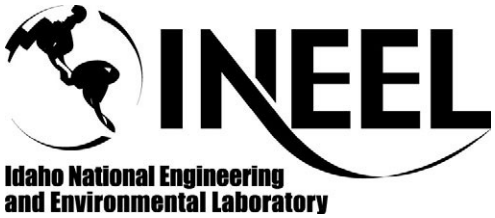

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PREPRINT

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TESTING OF GAS REACTOR MATERIALS AND FUEL IN THE ADVANCED TEST REACTOR

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SUMMARY
The Advanced Test Reactor (ATR) has long been involved in testing gas reactor materials, and has developed facilities well suited for providing the right conditions and environment for gas reactor tests. This paper discusses the different types of irradiation hardware that have been utilized in past ATR irradiation tests of gas reactor materials. The new Gas Test Loop facility currently being developed for the ATR is discussed and the different approaches being considered in the design of the facility. The different options for an irradiation experiment such as active versus passive temperature control, neutron spectrum tailoring, and different types of lead experiment sweep gas monitors are also discussed. The paper is then concluded with examples of different past and present gas reactor material and fuel irradiations.

I. BACKGROUND

The recent growth in interest for high temperature gas reactors has resulted in an increased need for materials and fuel testing for this type of reactor. As indicated above, the ATR has a long history and facilities/capabilities well suited for irradiation testing of gas reactor materials and fuels. These capabilities include both passive sealed capsule experiments, and instrumented/controlled experiments. The instrumented experiments typically contain thermocouples and control the irradiation temperature, but on-line measurements and controls for pressure and gas environment have also been performed in past irradiations. The ATR has an existing automated temperature control system that significantly reduces the cost for actively monitored/temperature-controlled experiments. The ATR's unique control system, which consists primarily of control drums used to rotate neutron poisons/reflectors toward or away from the reactor core, provides a constant axial flux profile over the duration of each operating cycle. This constant chopped cosine shaped axial flux profile, with a relatively flat peak at the center of the core, is more desirable for experiments than a constantly moving axial flux peak resulting from the typical control system of axially positioned control components which are withdrawn from the core during reactor operation.

The ATR is the world's premiere test reactor for performing long term, large volume irradiation test programs. The irradiation positions vary in diameter from 1.6 cm (0.625 inches) to 12.7 cm (5.0 inches) over an active core length of 122 cm (48.0 inches). In addition, the ATR's base program for the US Department of Energy's Office of Naval Reactors assures that other programs using the ATR will have reliable facilities for decades into the future. Other benefits of this base program are the continual upgrades of ATR (and its associated facilities), further assuring researchers of current equipment and facilities that can support completion of long term programs. The ATR maintains an availability of nearly 80%, with reactor cycles on approximately eight-week intervals, providing frequent opportunities for insertion and removal of experiments throughout the year for the experimenter.

II. TESTING OPTIONS

There are several testing options available for an experimenter in the ATR. These options include static capsule, lead experiment, and pressurized water loop testing.[1] The first two types of testing are applicable to gas reactor materials and are discussed below. In addition, the ATR is currently in the conceptual design phase for a new Gas Test Loop facility. The options currently being considered for this new facility are also briefly discussed.

A. Static Capsule Testing

The simplest type of irradiation performed in the ATR is a static capsule experiment (referred to as a drop-in capsule). The irradiation specimens (material or fuel) are sealed in aluminum, Zircaloy, or stainless steel tubing to provide containment.

The sealed tube is placed in a holder (referred to as a basket) that is inserted in the chosen irradiation position in the ATR. Static capsules are uniquely designed for each customer's needs, and are usually much less expensive than any of the other types of tests, but provide less flexibility and control of operating parameters.

Static capsules may include special passive instrumentation such as neutron fluence monitors or melt wires to provide indication of the maximum temperature achieved during irradiation. The temperature of a static capsule may also be controlled, within limits, by incorporating a small insulating gas jacket (typically filled with an inert gas to prevent chemistry issues) between the specimens and the outside capsule pressure boundary. The width of the gas jacket, the type of insulating gas, and the gamma heating characteristics of the specimens and capsule materials are all used to provide the irradiation temperature desired. Static capsules may vary in length from a few centimeters to the full height of the ATR core (about 1.2 meters) and may also vary in diameter depending on the specimens and the size of irradiation position chosen in the ATR (1.2-cm to 12.7-cm). Depending upon the contents and pressure of the capsule, a secondary containment may also be included to meet the ATR safety requirements.

