flux rate in this type of irradiation position. At the current typical operating power, the reactor physics analysis has shown the south flux trap irradiation position will provide the desired 6 to 7 displacements per atom (dpa) fast neutron damage to the AGC-1 graphite specimens in approximately 360 effective full power days of ATR operation. Since the fast neutron flux rate is greatest next to the fuel elements where less moderation of the neutrons occurs, the graphite specimens on the north side of the capsule receive a higher fast fluence than those on the south side of the capsule. In order to alleviate this problem, the experiment was designed to be rotated during reactor outages so the fast neutron fluence in the graphite specimens can be equalized as much as possible.

After AGC-1 and AGC-2, the subsequent AGC graphite experiments are anticipated to be irradiated in the ATR east flux trap, which is identical in size and shape to the south flux trap. However, the east flux trap irradiations will take an approximate 25% increase in duration due to a lower power level, partially due to the NGNP Advanced Gas Reactor (AGR) fuel irradiations in the adjacent northeast flux trap. These fuel irradiations will require a lower power level to avoid possible premature fuel particle failures similar to those experienced in past highly accelerated particle fuel tests.

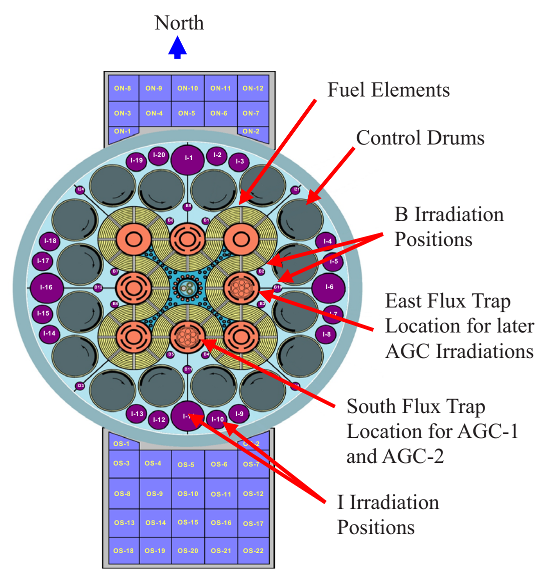

Fig. 3: ATR Core Cross-Section

Specific actions were taken in the design of the experiment to effectively limit the capsule internal heat transfer to conduction in order to increase the controllability of the experiment temperatures. These steps were necessary to meet the design requirement of maximizing the number of specimens at the required design temperature of 600 ºC over the entire 1.1 m (44 inch) height of the specimen stacks. In addition, the volume average temperature for each specimen over the entire irradiation time has to be 600 + 50 ºC, and each specimen's time average maximum can not be greater than 650 ºC or the minimum less than 550 ºC. These requirements were difficult to meet for AGC-1, however they will be more difficult to meet on the later experiments since the intent is to maintain the same tolerances (e.g. + 50 ºC) on the temperature requirements, which will be irradiated at 900 and 1200 ºC using the same experiment capsule/test train design, albeit with different (e.g. wider) insulating gas jacket widths.

III. TEMPERATURE CONTROL SYSTEM

As indicated earlier, the temperature of the experiment capsule is controlled by varying the mixture of two inert gases with differing thermal conductivities in a small insulating gas jacket between the specimens and the experiment containment. Helium is always the choice for the high thermally conductive gas, and argon was selected for the insulating gas in this experiment series. Argon provides a nice wide temperature control band due to its relatively low thermal conductivity, and therefore was selected to minimize the design changes needed between the different experiments that will be irradiated at a series of different temperatures (600, 900, and 1200 ºC). This gas has been used quite extensively at the INL in the past for material (e.g. versus fuel) irradiations. However, it is normally not used for fuel experiments since quite often the temperature control exhaust gas is monitored for fission gases and the radiation from activated argon (e.g. Ar-41) can easily over shadow the radiation from the very low concentrations of fission gases. For this reason, fuel experiments, such as the AGR experiments being irradiated in the ATR for the NGNP program, typically use neon as the insulating gas. Material experiments at the INL quite often use neon as well if an adequate temperature control band can be obtained, since it eliminates the need for a delay tank in the exhaust line to decay the activated gas prior to it being routed to the plant exhaust stack.

