INL/CON-08-15179
PREPRINT

The Next Generation Nuclear Plant/Advanced Gas Reactor Fuel Irradiation Experiments in the Advanced Test Reactor

Global 2009

S. Blaine Grover

September 2009

The INL is a
U.S. Department of Energy
National Laboratory
operated by
Battelle Energy Alliance

Proceedings of Global 2009
Paris, France, September 6-11, 2009
Paper 9319

The Next Generation Nuclear Plant/Advanced Gas Reactor Fuel Irradiation Experiments in the Advanced Test Reactor

S. Blaine Grover
Idaho National Laboratory
PO Box 1625, Idaho Falls, Idaho 83415
United States of America
Tel: 208-526-4489, Fax: 208-526-1078, Email: Blaine.Grover@inl.gov

Abstract – *The United States Department of Energy's Next Generation Nuclear Plant (NGNP) Program will be irradiating eight Advanced Gas Reactor (AGR) Fuel Development and Qualification Program in the Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL). The experiments will contain low enriched uranium (LEU) tri-isotropic (TRISO) particle fuel (in compact form) for use in high temperature gas reactors. The ATR has a long history of irradiation testing in support of reactor development and the INL has been designated as the new 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 irradiations and fuel development are being accomplished to support development of the next generation reactors in the United States, and the irradiations will be performed over the next ten years to demonstrate and qualify new particle fuel for use in high temperature gas reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing. The experiments, which will each consist of at least six separate capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation.

The first experiment (designated AGR-1) started irradiation in December 2006, and the second experiment (AGR-2) is currently in the design phase. The design of test trains, as well as the support systems and fission product monitoring system that monitor and control the experiment during irradiation are discussed. In addition, the purpose and differences between the two experiments will be compared and the irradiation results to date on the first experiment are presented.

I. INTRODUCTION

The fuel development and irradiations are being accomplished to support development of the next generation reactors in the United States. The Advanced Gas Reactor (AGR) Fuel Development and Qualification Program, which is part of the Next Generation Nuclear Plant (NGNP) Program, will irradiate the experiments over the next ten years to demonstrate and qualify new Low Enriched Uranium (LEU) tri-isotropic (TRISO) particle fuel for use in high temperature gas reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing.[1,2] The experiments, which will each consist of multiple separate capsules, will be irradiated in an inert sweep gas atmosphere with

individual on-line temperature monitoring and control of each capsule. The sweep gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation. The experiments are specifically designed for the irradiation position location and size, irradiation parameters (e.g. temperature, fluence, etc.) and with an umbilical tube routing necessary to connect the experiment capsules to the monitoring, control and data collection systems.

II. EXPERIMENT CAPSULES

The experiment test trains for both AGR-1 and AGR-2 consist of six separate stacked capsules vertically centered in the ATR core. Each capsule has its own custom blended gas supply and exhaust for independent temperature control and fission product monitoring. An AGR-1 capsule horizontal cross-section is shown in Figure 1 and a vertical section is shown in Figure 2. The majority of the test train and fuel details are identical for these two experiments, so this section is focused on the commonalities and similarities. The differences in both configuration and purpose/mission will be discussed in a later section.