B. Lead Experiment Testing

The next level of testing complexity provides continuous monitoring (and possibly control) of experiment parameters during irradiation utilizing instrumentation leads in the capsules. These experiments are commonly called ‘lead experiments’ after the instrument leads they contain. The experiment containment is very similar to a static capsule, with the major difference being an umbilical tube attached between the experiment containment and the reactor vessel wall. The umbilical tube is used to house instrumentation leads (i.e. thermocouples, pressure taps, neutron fluence, etc.) and possibly temperature control gas lines that lead outside the reactor vessel to data collection/monitoring equipment. Each instrumented lead experiment, which may contain several vertically stacked capsules, is uniquely designed for the irradiation position in the ATR and the umbilical tube routing needed to connect the experiment to the collection/monitoring equipment.

The most common parameter to be monitored and controlled is the specimen temperature. The temperature of each experiment specimen capsule is controlled by varying a mixture of two gases with differing thermal conductivities (e.g. an insulator and a conductor gas) in a small insulating gas jacket between the specimens and the experiment containment. Helium (conductor) and neon (insulator) are typically used today, but helium and argon have also been used in the past to provide the thermal conductivity variability. Normal operations are for the gases to be blended automatically (based upon feedback from the thermocouples) to control the specimen capsule temperature. The gas blending capability 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. Temperature measurements are taken with at least two thermocouples per experiment specimen capsule. The thermocouples typically used are type K (special grade, +/- 0.4%) 1.6-mm sheath diameter and high purity magnesia insulation. Other arrangements are possible including multi-junction thermocouples within a single sheath. The type K calibration was selected and is used in pairs to assure long-term service in the high radiation environment. The thermocouple reading is used as the direct control parameter to the gas mixing functions. Additionally, the control systems provide automatic gas verification to assure the correct gas is connected to supply ports in the system. Monitoring of the exhaust gases is possible and examples of several systems employed on previous temperature controlled experiments conducted in the ATR are discussed later in this paper. Alarm functions are provided to call attention to circumstances such as temperature excursions or valve position errors. 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. In order to minimize response time, the gas system provides a continuous flow to each specimen capsule. Manual control capability is also provided at the gas blending panels to provide helium purge in the event of a computer failure. 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 are also time stamped and recorded once every ten minutes (or more frequently by exception) not to exceed a rate of once every ten seconds. The control processor will

record these values in a circular first-in, first-out format for at least six months.

The Irradiation Test Vehicle (ITV) is a specialized lead experiment facility that was installed in the ATR in 1999. This facility consists of three Mini In-Pile Tubes (MIPTs) that were permanently installed in the center flux trap at the center of the ATR core. Each MIPT provides the pressure boundary with the ATR primary coolant, the temperature control gas inlets and outlets and houses the thermocouple leads for five vertically stacked experiment positions/temperature control zones. These five zones could each be used to control the temperature of five separate experiment capsules at different temperatures simultaneously or combined in any arrangement less than five based upon the experiment needs. The use of MIPTs reduced the cost of performing a lead experiment by reducing the requirements of the experiment to only housing the irradiation specimens inside of a minimal containment structure and including the desired thermocouples. The outside diameter of the specimen containment was used to provide the insulating gas jacket necessary for temperature control. The ITV is being removed in the current core replacement of ATR, and will not be re-installed unless this testing capability is required. The new ATR Gas Test Loop is anticipated to provide this and additional capability in the future.

C. New ATR Gas Test Loop

A new ATR Gas Test Loop is in the conceptual design phase, and is therefore alternatives and options to be developed in later design phases of the system are being identified. The system is currently being planned for installation in one of the flux trap positions in ATR to maximize the flux rates available to experimenters. In addition to use of a flux trap position, concepts under current consideration include fast flux boosting by including additional fuel around the outside of the test positions. Several different configurations have been proposed for the additional fuel and all are being evaluated for cost and increased capabilities.

The current existing gas reactor testing facilities at ATR utilize either no or very low temperature control gas flows (50 cc/min) and therefore rely on conduction and/or radiation heat transfer mechanisms. Consideration is being given to the use of convection heat transfer for cooling of the irradiation specimens in the new Gas Test Loop Facility, which would greatly expand the capability of the ATR for testing gas reactor fuels. Helium is the coolant under consideration and the heat rejection capacity of the high gas flow system is still under development. Consideration is being given to utilizing a single large position or several different positions of varying sizes. In addition, if several positions or in pile tubes are utilized within a single flux trap (similar to the ITV configuration), then the new facility may include different types of heat transfer control (convection versus conduction/radiation) in the different in-pile tubes. The Gas Test Loop is anticipated to replace the ITV and have significantly increased capabilities. These issues are currently being considered and may be carried forward into the preliminary design phase of the project.