The gas temperature control systems at ATR use computer controlled mass flow controllers to automatically blend the two inert gases based upon feedback from the experiment thermocouples. The mixture is controlled to provide the proper thermal conductivity in the insulating gas jacket to achieve and maintain the desired temperature(s) at the thermocouple location(s). In the AGC experiments, the temperature of the graphite specimen holder, which will be analytically coupled to the specimen temperatures, is measured and controlled to achieve and maintain the desired temperatures in the specimens. The gas blending system has a range of 2% to 98% of each gas (with the other gas making up the balance) allowing a very broad range of control. The gas system operates at low pressure (< 0.2 MPa) with a nominal flow rate of 50 cc/min. With these operating conditions, very small (approximately 1.5 mm inside diameter) stainless steel tubing was used to minimize the delivery or response time between the mass flow controllers and the experiment. Early in the irradiation, the mass flow controllers are "tuned" to adjust the time constant between feedback from the capsule thermocouples and the associated gas mixture changes. This tuning process is performed to avoid temperature fluctuations during normal operations and over/under shoot on achieving target temperatures on reactor start-ups. In order to minimize temperature changes and maintain the temperature as constant as possible, the gas system provides a continuous flow to the specimen capsule. Due to the relatively large volume of the experiment capsule (and gas jackets), two separate gas blending component systems, or channels, are being used for the AGC irradiations. Both channels supply the same gas mixture to the capsule to the same areas of the capsule. Each channel supplies blended gas to two gas lines providing sweep gas to the graphite specimens and specimen holder located inside of a radiation heat shield. The other gas line from each channel supplies blended sweep gas to the gas jacket between the radiation heat shield and the capsule pressure boundary. This approach was taken to (again) minimize the response time between gas mixture changes and temperature changes within the capsule.

The control system conducts an automatic gas verification to assure the correct gases are connected to the supply ports in the system prior to allowing a new gas bottle to be placed into service to prevent unplanned temperature excursions. Helium purges to cool the experiment capsule are under automatic control in the unlikely event that measurement or control of the capsule temperature is lost. Manual control capability is provided at the gas blending panels to provide helium purge in the event of a computer failure. The system will also automatically switch to helium purge on a power failure to the mass flow controllers.

The temperature measurements are taken by the twelve thermocouples in the experiment capsule, one of which is designated as the control thermocouple. In the event the control thermocouple fails open (as indicated by a significant increase in resistivity); temperature control of the capsule will automatically be switched over to the designated primary back-up thermocouple. The thermocouples typically used at ATR are 1.6 mm (0.062 inch) diameter type K. However, due to the very high thermocouple temperatures in the later experiments (up to 1200 ºC) coupled with the relatively long irradiation (up to approximately two years); there was concern on the survivability of the thermocouples. An evaluation of different thermocouples for this type of service was performed for the AGR irradiations [1, 2], and the results of that evaluation as well as the experience gained with the thermocouples in the AGR-1 irradiation was utilized in selecting the thermocouples for AGC-1. Since adequate space was available for larger diameter thermocouples, which have longer mean time to failure over smaller diameter thermocouples, it was decided to utilize 3.2 mm (0.125 inch) diameter type N thermocouples for AGC-1. Thermocouple selection for the later experiments at the higher temperatures, especially the 1200 ºC experiments, are anticipated to incorporate the INL developmental (molybdenum-niobium) thermocouples utilized in the AGR-1 irradiation; however, the lower irradiation temperature of AGC-1 was well within the range of commercial Type N thermocouples, so they were selected for this irradiation.

