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Design of the Advanced Gas Reactor Fuel Experiments for Irradiation in the Advanced Test Reactor

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ABSTRACT: The United States Department of Energy's Advanced Gas Reactor (AGR) Fuel Development and Qualification Program will be irradiating eight particle fuel tests in the Advanced Test Reactor (ATR) located at the newly formed Idaho National Laboratory (INL) to support development of the next generation Very High Temperature Reactor (VHTR) in the United States. 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. These AGR fuel experiments will be irradiated over the next ten years to demonstrate and qualify new particle fuel for use in high temperature gas reactors. The experiments will be irradiated in an inert sweep gas atmosphere with on-line temperature monitoring and control combined with on-line fission product monitoring of the sweep gas. The final design phase has just been completed on the first experiment (AGR-1) in this series and the support systems and fission product monitoring system that will monitor and control the experiment during irradiation. This paper discusses the development of the experimental hardware and support system designs and the status of the experiment.

KEYWORDS: *Advanced Test Reactor, Advanced Gas Reactor, Particle Fuel*

I. INTRODUCTION

Eight different fuel irradiations are planned for the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program which supports the development of the Very High Temperature Reactor (VHTR). The goals of these 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 first in this series of planned experiments to test TRISO-coated, low enriched uranium (LEU) oxycarbide (UCO) fuel has been designated AGR-1. This experiment, planned for insertion in the ATR in late 2006, is intended to serve as a shakedown test of a multi-capsule experiment design to be used in subsequent irradiations and to test early variants of the fuel produced under this program. The other tests in this series will also be utilized to provide irradiation performance of the fuel as well as provide fuel and materials for PIE to achieve all of the goals identified above.

The AGR fuel experiments belong to a category designated as instrumented lead experiments. This category derives its name from the instrument leads they utilize to provide continuous monitoring (and typically control) of experiment parameters during irradiation. Each instrumented lead experiment test train may contain several vertically stacked capsules, and is uniquely designed, as the AGR experiments are being done, for the specific irradiation position in the ATR and the umbilical tube routing necessary to connect the experiment to the monitoring, control and data collection equipment. The design of the experiment test train as well as the monitoring, control, and data collection systems are discussed in the following sections.

II. EXPERIMENT CAPSULES

The test train for AGR-1 will consist of six separate capsules vertically centered in the ATR core, each with its own custom blended gas supply and exhaust for independent temperature control and fission product monitoring. Temperature control of the capsules will be accomplished 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). Helium will be used as the high conductivity gas and neon will be used as the low conductivity gas.

A horizontal cross-section at the top of the test train is shown in Figure 1 and a vertical section of the experimental hardware is shown in Figure 2. The capsules are approximately 35 mm (1-3/8 inches) in diameter and 150 mm (6 inches) long - including the plenums between adjacent capsules. Each capsule will contain 12 prototypical fuel compacts approximately 12.3 mm (½ inch) in diameter and 25.4 mm (1.0 inch) long. The fuel is made up of 350 µm diameter fuel kernels, and the baseline fuel compacts will be made up of 780µm nominal diameter TRISO-coated fuel particles. There also will be four variants of the fuel with different coating and process development variations. 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 will surround and separate the three fuel compact stacks in each capsule to prevent any fuel particles on the outside diameter of one compact from contacting a fuel particle on an adjacent compact, which could possibly cause a premature particle failure. Very thin (0.5 mm) graphite top and bottom end caps are currently being considered for the fuel compacts, primarily to provide a region to inscribe an identification number on the compacts without impacting any fuel particles. Furthermore, this change would also help prevent particle to particle contact between adjacent axial compacts that may result in premature fuel particle failures.