III. SPECIMEN TESTING ENVIRONMENTS

Gas reactor experiments can be irradiated in almost any type of gas environment provided suitable containment materials are available to prevent leakage of the gas into the ATR's primary coolant. The gas environments can be divided into two distinct types of gas environments, inert and non-inert. These two types of irradiation environments are discussed below.

A. Inert Gas Environment

The irradiation specimens are quite often exposed to the temperature control gas during irradiation, which typically consists of inert gases to prevent unnecessary and/or unwanted chemical issues. These gases are usually helium, neon or argon. In the case of static capsule testing, the temperature control gas is selected based upon the amount of insulation required versus the gamma heat load in the specimen and capsule materials. In the case of instrumented lead testing, two gases are required: a conduction gas and an insulating gas. The selection of the conduction gas is easily determined to be helium due to its excellent heat transfer characteristics and it's low neutron activation potential. However, the insulating gas is a more difficult choice, since the two most attractive choices, argon and neon, each have an undesirable characteristic. Argon is inexpensive and a good insulator gas but it is easily activated in a high neutron flux. Fortunately, the activation product (Ar-41) has a reasonably short half life (1.82 hours), which is easily accommodated in static capsule testing. Argon can also be accommodated in lead experiment applications if the experiment effluent gas is either not being monitored for radiation (e.g. fission products, etc.) or can be delayed until the Ar-41 decays to an acceptable level. In order to minimize the ATR

plant stack effluents, delay tanks have been placed between the experiment gas exit from the reactor and the ATR plant exhaust system whenever argon is flowing through the reactor during experiment irradiation. On the other hand, neon has an order of magnitude lower activation potential and the activated gas (Ne-23) has a much shorter half life (37.2 seconds), which allows prompt radiation monitoring of the experiment effluent gas for short-lived activation or fission products. However, neon's insulating quality is not nearly as good as argon (resulting in a narrower temperature control band) and it is much more expensive. Both neon and argon have been successfully utilized as the insulating gas in lead experiment testing in the ATR, and based upon the experimenters needs, the insulating gas with the most desirable qualities can be selected for the temperature control of the experiment.

B. Non-Inert Environments

Occasionally an experiment may require a non-inert irradiation environment to simulate actual reactor conditions or there may be chemistry requirements that allow use of non-traditional temperature control gases. An example of the first situation is the Magnox graphite irradiation. The primary goal of the irradiation project was to produce highly radiolytically oxidized graphite specimens (produced from archive graphite materials) by simulating the British Magnox power reactor operating conditions (e.g. temperature, pressure, gas environment, etc.) during irradiation in a high gamma ray field. To simulate the operating conditions, a carbon dioxide cover gas (mixed with carbon monoxide and hydrogen) was purged over the graphite specimens while they were irradiated in the ATR. This carbon dioxide cover gas system was completely independent and isolated (by a second metal barrier) from the temperature control gas system. The rather complex carbon dioxide cover gas and graphite oxidation monitoring systems were developed through close interaction between ATR personnel and the BNFL Magnox project team. The irradiation was very successful in providing the graphite specimens to the required oxidation rates, and is discussed in greater detail in a later section of this paper.

An example of the second situation would be the use of a non-traditional temperature control gas such as nitrogen to gain additional temperature control bandwidth over the use of neon without incurring the activation issue associated with the use of argon. This type of gas has been investigated at ATR, but has not yet been utilized due to different chemistry issues. However, it is being kept as an important tool for consideration in future experiment irradiations.

IV. FLUX TAILORING

Quite often an experiment requires tailoring or manipulation of the neutron flux to provide the necessary neutron energy spectrum during irradiation. This tailoring can be accomplished in several ways, by absorbing unwanted (thermal) neutrons in a neutron poison (commonly referred to as a shroud), by positioning the experiment closer to the reactor driver fuel (to boost flux), or by including additional fuel around or possibly in the experiment to boost both the fast (to a greater degree) and the thermal (lesser degree) neutron flux rates. The shrouds can be either fixed (included as part of the experiment capsule containment) or removable (external to the experiment capsule). Each of these methods is discussed in the following sections.