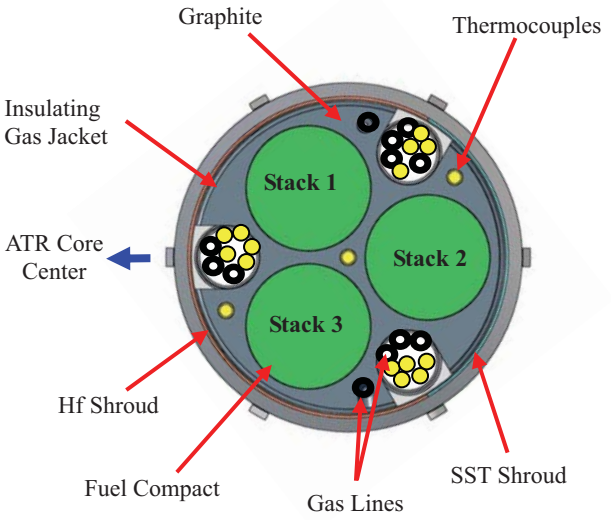

Fig. 1. AGR-1 experiment cross-section

The capsules are approximately 35 mm in diameter and 150 mm in height - including the plenums between adjacent capsules. Each capsule contains 12 prototypical right circular cylinder fuel compacts nominally 12.4 mm in diameter and 25 mm long. The AGR fuel is comprised of Low Enriched Uranium (LEU) fuel kernels, which are covered with a layer of silicon carbide, sandwiched between two pyrolytic carbon layers to make up the TRISO-coated fuel particles. The fuel particles are over-coated with a thermo-set resin and pressed into fuel compacts that are then sintered to remove the volatile compounds in the resin. The compacts are arranged in four layers in each capsule with three compacts per layer nested in a triad configuration. A nuclear grade graphite spacer surrounds and separates the three fuel compact stacks in each capsule to prevent any fuel particles on adjacent compacts from touching each other, which could possibly cause a premature particle failure. Very thin (0.5 mm or less) graphite top and bottom end caps on the compacts prevent particle to particle contact between adjacent axial compacts.

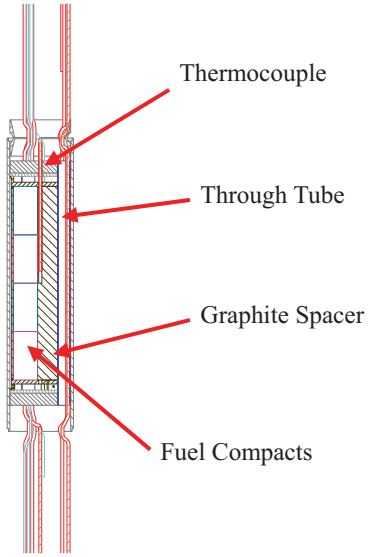

Fig. 2. AGR experiment vertical section

The graphite spacer also provides the inner boundary of the insulating gas jacket (approximately 0.25 mm to 1.0 mm thick depending on vertical location within the reactor core) for temperature control of the fuel during irradiation. Boron carbide is dispersed in the graphite spacer to serve as a consumable neutron poison. In addition to the boron carbide, a thin (0.25 mm thick) hafnium shield next to the outside capsule wall surrounds the two fuel compact stacks facing toward the center of the ATR core (stacks 1 and 3 shown in Figure 1 for AGR-1). A thin (0.25 mm thick) stainless steel shield next to the outside capsule wall blankets the other fuel compact stack (stack 2 shown in Figure 1) located on the side of the capsule facing away from the ATR core. A stainless steel shield versus hafnium was used on this side of the capsule to minimize the effects on the neutron flux to these already lower powered fuel compacts while retaining the same insulating gas jacket to maintain the proper irradiation temperature. The neutron poisons are necessary to limit the initial fission rate in the fuel and thereby provide a more consistent fission rate/power production during irradiation. As the boron carbide is consumed in the graphite, the fission rate in the fuel reaches a peak at about the mid-point of the irradiation

and then slowly decreases as the fuel continues to burn-up. Reducing and controlling the initial fission rate in this manner decreases the ratio of the maximum to minimum heat generation rates in the fuel, which provides better temperature control in the fuel during the rather long irradiation that will be in excess of two years. In addition to protecting the fuel, the graphite spacer has features machined to accommodate the thermocouples for measuring temperature within the capsule and the three through tubes containing the gas lines and thermocouples for adjacent capsules. The through tubes are positioned very precisely in the top and bottom heads of the capsules so they can also be utilized to center the graphite in the capsule and provide the necessary gas jacket for temperature control. The through tubes are in contact with the high temperature graphite throughout most of their length resulting in high temperatures in the tubes themselves. Therefore, one end (the bottom) of the tubes had to be fitted with a very tight (less than 0.013 mm) slip fit between the tubes and the capsule bottom head to prevent the significant difference in (axial) thermal expansion between the capsule shell and the tubes from causing excessive stresses in the tubes. These stresses would result in bowing of the tubes, which could put stress on the graphite spacer and possibly the fuel compacts. The tight slip fit was needed to strictly limit and control any leakage of the temperature control gas between the tubes and the capsule bottom head. To prevent possible cross contamination between the capsules, a small gas flow (total of less than 20 cc/min for all capsules) is introduced into the through tubes and plenums between the capsules to ensure any leakage between the tubes and capsule heads is into the capsules, preventing flow between capsules.