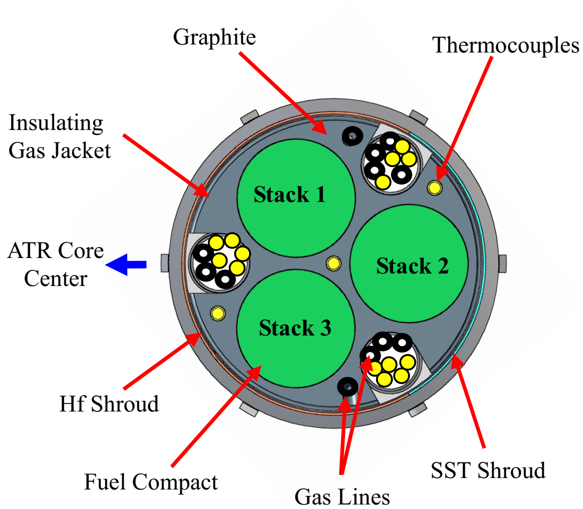

Figure 1: Horizontal cross-section of an AGR experiment capsule

The graphite spacer will also provide the inner boundary of the insulating gas jacket for irradiation temperature control in the compacts. Boron carbide will be 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). 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. Stainless steel was used for this shield (versus hafnium) in order 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 were necessary to limit the initial fission rate in the fuel and thereby provide a more consistent fission rate/power production during the irradiation. As the boron carbide is consumed in the graphite, the fission rate in the fuel will reach a peak at about the mid-point of the irradiation. The fission rate will then slowly decrease as the fuel continues to burn-up. Reducing and controlling the initial fission rate in this manner decreased the ratio of the maximum to minimum heat generation rates in the fuel, which will provide better control of the temperatures in the fuel over the length of the rather long two year irradiation. 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 also being utilized to center the graphite in the capsule and space it at the proper distance from the capsule wall to provide the necessary gas jacket for temperature control. The through tubes were originally located against the side of the capsule wall. However they had to be relocated inside of the insulating gas jacket to prevent excessive thermal stresses from the extremely high azimuthal temperature differences (over 800 ºC) between the side touching the capsule wall and the opposite side touching the graphite spacer. In addition, since the through tubes will be in contact with the high temperature graphite throughout their length, 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 head to prevent the significant difference in 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 severely limit and control any leakage of the temperature control gas between the tubes and the capsule head. To prevent any possible cross contamination between the capsules, the plenums between the capsules are being pressurized with helium to ensure any leakage between the tubes and capsule head will be into the capsules.

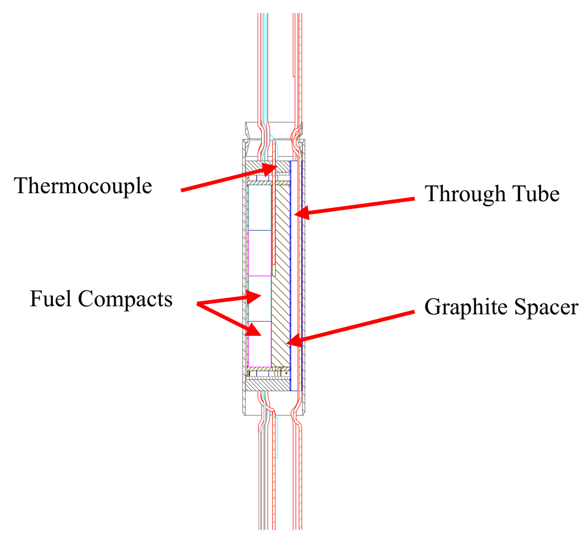

Figure 2: Vertical section of an AGR experiment capsule

There will be three thermocouples in each capsule located at the top, middle, and bottom of the graphite spacer measuring the temperature of the graphite. Since it would be extremely difficult to form the compacts with a thermocouple hole and drilling a hole was not a viable option because of damaging fuel particles, the thermocouples will measure the graphite temperature, and the corresponding fuel temperatures will be calculated. Flux wires will also be installed in the capsules to measure both the thermal and fast neutron fluence. As indicated earlier the outside diameter of the graphite establishes the inner boundary of the insulating gas jacket, and therefore very rigorous and closely integrated reactor physics and thermal analyses are necessary to establish the exact dimension for this diameter. Consequently, the outside diameter of the graphite spacer varies among the capsules depending on the flux value at the vertical location of the specific capsule within the ATR core. The boron carbide content in the graphite spacer is also different in the two end capsules due to the vertical neutron flux gradient in the ATR core. The graphite is also being carefully analyzed to ensure shrinkage and changes in its thermal properties during irradiation will not adversely impact fuel swelling as well as temperature control of the capsule.

An umbilical tube (termed a leadout) will vertically locate the experiment in position in the ATR core. The leadout also provides a conduit to house and protect the gas lines and thermocouple leads from the experiment capsules located in the east large B irradiation position to the reactor vessel wall penetration, where they will be connected to their facility counterparts in the temperature monitoring, control and data collection system.