A. Fixed Shrouds

Neutron poison shrouds are often included inside of the experiment capsules. This technique is used for several reasons: first, if the fast to thermal neutron flux ratio must be manipulated throughout the irradiation period; second, if the fission rate of a fueled test needs to be reduced throughout the irradiation period; or third, if the initial fission rate in a fueled capsule must be reduced by use of a burnable poison and adequate space for a removable shroud is not available. This method of shrouding also provides a wider selection of shroud materials due to the materials being isolated from the ATR primary coolant and therefore eliminating chemistry control issues with the primary coolant. The shroud materials used in ATR have included Inconel, stainless steel, hafnium, cadmium, and boronated materials (aluminum, graphite, etc.). The type of shroud is determined by the amount and duration of neutron manipulation as well as the portion of the neutron spectrum to be manipulated. Some neutron poisons absorb only thermal energy neutrons, while other neutron poisons can absorb intermediate energy as well as thermal energy neutrons. If the shrouding is being done to limit an initial fuel fission rate, then boronated material may be a good choice as it can be consumed during the initial portion of irradiation in the high flux environment of ATR, then later in the irradiation when the fuel is depleted, the boronated material would not affect the fission rate. However, if a more constant amount of neutron absorption is

required throughout the irradiation, especially over a long duration, then a hafnium (or cadmium) shroud for heavy absorption or a stainless steel (or Inconel) shroud for minimal absorption may be the best choice. Since a fixed shroud cannot be removed during irradiation, an extensive amount of analysis is required to ensure the correct type and quantity is selected based upon the experiment requirements.

B. Removable Shrouds

Removable shrouds have also been used extensively in ATR. The ITV incorporated a removable shroud that surrounded the outside of the three MIPTs and could be changed during reactor outages. If shrouding was not needed for the ITV experiments, then an aluminum filler was installed instead. Shrouds have also been included in the basket assembly used to support a static capsule. This technique allows removal or replacement of the shroud during outages by replacing the basket. Since removable shrouds are in contact with the ATR primary coolant, there are restrictions on the materials allowed for this type of shroud. Stainless steel, inconel, hafnium and boronated materials are all compatible with ATR primary coolant chemistry. However, other materials such as cadmium are not compatible and need to be encapsulated for this type of shroud application.

C. Flux Boosters

There are several methods to increase the flux rate surrounding an experiment capsule. The most common, easiest and least expensive method is to locate the experiment in an irradiation position with the necessary flux values. The flux rates vary in ATR based upon the proximity to the driver fuel and the nine flux traps. The A positions located next to the fuel have not only very high thermal flux rates, but they also have the highest fast neutron flux rates in ATR due to the low moderating material between them and the fuel (principally aluminum) and the relatively short distance for neutron moderation. However, these positions are among the smallest (diameter) positions in the ATR. In general, as the distance from the ATR fuel increases, the diameter/size of the reflector (e.g. non-flux trap) irradiation positions also increase whilst unfortunately, the flux rates decrease with the fast flux decreasing more than the thermal flux. This effect can be offset by incorporating a flux booster in the form of additional fuel in or around the experiment capsule. In addition to increasing the flux rate, additional fuel also increases the fast to thermal flux ratio. This effect is very important to many experimenters, since the fast fluence damage to materials and fuels is extremely important. Adding a flux booster to an experiment (or facility) in ATR has been included as an option many times in the past, and recently incorporated in an irradiation experiment. A flux booster was utilized in one of the large I positions (12.7 cm diameter) in the ATR to decrease the irradiation time by increasing the (total) flux rate. The resulting flux rate was increased by over a factor of three (after including perturbation by the experiment) by including the additional fuel. This option was necessary since the only other ATR irradiation positions large enough to accommodate the rather large specimens (10mm x 60mm x 100mm) were flux trap positions, where the flux rates were actually too high. Irradiation in a flux trap for one nominal ATR seven-week operation cycle would have greatly exceeded the desired specimen fluences. There have also been several proposals to develop a fast flux booster facility in the ATR (including the Gas Test Loop discussed earlier) to provide this capability that has been missing in the United States with the closure of its fast flux facilities.

V. EFFLUENT MONITORS

Different ATR lead experiments have incorporated systems on their temperature control exhaust gas to monitor for various materials and provide additional on-line indication of specimen performance. This monitoring is especially important in fuelled experiments, but can also be employed in other types of irradiation such as material containment barrier testing.

A. Fission Product Monitors

Fission products (e.g. gases) are the most common materials monitored in lead experiment temperature control exhaust gases. The fission product monitors have typically consisted 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 collection of fission gases typically indicates when a cladding leak or 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 cladding failure has occurred or if the fission products are merely being released from an existing failure or (in the case of pellet fuel) tramp contamination on the outside surface of the fuel. These details can be very

important in the qualification of fuel especially in small pellet fuels, where a few random pellet 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.

The spectrometer typically utilized in ATR fission product monitors has been a liquid nitrogen cooled High Purity Germanium (HPGe) detector, due to their well-established capabilities and reliability. If additional sensitivity is desired, especially on the absolute quantity of fission products, then trapping the gases over a long period of time or even the use of cryogenically cooled traps can be employed to collect and concentrate the fission products. The type of gross gamma detectors have varied from ion chambers to the present sodium iodide crystal scintillation detectors currently intended for use in the AGR fuel qualification tests discussed later in this paper. The shift was made from ion chambers to scintillation detectors to allow the gamma detector to be included in the same shielding enclosure as the spectrometer. Since the increased sensitivity of the scintillation detector did not require it be in as close proximity to the gas lines as the ion chamber required, it was deemed possible to have the scintillation detector view the same gas line section as the spectrometer. Fission product monitors have been incorporated in two of the ATR gas reactor experiment programs (NPR and AGR) discussed later in this paper.

