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The Advanced Test Reactor Irradiation Facilities and Capabilities

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Abstract

The Advanced Test Reactor (ATR) is one of the world's premiere test reactors for performing long term, high flux, and/or large volume irradiation test programs. The ATR is a very versatile facility with a wide variety of experimental test capabilities for providing the environment needed in an irradiation experiment. These different capabilities include passive sealed capsule experiments, instrumented and/or temperature-controlled experiments, and pressurized water loop experiment facilities. The ATR has enhanced capabilities in experiment monitoring and control systems for instrumented and/or temperature controlled experiments. The control systems utilize feedback from thermocouples in the experiment to provide a custom blended flowing inert gas mixture to control the temperature in the experiments. Monitoring systems have also been utilized on the exhaust gas lines from the experiment to monitor different parameters, such as fission gases for fuel experiments, during irradiation. ATR's unique control system provides axial flux profiles in the experiments, unperturbed by axially positioned control components, throughout each reactor operating cycle and over the duration of test programs requiring many years of irradiation. The ATR 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). Thermal and fast neutron fluxes can be adjusted radially across the core depending on the needs of individual test programs. This paper will discuss the different irradiation capabilities available and the cost/benefit issues related to each capability. Examples of different experiments will also be discussed to demonstrate the use of the capabilities and facilities at ATR for performing irradiation experiments.

1. Introduction

The Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL) is a valuable resource available for use in developing the materials and fuels necessary to support the next generation reactors and advanced fuel cycles. The ATR has a long history of irradiation testing in support of reactor development and the INL has been designated as the United States Department of Energy's lead laboratory for nuclear energy development. The ATR core is completely replaced every 7 to 10 years, with the last change having been completed in January 2005. In addition, the ATR reactor vessel is constructed of solid stainless steel and is located far enough away from the active core that neutron embrittlement of the vessel is not a concern. These two major factors, combined with a very proactive maintenance and plant equipment replacement program, have resulted in the ATR operational life being essentially unlimited. The ATR has a maximum power of 250 MW and can provide maximum thermal neutron fluxes of 1E15 neutrons/cm^2-second and maximum fast (E>1.0 MeV) neutron fluxes of 5E14 neutrons/cm^2-second. This allows considerable acceleration of accumulated neutron fluence to materials and fuels over what would be seen in a typical power reactor. These fluences combined with the 77 irradiation positions varying in diameter from 16 mm (0.625 inches) to 127 mm (5.0 inches) over an active core height of 1.2 m (48.0 inches) make ATR a very versatile and unique facility.

The ATR core cross section, shown in Figure 1, consists of 40 curved fuel elements configured in a serpentine arrangement around a 3 by 3 array of prime irradiation locations in the core termed flux traps. The flux traps derive their name from the high-intensity neutron flux that is concentrated in them due to the close proximity of the fuel and the materials used in these “traps”. The ATR’s unique horizontal rotating control drum system (termed outer shim control cylinders) provides stable axial/vertical flux profiles for experiments throughout each reactor operating cycle unperturbed by the typical vertically positioned control components. This stable axial flux profile, with the peak flux at the center of the core, allows experimenters to have specimens positioned in the core to receive different known neutron fluences during the same irradiation periods over the duration of test programs requiring several years of irradiation. This system also allows the reactor to operate different sections of the core at different power levels. The ATR core is divided into five different operating lobes: the four corner lobes and the center lobe. Each lobe of the reactor may be operated at a different power level (within specific limitations) during each reactor cycle.