There are nominally three thermocouples in each capsule (the top and bottom capsules have five and two thermocouples respectively for different reasons) located in the top, middle, and bottom areas of the graphite spacer. Since no metal could touch the fuel particles, the thermocouples measure the graphite temperature and the corresponding fuel temperatures are calculated. Flux wires are also installed in the graphite to measure both the thermal and fast neutron fluence. Since the outside diameter of the graphite establishes the inner boundary of the insulating gas jacket, it varies among the capsules depending on the neutron flux rate at the vertical location of the specific capsule within the ATR core. The boron carbide content in the graphite spacer is different in the capsules as well due to the chopped cosine shaped vertical neutron flux profile in the ATR core.

An umbilical tube (termed a lead-out) houses and protects the gas lines and thermocouple leads from the experiment capsules to the reactor vessel wall penetration. Outside the reactor vessel wall, the gas lines and thermocouple leads are connected to their facility counterparts in the temperature monitoring, control and data collection system. The lead-out also vertically locates the experiment within the applicable large B irradiation position (shown in Figure 3) in the ATR core. The large B positions (38 mm diameter) were chosen for these two AGR fuel irradiations due to the rate of fuel burn-up and fast neutron fluence accumulation in these positions providing an acceleration factor of between one and three times that expected in the Very High Temperature Reactor (VHTR). This acceleration factor was high enough to accomplish the irradiation within a reasonable time, but yet low enough to avoid possible premature fuel particle failures similar to those experienced in past highly accelerated particle fuel tests.

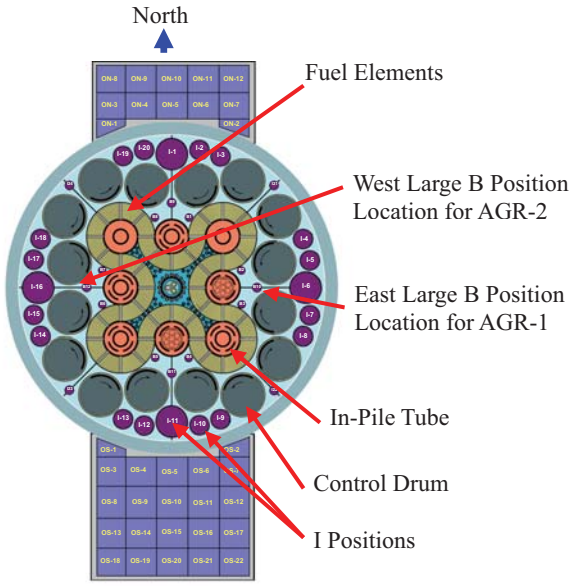

Fig. 3. ATR core cross-section showing AGR experiment locations

In addition to limiting the acceleration factor, avoiding contact between fuel particles as well as limiting the materials contacting the fuel compacts/particles to only graphite and the inert temperature control gas was done to prevent possible premature fuel particle failures. In essence, limiting the acceleration factor also determined the irradiation time for these AGR experiments since the neutron flux rate is one of the major controlling factors for the irradiation time. The AGR-1 and AGR-2 irradiations each have their own Fissions per Initial Metal Atom (FIMA) burn-up requirements, which in conjunction with the fuel enrichments and the Large B neutron flux rate resulted in rather long irradiation times. Along with the long irradiation times, these requirements also resulted in a significantly reduced heat generation rate towards the end of the irradiation. As indicated earlier, every effort was made to flatten the heat generation rate curve as much as

possible to increase the controllability of the temperatures at the end of the irradiation. This controllability was necessary to meet the time-average volume-average temperature requirements during irradiation while staying below the time-average and the instantaneous peak temperatures. The combination of these requirements provided some significant challenges in the design of the AGR experiments and their control systems.