Data acquisition and archiving are also included as part of the control system function. Real time displays of all temperatures, gas mixtures, and alarm conditions are provided at the operator control station. All data are recorded once every minute, time stamped and archived to removable media. The control processor will record these values in a circular first-in, first-out format for a minimum of six months.

Monitoring the continuous sweep gas flow for various gases can provide valuable information on conditions inside the irradiation capsule such as possible oxidation from trapped air/oxygen or possibly other gases being baked out of the graphite during the first few weeks of the irradiation. For this reason, the exhaust temperature control gas from the capsule was routed past a grab sample station, after passing through a delay tank (to decay any activated argon Ar-41), before being sent to the ATR exhaust stack. The grab samples are analyzed on a gas chromatograph for various gases (e.g. CO, CO2, etc.) with verification by a mass spectrometer in a laboratory located at the ATR Complex.

IV. COMPRESSIVE LOAD CONTROL SYSTEM

The compressive loads on the graphite specimens in the perimeter stacks is provided by the pneumatic rams located in the top of the test train away from the high radiation fields in the reactor core. A separate pneumatic ram is located above each specimen stack, and the forces exerted by the rams are controlled by a dedicated gas supply system. Each ram applies a downward force to a stainless steel push bar that transfers the force to a graphite push rod extending from above the top of the experiment capsule down to the top of the graphite stack. The force is then transmitted through the graphite specimens to a piston located at the vertical center of the ATR core, which sits on a ledge in the specimen holder to resist the force from the rams and therefore place the specimens under a compressive load. There is a space between the bottom of the ledge in the specimen holder and the top of the lower specimens to prevent the force/load from being applied to the lower specimens. The compressive loads applied to the specimens ranges from approximately 14 MPa (2,000 psi) to 21 MPa (3,000 psi), and the same load is applied to diametrically opposite pairs of specimen stacks in the capsule to prevent eccentric loads on the test train housing. The analysis of the capsule pressure boundary indicated the stresses in the capsule were acceptable for eccentric compressive specimen loading, but the resultant slight deflection in the graphite specimen holder could potentially result in uneven gas jacket widths around the perimeter of the capsule causing undesirable temperature variations.

The force being applied to the specimens by the rams is monitored by load cells located between the rams and the push bars. In addition, the gas pressure being supplied to the rams is also monitored to provide a verification of the load cell readings. Position indicators monitor the relative movement of each push rod above the capsule (as far away from the radiation field as possible) to measure the displacement of the graphite stack during each reactor outage when the stack is lifted upward a short distance. The upward lift of the specimens is accomplished using a series of gas bellows assemblies located at the bottom of the experiment capsule directly beneath each of the perimeter specimen stacks. The lifting operation is performed to ensure none of the specimens have become lodged in the specimen holder, which would prevent the compressive load from being applied equally to all specimens within the affected specimen stack. The gas bellows are operated using the same dedicated gas control system as the upper pneumatic rams. Helium is used for the working fluid in the compressive load system so any leaks would have a conservative (or cooling effect) on the graphite specimen temperatures. The control system components outside of the test train mainly consist of control and relief valves as well as pressure regulators. These components control and direct the helium supply gas to achieve the desired pressures in the pneumatic rams which in turn will provide the desired loads on the specimens. Signals from the load cells, position indicators and pressure transmitters are routed to the same distributed control system used to control the specimen temperatures, which provides the appropriate alarm functions to notify the experiment operators when corrective actions are necessary.

V. EXPERIMENT PROGRESS AND STATUS

Three major proto-type tests (or mock-ups) of the experiment components, assemblies, and systems were conducted in 2007 to support development of the experiment. First, mock-up fabrication of the most intricate test train components was accomplished to ensure the components could be produced in the complicated configurations and to the exacting tolerances necessary to meet the experiment assembly and operating requirements. Whenever possible, the components were fabricated by commercial specialty machine shops; however the technique/ability to fabricate some components had to be developed in-house at the INL. The second test was a complete mock-up assembly of the test train to ensure the intricate and delicate series of components could be assembled as envisioned, especially with some of the complex interlocking features. The components were assembled inside a mock-up of the test train pressure boundary, which was then inserted into an automatic welding lathe to perform the welds. A welding lathe was used for the pressure boundary welds to ensure the test train would meet the stringent straightness required to ensure proper fit and cooling during irradiation in the ATR. The third major test was a mock-up of the compressive load control system to test the selected components, and to verify the calculations and predictions of the compressive load effects on the components and graphite materials. These three mock-up tests provided valuable insight and information on the various components and design of the experiment.