B. Other Monitors

The temperature control exhaust gas from a lead experiment can also be monitored for other materials to provide on-line information on the performance of the irradiation specimens. This technique can be utilized in detecting the production of specific materials or isotopes as well as testing containment materials for specific isotopes. The Modular High Temperature Gas Reactor (MHTGR) portion of the New Production Reactor (NPR) irradiations utilized a monitor in this fashion to determine the capability of TRISO coated particles for containing the tritium produced inside of them. This monitor simply utilized getter beds to trap tritium from the gas exhaust stream and concentrate it for detection. This type of monitoring could also potentially be applied to testing of other types of gases in the exhaust stream of a lead experiment.

VI. PAST AND CURRENT IRADIATIONS

Different gas reactor materials and fuels have been tested in different irradiation programs at ATR. A few examples of past and current programs are included below.

A. New Production Reactor

The irradiation of New Production Reactor materials was started in the 1980's and continued into the early 1990's. This relatively large irradiation program consisted of two different types of irradiation, fuel and target irradiations, and included in excess of twelve static capsule irradiations and six lead experiment irradiations in ATR. Both the fuel and target irradiations were testing TRISO coated particles for containment of either fission products or tritium and included monitors in the exhaust gas stream of the lead experiments for each type of irradiation. The irradiations were very successful though the project (and ultimately the whole NPR program) was cancelled. However, this irradiation program provided the added benefit to ATR of pioneering the use of Mass Flow Controllers and computer control in the lead experiment temperature control gas systems.

B. Magnox Graphite Irradiation

The graphite irradiation was performed in MIPT #3, which is the west MIPT in the Irradiation Test Vehicle.[2] The experiment consisted of a single test train, which was split into two capsules containing the Magnox graphite specimens. The two capsules were of equal length, separated at the vertical center of the ATR core by a sealed bulkhead, and extended from the center to the upper and lower ends of the active fuelled region of the reactor core. The top capsule, with a flowing inert (helium) gas environment, contained fast neutron damage control specimens and the bottom capsule, with a flowing oxidizing (CO_2) gas environment, contained the specimens radiolytically oxidized to high weight losses. In both capsules, the graphite was positioned within a specimen carrier to ensure the applicable gas flow was positively directed over as much of the specimen surface as possible. This was done to minimize the diffusion distance for the gas within the porosity of the graphite specimens. To ensure data from the irradiation specimens would be directly comparable to data obtained from samples trepanned from Magnox reactor cores, the same standard specimen size was used in the irradiation. Other prototypic conditions mandated for the irradiation included specimen temperatures and gas environment (gas

composition and gas pressure) of Magnox reactors. The length of irradiation was determined using a radiolytic oxidation model developed in support of the Magnox reactors. This model takes into account the total nuclear (gamma plus neutron) heating of the specimens, the composition of the gas and the desired weight loss of the specimens. Using this input, the model predicted approximately 140 irradiation days in the ATR ITV would lead to radiolytic weight losses which would bound those calculated to arise over the planned lifetimes (including planned life extension) of the Magnox power reactors. The actual irradiation period was 150 days, and was achieved over three standard seven and eight week ATR irradiation cycles.

Extreme care was taken in the design of the experimental hardware to maintain prototypic chemistry control of the specimen environment to limit the unknown variables and prevent any unwanted chemical reactions during the irradiation. Materials that could either affect (e.g. catalyze or block) or mask the oxidation rate (e.g. carbon deposition) were excluded from the experimental hardware and all communicating systems. The major material used in most ATR test trains and capsule shells, stainless steel, was excluded due to its nickel content. To satisfy the chemistry requirements, the capsule material was researched extensively and 9Cr 1Mo alloy steel was selected. This material was able to meet the chemistry requirements and also survive the high neutron flux environment of the ATR without experiencing a significant increase in its brittle fracture transition temperature. However, since the design code required a post weld heat treatment for this material, special techniques were developed to prevent melting of the aluminum specimen carrier during this process.

A horizontal cross-section at the top of the capsules is shown in Figure 1, and a vertical section of the experimental hardware is shown in Figure 2. The specimen carrier consisted of two clamshell halves that are held together by thin aluminum straps. These straps also held the thermocouple leads, gas lines, and flux monitors in grooves machined in the outer surface of the carrier. Aluminum was chosen for the specimen carrier material for several reasons including chemistry control, low neutron absorption rate, high thermal conductivity and a high thermal expansion rate.