The other six AGR experiments are currently planned to be performed in a different, larger ATR irradiation position with a higher neutron flux in order to achieve their burn-up and fast fluence requirements faster. However, the acceleration factor between ATR and the VHTR for fuel burn-up and fast neutron fluence rates will remain at or below three to prevent premature fuel particle failures. The test trains for these later experiments will be different in size and shape, and are currently planned to be doubled up (with essentially twice as many capsules) in order to reduce the time required by half to obtain the necessary irradiation data. Nonetheless, the same type of temperature control system and fission product monitors will be used, along with a lot other similarities in the capsule configurations and design (e.g. graphite specimen holders, insulating gas jackets, individual capsule temperature control and fission product monitoring, etc.).

III. TEMPERATURE CONTROL

The desired temperatures in the capsules are achieved by adjusting the mixture ratio of two gases with differing thermal conductivities to control the heat transfer across an insulating gas jacket between the heat source (fuel fissions and gamma heating of capsule materials) and the relatively cold reactor coolant (52 ºC). The experiment flow path is shown in Figure 4.

Helium is used as the high (thermally) conductive gas and neon is used as the insulating gas. Neon (versus argon that can provide a wider temperature control band) was selected for the insulating gas in these experiments to avoid the effects of the activated argon gas on the fission product monitors. Computer controlled mass flow controllers are used to automatically blend the gases (based upon feedback from the experiment thermocouples) to control the graphite spacer temperatures, which are analytically coupled to the fuel specimen temperatures. 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 30 cc/min and a maximum of 50 cc/min. With these relatively low operating parameters, very small size (1.5 mm inside diameter) stainless steel tubing was used to minimize the blended gas delivery times between the mass flow controllers and the experiment and also between the experiment and the fission product monitors to a nominal value of 2 to 2.5 minutes.

The temperature measurements are taken with the thermocouples located in each 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 for the capsules will automatically be switched over to the designated back-up thermocouple, and it will be designated as the new control thermocouple. The thermocouples typically used at ATR are 1.6 mm sheath diameter type K, with high purity magnesia insulation. However, due to the very high thermocouple temperatures (up to 1100 ºC) coupled with the relatively long irradiation; there was concern on the survivability of the thermocouples. In order to achieve the best thermocouple survivability possible, a selection of the most promising long life type K and type N thermocouples were purchased and tested in a thermal mock-up of the AGR irradiation conditions. In addition, several INL developmental (molybdenum-niobium) thermocouples were also included in the thermal testing to determine how they would survive the irradiation conditions.[3] The testing was conducted for four months, and based upon the test results, the best performing Type N thermocouples were selected for use in the cooler positions in the capsule (away from core center) and the INL developmental thermocouples were selected for use in the higher temperature positions in the capsule (towards core center).

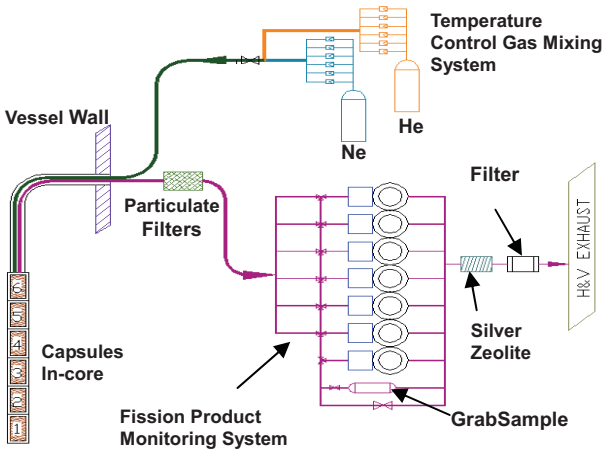

Fig. 4. AGR-1 experiment flow path

IV. FISSION PRODUCT MONITOR

In order to minimize temperature changes and maintain the temperature as constant as possible, the temperature control gas system provides a continuous flow to each specimen capsule. Monitoring this continuous gas flow for fission gases can provide valuable information on the fuel performance during irradiation.

