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

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1. Introduction

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. The Advanced Test Reactor (ATR), located at the US Department of Energy's Idaho National Laboratory, has long been involved in testing gas reactor fuel and materials, and has facilities and capabilities to provide the right environment for gas reactor irradiation experiments. These capabilities include both passive sealed capsule experiments, and instrumented/actively controlled experiments. The instrumented/actively controlled 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 gas temperature control system that can maintain temperature in an irradiation experiment within very tight bounds, and an on-line fission product monitoring system has been developed that is especially well suited for testing gas reactor particle fuel. The ATR's control system, which consists primarily of vertical cylinders used to rotate neutron poisons/reflectors toward or away from the reactor core, provides a constant vertical flux profile over the duration of each operating cycle. This constant axial flux profile is more desirable for experiments than the constantly moving axial flux peak resulting from a control system with vertically positioned control components that are slowly withdrawn from the core during reactor operation.

The ATR is one of the world's premiere test reactors 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 height of 1.2 m (48.0 inches). In addition, the ATR's base program for the US Department of Energy 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 to 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. This paper will discuss the ATR's capabilities for performing tests on gas reactor fuels and materials including the new Gas Test Loop currently being planned for the ATR.

2. Testing Options

As mentioned above, there are several testing options available for an experimenter in the ATR. These options include static capsule, instrumented/actively controlled experiments, and pressurized water loop testing. 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, which is also briefly discussed.

2.1. Static capsule testing

The simplest type of irradiation performed in the ATR is a static capsule experiment. The irradiation specimens (material or fuel) are typically sealed in aluminium, Zircaloy, or stainless steel tubing and surrounded with an inert gas environment. However, occasionally, the capsules may be unsealed which allows the experiment specimens to be in contact with the reactor primary coolant to prevent excessive temperatures during irradiation. The capsule tube is then 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 experiment'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 flux wires, or possibly temperature monitors 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) 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 centimetres to the full height of the ATR core (about 1.2 metres) 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 (e.g. fuels, reactive materials, etc.) and pressure of the capsule, a secondary containment may also be needed to meet ATR safety requirements.

2.2. Lead experiment testing

The next level of testing complexity provides continuous monitoring (and typically control) of experiment parameters during irradiation utilizing instrumentation leads in the capsules. These experiments are commonly referred to as ‘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, etc.) and temperature control gas lines that lead outside the reactor vessel to the data collection/monitoring equipment. Each instrumented lead experiment may contain several vertically stacked capsules, and is uniquely designed for the experiment based upon 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 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 can also be used to provide a wider temperature control band. The gases are blended automatically (based upon feedback from the thermocouples) to control the capsule temperature, and the gas blending system has a range of 2% to 98% of each gas (with the other gas making up the balance) allowing a maximum range of control. Temperature measurements are taken with at least two thermocouples per experiment capsule, and are typically 1.6-mm sheath diameter type K thermocouples with high purity magnesia insulation. Other arrangements are possible including multi-junction thermocouples within a single sheath. The type K thermocouples were selected and are typically used in pairs to assure long-term service in the high radiation environment. However, the INL is also developing special high temperature Mo-Nb thermocouples that may be used in gas reactor experiments [1]. In order to minimize temperature variations, the gas system provides a continuous flow to each capsule, and monitoring of the temperature exhaust gases is also possible (examples of several systems employed on previous temperature controlled experiments conducted in the ATR are discussed later in this paper). Alarm functions are utilized to call attention to circumstances such as parameters (e.g. temperatures, pressures, etc.) being outside of the established control band or gas bottles requiring replacement. The gas temperature control system provides automatic gas verification to assure the correct gases are connected to the supply ports in the system to prevent unplanned temperature excursions. Helium purges to cool the individual 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. Data acquisition and archiving are also included in the control system functions and all data are archived to removable media. The data are 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 a minimum of six months. Real time displays of all temperatures, gas mixtures, and alarm conditions are provided at the operator control station and at the experimenter’s monitor located in the reactor building.

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 installed in the center flux trap at the centre 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 lowered the costs of a lead experiment by reducing the requirements of the experiment to providing a minimal containment structure for the irradiation specimens and including the desired instrumentation (e.g. thermocouples, etc.). The outside diameter of the specimen containment was also used to provide the insulating gas jacket boundary for temperature control. The ITV was removed in the last core replacement of ATR in 2004, but could be re-installed if this testing capability were required. The new ATR Gas Test Loop is anticipated to replace the ITV and provide additional capability in the future.