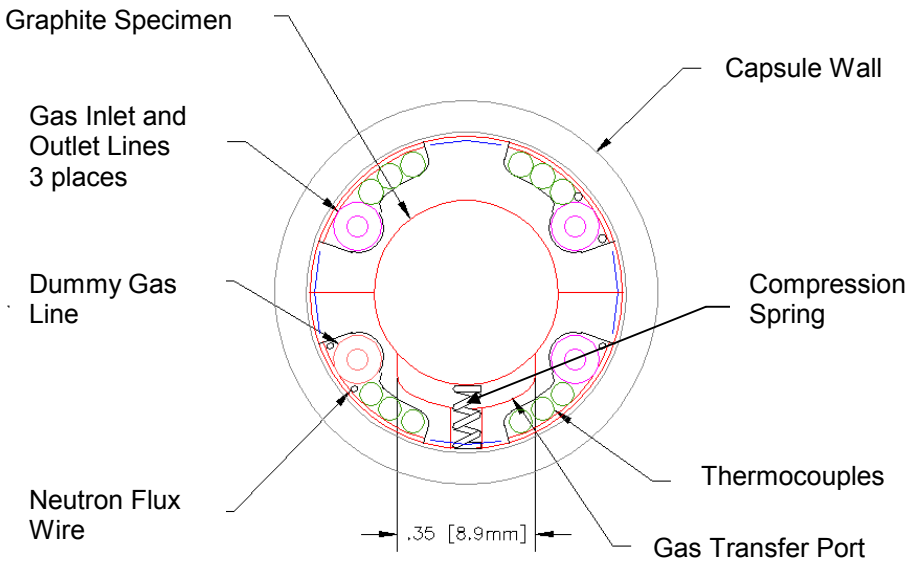

Figure 1: Cross-section of Magnox graphite irradiation experiment capsule showing the graphite specimens located in the center of the capsule and surrounded by the specimen carrier and other key components.

The last two properties enabled the carrier to provide an excellent heat transfer path between the specimens and the capsule wall. The high thermal expansion rate also helped in the assembly and later disassembly of the capsules by providing needed clearance between the carrier and the capsule wall at room temperature. However, during irradiation the aluminum expanded to provide positive thermal contact between the carrier and the capsule wall.

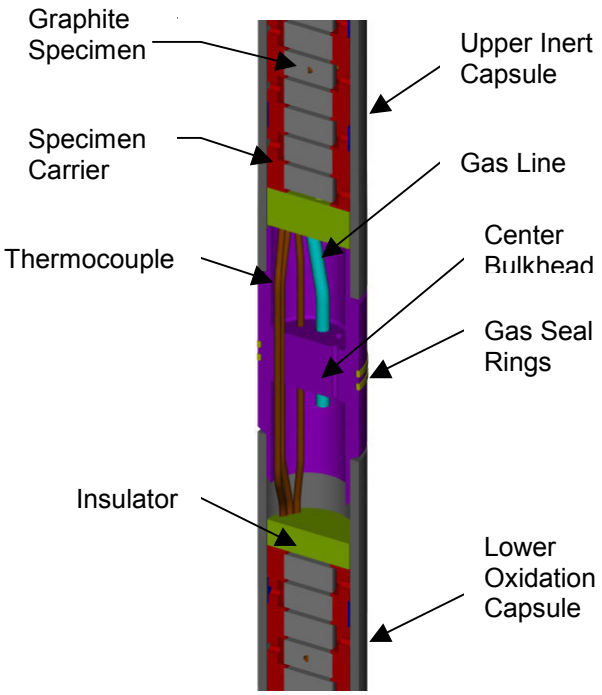

Figure 2: Vertical section of the Magnox graphite experiment capsule showing the orientation of the capsules and the bulkhead separating the two capsules