As shown in figure 4, the outlet gas from each capsule is routed to individual fission product monitors, and the gas flows can be rerouted to an online spare monitor if any monitors experience detector or other failures. There is also the capability to take a grab sample of the effluent gas from each capsule. The fission product monitors consist of a spectrometer for identifying and quantifying the fission gas nuclides and a gross gamma detector to provide indication when a puff release of fission gases passes through the monitor. The gross gamma detector also provides the release timing. With the combination of a gross gamma detector and a spectrometer being continuously on-line, the gross gamma detector results can be scanned quickly to determine which portions of the voluminous spectrometer data need to be closely scrutinized. A puff release of fission gases typically indicates when a TRISO fuel coating failure may have occurred. Through identification and quantification (with uncertainties) of the isotopes, the spectrometer can be used to determine the isotopic release to birth ratio (with uncertainties) of the fission gases being detected. The determination of the release to birth ratios can establish whether a new TRISO fuel coating failure has occurred or if the fission products are merely being released from an existing failure or tramp contamination on the outside surface of the fuel particles. These details can be very important in the qualification of fuel especially in small TRISO particle fuels, where a few random particle failures are anticipated and need to be tallied very accurately to support statistical qualification of the fuel. The system was designed and response modeled to detect and quantify each individual fuel particle failure up to and including a very unlikely 250th fuel particle failure.

V. AGR-1 AND AGR-2 EXPERIMENT MISSIONS AND DIFFERENCES

The irradiation of AGR-1 is currently scheduled for completion in early October, and the irradiation of AGR-2 is currently planned to start in the first quarter of calendar 2010. Before discussing the differences in these two experiments, the similarities between them should be explained. As indicated earlier, these two experiments are both being irradiated in the Large B irradiation positions in ATR, though on opposite sides of the ATR core (shown in Figure 3). The irradiation of AGR-2 on the west side instead of the east side of the ATR core is being done to maximize the planned power levels in the different sections (or lobes) of the ATR to achieve the irradiation goals of AGR-2. Since the experiments will be utilizing the same type of irradiation positions, the experiment capsule designs will be essentially identical. AGR-2 will also use the same temperature control and fission product monitoring systems designed and installed for AGR-1. However, with AGR-2 located on the opposite side of the ATR core, some simple mirror imaging of the capsule features was necessary. The two fuel stacks in AGR-2 facing toward the ATR core will be on the opposite of the capsules compared to the fuel stacks facing towards the core in the cross-section of AGR-1 (e.g. right side versus left shown in Figure 2). The routing of the lead-out from the experiment capsules to the reactor vessel wall will also be reversed, and the connections to the control and monitoring systems will be moved from the east side to the west side of the reactor vessel for connection to the test train.

There are three major differences between AGR-1 and AGR-2. The first significant difference is the purpose or missions for the two experiments (as defined in References 1 and 2). The primary mission for AGR-1 was to provide a shakedown the experiment capsule/test train design. This shakedown or test of the experiment design was to be performed using early laboratory scale fuel with different coating variants. Irradiation of baseline fuel as well fuel with different coating variants could provide data on fuel irradiation performance to support further development of the fuel to be used in the later AGR irradiations. In fulfilling its shakedown mission, AGR-1 has provided some good lessons learned in the design, assembly and operation that are being incorporated into the design and irradiation of AGR-2. On the other hand, the primary mission for AGR-2 is to test production scale fuel versus laboratory scale fuel used in AGR-1. In this capacity, AGR-2 will provide valuable feedback, both during irradiation and from post irradiation examination, to support further development and fabrication of the fuel to be used in the actual fuel qualification irradiations planned as AGR-5 and AGR-6.

The second major difference between AGR-1 and AGR-2 is the fuel types and sources in the two experiments. The fuel irradiated in AGR-1 was exclusively uranium oxycarbide (UCO) type fuel fabricated on a laboratory scale and included several different variants in the TRISO coating used on the fuel particles. As indicated earlier, the fuel to be irradiated in AGR-2 will be fabricated on a production scale, but it will also include both UCO and uranium dioxide (UO_2) type fuel. In addition, the two different fuel types will also have different fuel kernel and particle sizes, enrichment levels, burn-up and temperature

requirements, etc. Since there are many differences in the details for the fuel and irradiation requirements for AGR-1 and AGR-2, they will be provided in the following subsections.