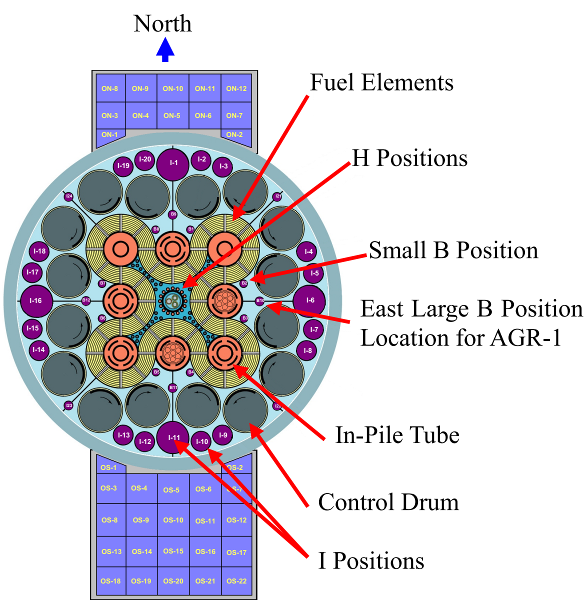

Figure 3: ATR Core Cross-Section

The large B positions (38mm or 1.5 inch diameter) were chosen for the AGR fuel irradiations due to the rate of fuel burnup and fast neutron fluence accumulation in these positions providing an acceleration factor of less than 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 as to avoid possible premature particle fuel failures similar to those experienced in past highly accelerated particle fuel tests. As indicated earlier, in addition to limiting the acceleration factor, avoiding contact between fuel particles and limiting the materials contacting the fuel compacts/particles to only graphite and the inert temperature control gas were done to prevent possible premature fuel particle failures. The irradiation time for the AGR-1 experiment was determined by the neutron flux in the large B and the Fissions per Initial Metal Atom (FIMA) average burnup goal of 18% for all fuel compacts, and minimum of 14%[3]. This requirement in combination the 20% fuel enrichment resulted in a rather long irradiation time, and (of course) 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 for the irradiation period to increase the controllability of the temperatures at the end of the irradiation. This controllability was necessary to meet the time-average volume-average temperatures of 1150 +30/-75 ºC for the irradiation while staying below the time-average peak temperature of 1250 ºC and maximum instantaneous peak temperature of 1400 ºC. These requirements provided some significant challenges in the design of the AGR-1 experiment and control systems.

III. TEMPERATURE CONTROL SYSTEM

The most common parameter to be monitored and controlled in an instrumented lead experiment is the specimen temperature. As indicated earlier, the temperature of each experiment capsule will be controlled by varying the mixture of two gases with differing thermal conductivities in a small insulating gas jacket between the specimens and the experiment containment. Helium and argon have been used in the past, and this combination provides a nice wide temperature control band for the experiments. Unfortunately, argon could not be used in the AGR fuel experiments due to the effects of the activated argon gas on the fission product monitors. Therefore, helium and neon, which is the typical gas combination currently used at ATR, will also be utilized in the AGR fuel experiments. Computer controlled mass flow controllers will be used to automatically blend the gases (based upon feedback from the thermocouples) to control the graphite spacer temperatures, which will be 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 gases will flow at a nominal rate of 50 cc/min, and stainless steel tubing with a very small internal diameter (1.5 mm) is used to minimize delivery times between the mass flow controllers and the experiment and also between the experiment and the fission product monitors.

The temperature measurements will be taken with three thermocouples per experiment specimen capsule, one of which will be designated as the control thermocouple. In the event the control thermocouple fails open (as indicated by a significant increase in resistivity), a designated primary back-up thermocouple will automatically be switched to the control thermocouple. The thermocouples typically used at

ATR are type K (special grade, +/- 0.4%) 1.6 mm (0.062 inch) sheath diameter and high purity magnesia insulation. However, due to the very high thermocouple temperatures (up to 1150 ºC) coupled with the relatively long irradiation (approximately two years), there is concern on the survivability of the thermocouples. Type C thermocouples were considered, but it was felt there would be too much transmutation in the type C thermo-elements due to their higher neutron absorption cross sections. Type N thermocouples are also a possibility, but they have very similar temperature limitations to the type K thermocouples. To ensure the best survivability of the thermocouples used in the AGR irradiations, a selection of the most promising long life type K and type N thermocouples were purchased and are scheduled for testing in a thermal mock-up of the AGR irradiation conditions. In addition, several developmental thermocouples are also being included in the thermal mock-up testing to determine how they would survive the irradiation conditions. The high temperature testing of the thermocouples will be conducted for four months, and low temperature cycling will also be conducted to represent the reactor outages that will be experienced by the thermocouples during the experiment irradiation. At the end of the four month testing period, the temperature of the mock-up will be steadily increased at regular intervals until all thermocouples have failed. The time survived at the higher temperatures can then be scaled to equivalent time at the irradiation temperatures to provide accelerated results in time to support the fabrication and assembly schedule of the AGR-1 experiment.

Alarm functions are provided in the control system to call attention to circumstances such as temperature excursions or valve position errors. The control system conducts an automatic gas verification to assure the correct gas has been connected to supply ports in the system prior to allowing a new gas bottle to be placed into service. This process was incorporated to prevent uncontrollable temperature excursions due to having an insulator gas connected to the conductor gas port. Helium purges to cool the individual specimen capsules are under automatic control in the unlikely event that measurement or control of the capsule temperature is lost. Manual control capability is also provided at the gas blending panels to provide helium purge in the event of a computer failure. In order to minimize any temperature changes and maintain the most constant temperature 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 and this function is discussed in the next section of this paper.