The results of the three mock-up tests were reviewed and an independent critical review of the experiment design was also conducted to identify what changes should be made to the design to decrease complexity while increasing the reliability and functionality of the experiment. The selected changes were incorporated into the analysis and preliminary design of the experiment. Two separate reviews of the design were conducted at this stage of the project. A preliminary design review was conducted for ATR personnel (along with minimal program personnel) to ensure the experiment could be irradiated safely in the ATR and achieve the desired experimental results. A second or programmatic review for the NGNP program personnel, as well as external reactor experiment and graphite experts, was also conducted to ensure the experiment would meet the desired requirements and provide the necessary data for the NGNP program. The comments from these two reviews were resolved and incorporated into the experiment final design and analysis. The final design review for the gas control systems was conducted in late July 2007, and the final design for the test train was conducted in early September 2007.

The fabrication and assembly of the gas control systems and test train were the next activities for the experiment. The parts for gas control system were purchased and the gas control panels were fabricated and assembled in September 2008. The panels were installed in the ATR facility in late calendar 2008 and the interconnecting gas lines and wiring installation along with system testing was accomplished in early calendar 2009.

The materials and commercial parts for the test train were purchased and fabrication of the components was also completed in early calendar 2009. In parallel with the component fabrication, development of the test train weld processes and procedures, as well as additional component mock-up testing was performed to support completion of the test train final assembly. Development of the welding procedure for the stainless steel experiment pressure boundary on the automatic welding lathe was accomplished in accordance with the INL weld program and NGNP program requirements as well as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. During the assembly of the test train, quality assurance personnel were involved in all of the special processes such as welding, specimen insertion, leak testing, etc. They also performed various quality assurance tests such as weld inspection, helium leak detection, thermocouple continuity, etc. to ensure the test train was assembled in accordance with the drawings and the ASME NQA-1 2000 requirements.

In order to minimize oxidation of the experiment graphite components, precautions were taken to eliminate as much air from the experiment test train as possible. Specifically, the test train was repeatedly evacuated and back filled with dry helium gas, followed by final pressurization with helium and sealing of the test train until final connection to the temperature control system. In addition, purging of the temperature control system with dry helium gas prior to connection of the experiment was also conducted for several days to remove as much residual air in the system as possible.

The INL, with support from the United States Department of Energy's Oak Ridge National Laboratory, completed a major Department of Energy milestone by completing all tasks necessary for the experiment to be ready for insertion into the ATR by April 30, 2009. The experiment was inserted into the ATR in August 2009 during the next scheduled reactor outage. Final testing of the temperature control and compressive load gas control system installations was accomplished after the experiment had been inserted. This final testing had to be done after experiment insertion to ensure the gas control lines, thermocouples, wiring, etc. had been correctly connected to the experiment.

The irradiation of the experiment was initiated on September 5, 2009. The compressive load control system has performed very well. The system has been very stable and predictable. The position indicators and load cells are both performing well, and providing indications of the specimen movements due to irradiation shrinkage and creep as well as the imposed compressive loads on the specimens. The gas bellows have worked well in verifying the specimens are remaining free in the specimen holder and the compressive loads are being applied to all of the specimens in each vertical stack. As indicated earlier, sampling of the temperature control exhaust gas was included as part of the irradiation tasks to determine if oxidization of the graphite specimens and specimen holder due to trapped air/oxygen in the graphite occurred primarily during the initial start of irradiation. The gas samples have shown only slight indication of oxidation of the samples at the very start of the irradiation, which testifies to having a very tight experiment with no leaks and very high gas purity.