The final difference between AGR-1 and AGR-2 is the sources for the fuel. As part of the Generation IV (GEN IV) International Forum, two capsules in AGR-2 were offered to two other GEN IV countries, France and South Africa, to irradiate fuel in support of their gas reactor development programs. The fuel in one capsule will contain fuel for the Pebble Bed Modular Reactor (PBMR) program in South Africa, and a second capsule will contain fuel fabricated in France as part of their Very High Temperature Reactor (VHTR) program. However, the fuel and irradiation details provided in the following subsections only encompass the NGNP/AGR program fuels since the fuel and irradiation details for the French and South African fuel are beyond the scope of this paper., are protected under their irradiation agreement with the INL.

V.A. AGR-1 Fuel and Irradiation Details

As indicated earlier, the AGR-1 experiment contains exclusively UCO type fuel, which has an LEU enrichment level of 19.8%. The fuel was fabricated into 350 μm nominal diameter fuel kernels, which were then covered with the TRISO coatings to make 780 μm nominal diameter fuel particles. Approximately 4,150 fuel particles with a mean total uranium content of approximately 0.9 grams were used to make up each fuel compact. Compacts containing baseline fuel, fabricated to the baseline process parameters, as well as three fuel variants with different coatings and process development variations, were included in the experiment. Since all of the fuel in AGR-1 had the same enrichment, the boron carbide concentration used in the graphite spacer for the top and bottom capsules was different than the concentration used in the other four capsules to compensate for the chopped cosine shaped vertical neutron flux profile in the ATR core. As previously noted, the irradiation time for the AGR-1 experiment was essentially determined by the neutron flux rate in the large B position and the average burn-up goal of 18% FIMA for all fuel compacts with a minimum of 14% FIMA for each fuel compact.[4] The temperature requirements for AGR-1 were to maintain a time-average volume-average temperature of 1150 +30/-75 ºC during the irradiation while staying below a time-average peak temperature of 1250 ºC and a maximum instantaneous peak temperature of 1400 ºC.

V.B. AGR-2 Fuel and Irradiation Details

In contrast with AGR-1, the AGR-2 experiment contains both UCO and UO_2 type fuels, which are different in many ways besides the fuel type (e.g. enrichment, fuel kernel and particle size, particles/compact, etc.). In addition, the UCO type fuel is also different in enrichment, kernel size, etc. from the UCO fuel irradiated in the AGR-1 experiment. These fuel changes have resulted in other changes in the capsule design that are identified later.

The UCO fuel type was fabricated from 14.0% enriched LEU into 425 μm nominal diameter fuel kernels, which after being covered with the TRISO coatings result in 850 μm nominal diameter fuel particles. Approximately 3,160 fuel particles are used to make up each fuel compact with an approximate mean total uranium content of 1.3 grams. Somewhat similar to AGR-1, baseline fuel compacts as well as one type of fuel variant compacts are being included in the experiment. The specific burn-up requirements for this fuel have not been fully developed and agreed upon yet due to the changes in several key fuel parameters from those used in AGR-1 including fuel enrichment and the number of particles in each compact. In addition, the time available for the irradiation and PIE to be completed in order to obtain the data prior to development of the fuel for the latter experiments must also be considered in establishing burn-up requirements. Furthermore, one of the capsules with this fuel type will be located at the edge of the test train, which will be exposed to a lower neutron flux and therefore result in lower fuel burn-up compared to the burn-up levels in the other capsules containing this fuel type. In order to account for this lower flux rate, the burn-up goal being considered for this capsule is 10% FIMA in all fuel compacts and a minimum of 8% in each fuel compact. For the other capsules containing this type of fuel located in the higher neutron flux region, the values under consideration are a goal of 12% FIMA for all fuel compacts and a minimum of 10% FIMA in each fuel compact. The temperature requirements for this fuel have also not been completely defined yet; however, the instantaneous peak temperature of 1400 ºC is anticipated to remain the same, and the other values used for the UCO fuel in AGR-1 (time-average volume-average temperature of 1150 +30/-75 ºC and time-average peak temperature of 1250 ºC) are the obvious baseline values under consideration.