Nonetheless, the carrier's main role was to provide support for the graphite specimens, whilst separating them by a 1-mm gas space between adjacent top and bottom surfaces of the specimens. The gas spaces (or gas path) between the specimens were connected by gas ports located on alternating sides of the specimens. The specimens were held against the side of the carrier opposite the gas port by a compression spring to ensure good thermal contact between the specimen and the carrier for heat transfer purposes. Thermocouples were located at the top, middle and bottom of each capsule for both temperature monitoring and control of the specimens. At each of these locations there were two thermocouple junctions located diametrically opposite each other: one measuring the centerline temperature of a graphite specimen and one measuring the temperature of the specimen carrier. Neutron flux monitors were installed to measure both the fast and thermal neutron fluences. Iron, nickel, and niobium wires were used to measure the fast spectrum, whilst cobalt-aluminum alloy wires were used to measure the thermal spectrum. Two iron flux monitors were also positioned diametrically opposite each other in each capsule to measure the fast neutron flux gradient across the capsules. Bare monitor wires were utilized in the upper inert capsule, but to prevent any unknown chemical effects on the specimens or wires, the monitors were encapsulated in a sealed aluminum tube in the lower oxidation capsule. Since each capsule had a different gas environment, there were separate gas inlet and outlet lines for each capsule. The inlet gas lines terminated at the bottom and the outlet gas lines were located at the top of the capsules. The gas (either oxidizing or inert) entered a gas plenum from the inlet gas line at the bottom of each capsule. It then traversed the tortuous path up between the specimens via the spaces between the specimens and the gas ports to ultimately enter the outlet line at the top of the capsule.

The outside diameter and profile of the capsule was determined based upon very rigorous reactor physics and thermal analyses. In order to ensure the data from this experiment would be directly comparable with the existing database, an equivalent flux and temperature relationship established using data from the DIDO reactor was used to determine the required specimen temperatures. This relationship was applied to the neutron flux profile of the ATR to determine the correct temperature of the specimens based upon their axial position within the core. The outside diameter of the capsule wall was then tapered to provide the correct insulating gas jacket between the capsule and the MIPT as a function of vertical location within the ATR core.

The capsule environment system was a new capability added to the ITV specifically for this project. It consisted of the two different gas systems (inert and oxidizing) connected to the inert and oxidizing capsules in the MIPT. The inert gas system contained pure helium gas, and the oxidizing gas system contained a carbon dioxide gas that was blended with a carbon monoxide/hydrogen mixture. Inlet and outlet gas

compositions were monitored over the duration of the experiment using a gas chromatograph. Oxidizing gas flow rates and composition were adjusted to control the oxidation of the graphite specimens. In addition to purchasing high quality gases for these systems, the moisture content of each gas was also monitored during the irradiation.

C. Advanced Gas Reactor

The design of the first experiment test train assembly, temperature control gas system modifications, and fission product monitors for the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program is currently in progress. A horizontal cross-section at the top of the test train is shown in Figure 3 and a vertical section of the experimental hardware is shown in Figure 4, and. Eight different fuel irradiations are planned for the program, with the first (AGR-1) planned for insertion in the east large 1.5" or 38.1mm diameter) B position (B-10) in ATR in early 2006. 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. The capsules are approximately 35 mm (1-3/8 inches) in diameter and 130 mm (5 inches) long, and will contain 12 prototypical fuel compacts approximately 12.5 mm (½ inch) in diameter and 25 mm (1.0 inch) long. The fuel compacts are made up of 780μm diameter TRISO-coated fuel particles. 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 and also provides the inner boundary for the insulating gas jacket. The graphite spacer will contain boron carbide as a consumable neutron poison to limit the initial fission rate in the fuel providing a more consistent fission rate/power production during the planned two-year irradiation. As the boron carbide is consumed in the graphite, the fission rate in the fuel actually reaches a peak at about mid-point of the irradiation. Controlling the fission rate provided better control of the temperatures in the fuel over the duration of the rather long irradiation.