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

IV. FISSION PRODUCT MONITOR

Fission gases are the most common materials monitored in lead experiment temperature control exhaust gases, and the AGR fuel experiments are no exception and are in fact unique in monitoring each capsule. The outlet gas from each capsule will be routed to individual fission product monitors being specifically designed for use in the AGR series experiments. The experiment flow path is shown in Figure 4 below. The monitors will have the capability to be rerouted to an online spare if any monitors experience detector or other failures. There will also be the capability to take a grab sample of the effluent gas from each capsule. The fission product monitors will consist of a spectrometer for identifying specific fission gases and a gross gamma detector to provide indication when a small cloud or wisp of fission gases passes through the monitor. This small cloud of fission gases typically indicates when a TRISO fuel coating failure may have occurred. Through identification of the specific isotopes, the spectrometer can be used to determine the birth to release ratio of the fission gases being detected. This determination 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. By utilizing the combination of a spectrometer and a gross gamma detector and having both items continuously on-line, the gross gamma detector results can be scanned quickly to establish which portions of the voluminous spectrometer data need to be closely scrutinized.

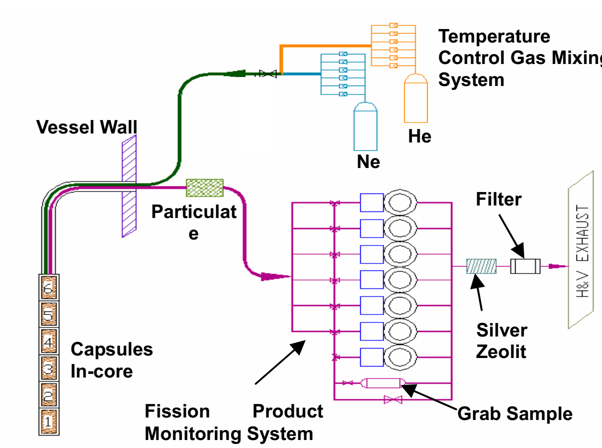

Figure 4: AGR-1 Experiment Flow Path

The spectrometers for the fission product monitors used for the AGR fuel irradiations will be liquid nitrogen cooled High Purity Germanium (HPGe) detectors, because of their well-established capabilities and reliability. In order to increase the sensitivity of the monitors, especially on the absolute quantity of fission products, the effluent gases will be collected over a long period of time by incorporating a large diameter thin wall gas detection chamber filled with baffles to slow the movement of the gas in front of the spectrometer detector. The use of cryogenically cooled traps could also be employed to collect and concentrate the fission products even more; however, there are no plans to implement this option on the first AGR fuel experiments. The type of gross gamma detectors utilized in the fission product monitors at ATR have varied from ion chambers to the present sodium iodide crystal scintillation detectors currently intended for use in the AGR fuel qualification tests. The shift was made from ion chambers to scintillation detectors to increase the sensitivity and therefore relax the proximity requirement between the gas lines and the detector. This is especially important if too many fission gas daughter products accumulate (from plate out) in the area viewed by the gross gamma detector.

V. EXPERIMENT STATUS

AGR-1 is scheduled to be ready for insertion in the east large B position (B-10) in the ATR core in September 2006. The actual insertion date will depend on the ATR operation schedule and may occur after September when the next regularly scheduled reactor outage occurs. The final design review of the experiment test train, temperature control system and fission product monitors was completed in March 2005. Current activities under way include assembly and testing of the fission product monitors, and preparing an area in the ATR building to house the seven fission product monitors (six prime monitors plus the on-line back-up monitor). The modifications needed to customize an existing temperature control system for use on the AGR irradiations are also being initiated.

Various different tests are also currently being conducted (or have recently been completed) to support the test train fabrication and assembly scheduled to start in October 2005. The high temperature testing on the thermocouples to support selection of the actual thermocouples that will be used in AGR-1 will be starting in early September, and is scheduled for completion in early January 2006. Testing on the gas leakage through the slip fit between the through tubes and the capsule bottom head has been completed and the leakage experienced in the mock-up testing has confirmed the design calculations used to determine the clearance on the through tubes. Testing is also being conducted on the capsule assembly processes (i.e. clearances, welding, brazes, etc.) to ensure the assembly of the test train will be accomplished as designed. During the assembly of the actual test train, quality assurance personnel will be involved in all special processes such as welding, brazing, specimen insertion, etc. They will also perform various quality assurance tests such as weld inspection, helium leak checks, thermocouple continuity, etc. to ensure the test train is assembled in accordance with the drawings and will perform as planned.

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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, 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. T. Maki, “AGR-1 Irradiation Experiment Test Plan”, Idaho National Laboratory Report INL/EXT-05-00593, August 2005.