The UO_2 fuel type was fabricated from 9.6% enriched LEU into 510 μm nominal diameter fuel kernels, which result in 940 μm nominal diameter fuel particles after the TRISO coatings are applied. Approximately 1,520 fuel particles are used to make up each fuel compact with an approximate mean total uranium content of 1.0 gram. There will be only one capsule of this fuel type irradiated for the AGR program, which means only baseline fuel compacts (e.g. no fuel variant type compacts) will be

included in the experiment. As with the UCO fuel, the specific burn-up requirements for this fuel have also not been fully developed and agreed upon. Along with being a different fuel type, there are also similar changes in the key fuel parameters including fuel enrichment, number of fuel particles in each compact, etc. along with the same limitations on irradiation and PIE schedules. However, baseline values have been developed for consideration, which are 10% FIMA for the average burn-up goal in all fuel compacts and a minimum of 9% FIMA in each fuel compact. The temperature requirements for this fuel have also not been completely defined yet, but again the instantaneous peak temperature of 1400 ºC used for AGR-1 UCO fuel is anticipated to be used for this fuel. However, the more constant operating temperatures will be lower than those used in AGR-1. The reason for the operating lower temperatures is the UO_2 fuel type would be used in a pebble bed type gas reactor with lower operating temperatures than a prismatic type gas reactor that would use the UCO type fuel. The baseline values being considered are a time-average volume-average temperature range of 950 to 1100 ºC and a time-average peak temperature of 1150 ºC.

The different fuel types with widely different enrichments, fuel particles per compact, burn-up requirements, etc. presented a whole new set of challenges in the design of the AGR-2 capsules and incorporating them into a single test train. However, some of these differences were used to help offset the effects of other differences to result in a fairly efficient design and use of the ATR core space. One key parameter used in this optimization was the placement of the different fuel types and enrichment levels in the vertical neutron flux profile of the ATR core. This variable was utilized by placing the low enriched UO_2 fuel at the center of the core where the neutron flux is highest and placing the higher enriched UCO fuel towards the edges of the test train in the slightly lower neutron flux rates. This vertical placement scheme helped to balance the effects of the different enrichments (with their associated different burn-up requirements) and therefore achieve the required uniform irradiation time for the experiment. Since the experiment utilizes active monitoring and control, it is not possible to remove individual capsules at different irradiation times without reconstitution of the test train in a hot cell facility, which was determined to be cost prohibitive for this program. The other variable used to help offset the effects of fuel loading and burn-up requirements was the boron concentration in the graphite holder. The boron concentration is approximately 25 % less for the lower enriched UO_2 fuel as well as the outermost UCO capsule located in the slightly lower neutron flux region versus the concentration used in the UCO capsules located within a higher neutron flux region of the test train.

VI. AGR-1 EXPERIMENT EXPERIENCE AND RESULTS

A variety of tests were conducted prior to the AGR-1 test train fabrication and assembly, including the high temperature thermocouple testing mentioned earlier and testing of the gas leakage through the very tight slip fit between the through tubes and the capsule bottom heads.[5] Development and testing was also conducted on various capsule assembly processes (i.e., clearances, welding, brazing, etc.) to ensure the assembly of the test train could be accomplished as designed. Assembly of the experiment, along with the installation of the fission product monitors and the modifications to tailor the existing temperature control system to the experiment needs, was completed in September 2006. The experiment was inserted in the ATR in mid December 2006, and final flow testing of the temperature control and fission gas monitoring system installations was performed after the insertion of the experiment in ATR but prior to reactor start-up. Irradiation of the experiment was initiated in late December, and is currently anticipated to be completed in October 2009.

The performance and sensitivity of the fission product monitor system (FPMS) continues to be excellent. The extremely low levels of fission gases (peak release to birth ratios of $< 3 \times 10^{-8}$) from the anticipated low level tramp contamination on the outside of the fuel continue to be measured and recorded by the FPMS. The ability to measure these very low fission gas levels in the temperature control exhaust gas demonstrates both the sensitivity of the system as well as the integrity of the fuel. Detailed analyses of the experiment as well as analysis and testing of the monitors were performed to accurately predict the performance of the FPMS. The results of these analyses and testing determined that a single fuel particle failure will result in a fission gas release being detected at the monitor equal to approximately two orders of magnitude greater than the current fission gas levels being measured by the system. A validation of the sensitivity of this system is its ability to detect activated gases resulting from approximately 5 ccs (or less) of air introduced into the system during gas bottle changes in the temperature control system. Another demonstration of the system sensitivity was its use in verifying the transport volume (and therefore transport time based upon an established gas flow rate) between the capsules and the FPMS by detecting the very short lived activated Ne-23 isotope in the temperature control gas. The system was also used to establish the minimum required flow into the lead-out to prevent cross flow between capsules.[5] These two tests were conducted during the first two irradiation cycles. During design, the gas lines were sized to allow as much

decay of the activated neon as possible while limiting the decay of the short lived fission gases of interest.