One slight exception to the otherwise great irradiation results in the AGC-1 irradiation is the temperatures of the irradiation specimens. At the start of the irradiation, the peak specimen temperatures were approximately 50ºC over the design value of 600ºC while flowing pure helium (e.g. conductive) gas, and the axial temperature range was approximately 150ºC versus the desired 50ºC span. Unfortunately, the peak specimen temperatures have increased approximately another 60ºC due to the reduced graphite thermal conductivity resulting from the neutron irradiation damage, but have stabilized at approximately 710ºC. However, it should also be pointed out that at the start of irradiation, the compressive loaded and unloaded paired specimens in each of the six specimen stacks were within 60ºC of each other since the ATR has a neutron flux (and power profile) that is symmetric about the vertical centerline of the reactor core. In addition, most of the specimens are within a temperature range of approximately 100ºC, albeit at higher temperatures.

An exhaustive investigation was performed to determine the reason for these elevated temperatures. Of course, the first step was a thorough review of the reactor physics and thermal analysis models and the translation of data between these analyses. However, this review did not provide any plausible causes for the high temperatures, and the results of the analyses could not be brought into agreement with the measured temperatures and gas flow rates. Sensitivity studies on different thermal properties (e.g. conductivity, emissivity, etc.) used in the analysis were also performed, but none of the results could explain the higher temperatures. Investigations into the accuracy of the thermocouple measurements, including gamma self heating resulting from loss of contact between the thermocouples and the graphite holder, were also performed but (again) the results could not justify the elevated temperatures. Japanese and European gamma heating cross section libraries were incorporated into the reactor physics models to compare their results with those from the original American cross sections, but the calculated gamma and neutron heating rates using all three libraries were very consistent. Finally, a procedure introducing argon gas into the experiment in an effort to flatten the axial temperature profile produced results that indicated the two insulating gas jackets in the capsule were being treated differently by the thermal analysis code. Further investigation revealed that, although the two gas jackets were modeled in the same manner and employed the same analysis code features, the insulating effects of the inner gas jacket were being incorporated in the results but the effects of the outer gas jacket were not. When several features in the analysis code previously applied to the outer gas jacket were bypassed, effectively forcing the code to recognize the effects of the outer gas jacket, then excellent agreement was obtained between the analyses and the measured temperatures. It was rather surprising to encounter this type of issue on a fully verified and validated commercially produced analysis code that was being used on a fully verified and validated computing platform. The INL software application group has been working with the analysis code vendor to resolve the issues within the code and prevent future occurrences similar to AGC-1, both by INL as well as other code customers. In addition, this lesson learned is being applied to the design of other INL experiments using this type of control system and design approach including the NGNP AGC and AGR experiment series.

The AGC-1 irradiation is anticipated to require approximately eighteen months to attain the accumulated fast fluence damage levels desired by the NGNP Program, and will be removed from the ATR in January 2011. Upon removal of AGC-1, the second experiment (AGC-2) will be inserted into the same irradiation position within the ATR core. In addition, activities are currently underway in developing the tooling and procedures to size AGC-1 for shipment to the Hot Fuel Examination Facility at the INL for disassembly of the experiment to allow post irradiation examination of the graphite specimens.

VI. CONCLUSIONS

Many valuable insights and lessons learned have been achieved during the design, assembly and irradiation of AGC-1 that can be applied to the other future NGNP experiments. Specifically the resolution to the analysis code issue experienced on AGC-1 is being applied in the design of AGC-2, and considered in all future NGNP experiments. It is anticipated that careful attention to the continued irradiation of AGC-1 may provide additional insights into the design and operation of future NGNP and specifically AGC experiments. The results of the irradiation of this series of experiments will provide valuable data on the currently available nuclear grade graphites, which can then be used in the development and design of high temperature gas reactors.

ACKNOWLEDGMENTS

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