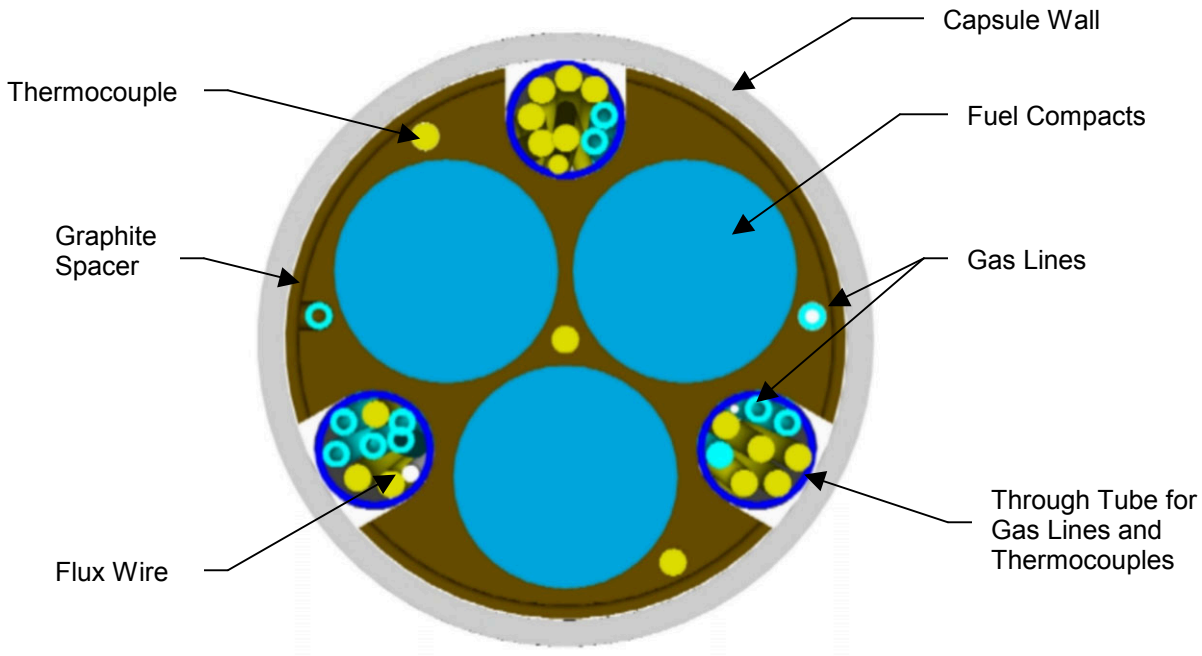

Figure 3: Cross-section of an Advanced Gas Reactor fuel experiment capsule showing the fuel compacts located in the center of the capsule and surrounded by the graphite spacer and other key components.

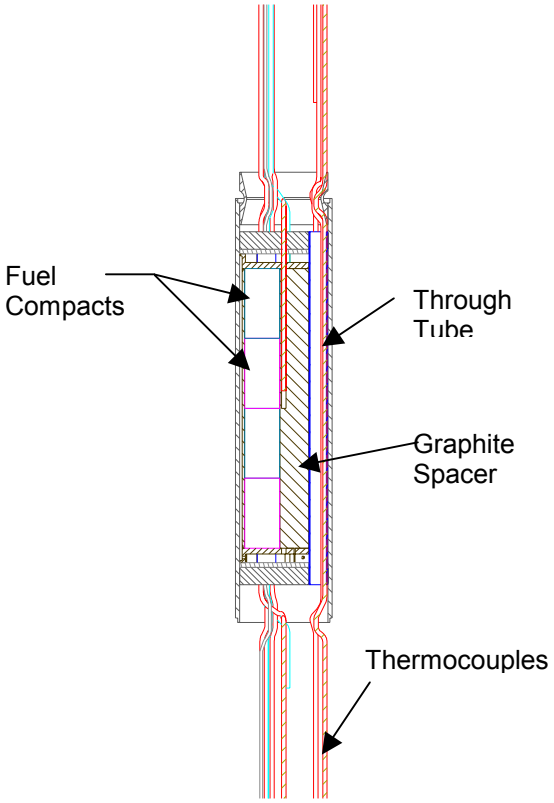

Figure 4: Vertical section of an Advanced Gas Reactor fuel experiment capsule showing the layers of fuel compacts and the gas lines and thermocouples passing to the lower capsules.

The Large B positions were chosen for the AGR fuel irradiations due to the flux rate providing a comfortable acceleration factor of three for the irradiation. 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 earlier highly accelerated particle fuel tests. Of course the length of irradiation was ultimately determined by the fuel burnup or Fissions per Initial Metal Atom (FIMA) requirement established by the AGR Fuel Development and Qualification Program.
In addition to the acceleration factor, other precautions required to prevent possible premature fuel particle failures were not allowing the fuel compacts to come in contact with each other in the radial direction (only axial) or any material other than graphite and the inert temperature control gas.

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 gas lines and thermocouples for adjacent capsules. The graphite is being carefully analyzed to ensure shrinkage during irradiation will not adversely impact fuel swelling as well as temperature control of the capsule. In addition to providing a pathway for the gas lines and thermocouples from adjacent capsules, the placement of the three through tubes is being utilized to space the graphite at the proper distance from the capsule wall thereby providing the necessary gas jacket for temperature control. There will be a total of three thermocouples in each capsule located at the top, middle and bottom measuring the temperature of the graphite. Since the thermocouples could not contact the fuel (due to concern about resulting fuel particle failures), 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 discussed earlier the outside diameter of the graphite establishes the insulating gas jacket, and therefore the dimension for this diameter is being established through very rigorous and closely integrated reactor physics and thermal analyses. Consequently, the outside diameter of the graphite spacer for each capsule may vary depending on the flux value at the vertical location of the specific capsule within the ATR core.

The outlet gas from each capsule will be routed to a separate fission product monitor with 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 be configured as described earlier in this paper utilizing an HPGe spectrometer and a sodium iodide scintillation gross gamma detector.

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