Initially, the experiment design temperatures could not be achieved due to the boron content in the graphite spacer. However, as anticipated, as the boron started to burn out in the graphite, the temperatures of the fuel compacts achieved the design temperatures in all but the bottom capsule by the end of the second ATR irradiation cycle (e.g. within the first 100 days of irradiation). The bottom capsule achieved the design temperature during the fourth irradiation cycle. The experiment achieved and passed through the peak heat generation in the fuel at approximately 250 to 300 ATR Effective Full Power Days (EFPDs), and is now experiencing lower heat generation rates. The desired temperatures in the fuel will become harder to achieve as the fuel continues to deplete; however, the unique operating characteristics of the ATR as well as replacing the leakage gas into the capsules from the lead-out with neon instead of helium is anticipated to overcome the reduced heat generation within the fuel and allow continued operation at the desired temperatures.

At the end of February 2009, the experiment had been irradiated for a total of approximately 470 ATR EFPDs, and achieved a peak burn-up of 16% FIMA and a peak fast neutron fluence 3.0×10^{25} n/m^2. These levels of fuel burn-up and fast neutron fluence have been achieved with the fuel continuing to perform exceptionally well. No fuel particle failures and only low levels of fission gases from tramp contamination have been detected thus far. In early October 2009, when the experiment is removed from the ATR, it will have achieved approximately 620 ATR EFPDs. At that time, it will have also achieved the 14% FIMA minimum burn-up in over 95% of the fuel compacts and the 18% FIMA burn-up goal in over 40% of the fuel compacts.

As originally anticipated, there have been multiple thermocouple failures. At the end of February 2009, 10 of the 18 thermocouples had failed including all thermocouples in half of the experiment capsules. However, temperature control of all capsules has been maintained using the remaining thermocouples and the reactor physics and thermal analysis models that were benchmarked against the thermocouple readings early in the irradiation. The model predictions and statistical analysis of the data are also used to update the thermocouple control temperature set points to account for the anticipated nuclear transmutation and drift in the thermocouples.

VII. CONCLUSIONS

Development and irradiation of the AGR-1 experiment has provided some valuable insights and lessons learned as it completes its primary mission as a shakedown of the experiment design and operating characteristics as well as the temperature control and fission product monitoring systems. A very valuable added bonus of the experiment is the data being gained on the irradiation performance of the fuel developed by the AGR program. The insights and lessons learned on AGR-1 are being incorporated into the design of AGR-2, which will provide additional data on the irradiation performance of both UCO and UO_2 fuel. The results of both of these experiments can then be used to support qualification of particle fuel for use in high temperature gas reactors.

ACKNOWLEDGMENTS

This work was supported by the United States Department of Energy (DOE) under DOE Idaho Field Office Contract Number DE-AC07-05ID14517.

REFERENCES

1. G. L. Bell, et al, “Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program”, *Oak Ridge National Laboratory Report ORNL/TM-2002/262*, Revision 0 (April 2003).

2. D. A. PETTI, et al, “Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program”, *Idaho National Laboratory Report INL/EXT-05-00465*, Revision 1 (August 2005).

3. J. L. REMPE, et al, “Evaluation of specialized thermocouples for high-temperature in-pile testing”, *Proceedings of the International Congress on Advances in Nuclear Power Plants*, Reno, NV, USA, June 4-8, 2006, Paper 6068 (2006).

4. J. T. MAKI, “AGR-1 Irradiation Experiment Test Plan”, *Idaho National Laboratory Report INL/EXT-05-00593*, (August 2005).

5. S. B. GROVER and D. A. PETTI, “Initial irradiation of the first advanced gas reactor fuel development and qualification experiment in the Advanced Test Reactor”, *Proceedings of Global 2007 Advanced Nuclear Fuel Cycles and Systems*, Boise, ID, USA, September 9-13, 2007, Paper 177457, (2007).