2.3. New ATR Gas Test Loop

A new Gas Test Loop (GTL) for ATR is in the conceptual design phase, and therefore concepts to be developed in later design phases of the system are being identified. The current configuration is planned for installation in one of the large flux trap positions (e.g. NE or NW) to maximize the flux rates available to experimenters. In addition to use of a flux trap position, the concept also includes fast flux boosting by including additional fuel around the outside of the test positions. A configuration has been proposed for the additional booster fuel and development is currently being pursued.

In order to achieve the high fast flux rate goals of the GTL (by minimizing the moderation effects of the coolant system on the neutron spectrum within the GTL facility), a large forced convection gas heat transfer system is needed for cooling of the GTL facility. Helium is the coolant under consideration for this convection system and the heat rejection capacity of the high gas flow system is under development. The existing gas testing facilities at ATR utilize either no (static capsule) or very low (lead experiments – 50 cc/min) temperature control gas flows, and therefore rely mainly on conduction but may also include radiation heat transfer mechanisms. Several irradiation positions (or MIPTs) are planned within the new GTL flux trap (similar to the ITV configuration), and the current gas conduction/radiation heat transfer system is planned for use within the MIPTs for final temperature adjustment of the irradiation specimens. The Gas Test Loop is anticipated to replace the ITV and have significantly increased capabilities.

3. Specimen testing environments

Gas reactor experiments may 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.

3.1. 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 helium due to its excellent heat transfer characteristics and its 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 can be accommodated by delaying the gas until the Ar-41 decays to an acceptable level for ATR plant stack effluents. However, in lead experiment applications, the Ar-41 may preclude fission product monitoring of the experiment effluent gas. 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). These properties allow 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 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.

3.2. 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 mixture was purged over the graphite specimens during irradiation. 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.

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 an important tool for consideration in future experiment irradiations.

4. 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: 1) by positioning the experiment closer to the reactor driver fuel (to boost fast flux); 2) by absorbing unwanted (thermal) neutrons in a neutron poison (commonly referred to as a shroud); or 3) 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).

4.1. Fixed shrouds

Non-replaceable neutron shrouds are often included inside of the experiment capsules. This technique may be used for several reasons: 1) the fast to thermal neutron flux ratio may need to be manipulated throughout the irradiation period; 2) the fission rate of a fueled test needs to be reduced throughout the irradiation period; or 3) the initial fission rate in a fueled capsule must be reduced by use of a burnable poison when space for a removable shroud is not available. This method of shrouding 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 (aluminium, 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. 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.

4.1. 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 aluminium 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 quite often 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.

4.2. 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. This is the result of the minimal amount of moderating material between the A positions and the fuel (principally aluminium) 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 increase and 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 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 by including the additional fuel. This approach was utilized since the only other ATR irradiation positions large enough to accommodate the large specimens (10 mm x 60 mm x 100 mm) 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 the fast flux capability that has been missing in the United States since the closure of its fast flux facilities.

5. 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 fueled experiments, but can also be employed in other types of irradiation experiments such as material containment barrier testing.

5.1. 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 gross gamma detector to provide indication when a small puff of fission gases passes through the monitor and a spectrometer for identifying the specific fission gases. 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 establish which portions of the voluminous spectrometer data need to be closely scrutinized. This small puff of fission gases typically indicates when a cladding leak or failure may have occurred. Through identification of the specific isotopes, the birth to release ratio of the fission gases can be established. This ratio can be used to determine if a new cladding failure has occurred or if the fission products are merely being released from an existing failure or (in the case of particle fuel) tramp contamination on the outside surface of the fuel. These details can be very important in the qualification of fuel especially in small 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 spectrometer typically utilized in the 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 US Department of Energy Advanced Gas Reactor fuel qualification tests. The shift was made from ion chambers to scintillation detectors to take advantage of the increased sensitivity of the scintillation detector and allow more flexibility in the placement of the detector to the gas lines.

5.2. 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.

6. Conclusion

Over several decades of performing gas reactor experiments at ATR, a wide variety of facilities and capabilities required have been developed to perform this complex and intricate type of testing. The capabilities and facilities at ATR have been utilized to provide the right environment and conditions to simulate a wide variety of irradiation experiments in support of different gas reactor programs.

7. Acknowledgements

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8. References

[1] Rempe J. L., Knudson D. L., Condie K. G., Wilkins S. C., "Evaluation of specialized thermocouples for high temperature in-pile testing", International Congress of Advances in Nuclear Power Plants, Reno, NV, USA, June 4-8, 2006, Paper 6068