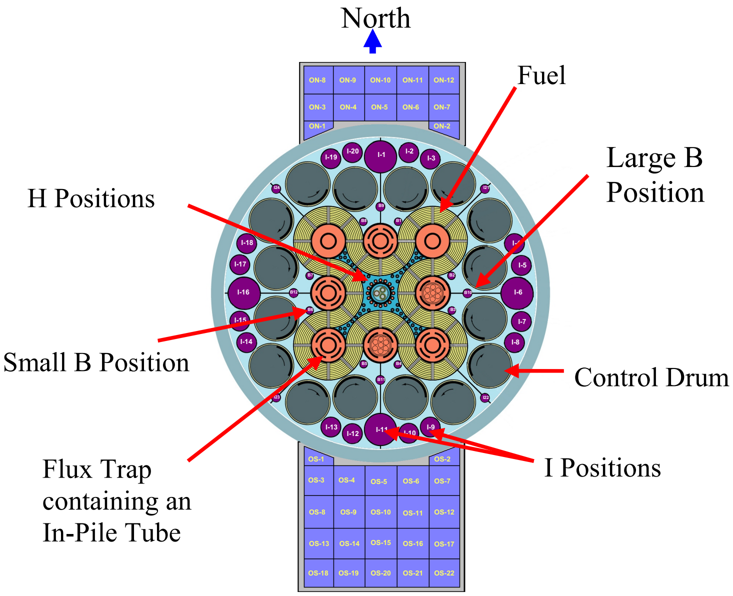

Figure 1 - ATR Core Cross Section

2. Experiment Types

Three major types of irradiation testing are employed in the ATR. The simplest and least expensive type is a static sealed capsule with only passive instrumentation. The next level of complexity in testing includes active instrumentation for measurement and/or control of specific testing parameters, typically temperature and/or pressure. The last and most complex method is the pressurized water loops that are connected to in-pile tubes located in the flux traps. Each of these irradiation types and their relative cost, schedule and operation differences are discussed in detail in the following sections.

2.1. Static Capsule Experiments

Static capsules experiments are self-contained (typically) sealed experiment encapsulations surrounding the irradiation specimens with an inert gas environment. However, occasionally the capsules are not sealed but allow the experiment specimens to be in contact with the reactor primary coolant to prevent excessive temperatures during irradiation. These capsules typically include passive instrumentation such as flux wires for neutron fluence monitoring and/or melt wires for temperature monitoring during irradiation. In addition, the temperature of a static capsule may also be controlled, within limits, by incorporating a small insulating gas jacket (filled with an inert gas) between the specimens and the outside capsule wall or pressure boundary. A suitable gas jacket width can usually be selected to provide the irradiation temperature desired by the experiment customer based upon the gamma and reaction heating characteristics of the specimens and capsule materials and proper selection of the insulating gas.

The static capsules may vary in length from several centimeters to full core height of 1.2 meters. They also may vary in diameter from 12-mm or possibly less for the small irradiation positions (or a portion of an irradiation position) to more than 120-mm for the larger irradiation positions. The capsules are typically constructed of aluminum or stainless steel, but zircaloy has also been utilized. Depending upon the contents and pressure of the capsule, a secondary containment may be included to meet the ATR safety requirements. The capsules are usually contained in an irradiation basket, which radially locates the capsules in the irradiation position and vertically positions them within the ATR core. Occasionally due to space limitations, a static capsule has been used to also serve the function of the basket, but in these cases, the capsules must fill the entire irradiation height and have a similar handling feature at the top of the capsule for installation and removal from the core.

The benefits of utilizing static capsules for irradiation testing include the ease of removal from and replacement into the reactor vessel to support specimen or capsule replacements or to avoid one of ATR’s short high power cycles. This ease of removal and replacement can also be utilized to relocate fueled capsule experiments to a higher power location to compensate for fuel burn-up. This type of testing is also less expensive than the other types of irradiation testing and due to its simplicity; it requires the least amount of time to get specimens into the reactor. However, static capsule testing has less flexibility and control of operating parameters (such as specimen temperatures) during the irradiation and greater reliance is made on the design analyses since passive instrumentation can only provide snap shot values of the operating parameters during irradiation (i.e. a melt wire can provide the maximum temperature attained during an irradiation but not the amount of time or when the maximum temperature was achieved).

2.2. Instrumented Lead Experiments

The next level of complexity in testing incorporates active instrumentation for continuous monitoring and control of certain experiment parameters during irradiation. These actively monitored and controlled experiments are commonly referred to as instrumented lead experiments, deriving their name from the active instrument leads (such as thermocouples or pressure taps) that they contain. An instrumented lead experiment containment is very similar to a static capsule, with the major difference being an umbilical tube connecting the experiment to a control system outside of the reactor vessel. The umbilical tube is used to house the instrument leads (thermocouples, pressure taps, etc.) and temperature control gas lines from the irradiation position within the reactor core to the reactor vessel wall. The instrument leads and gas lines are then routed outside the reactor vessel to the control and data collection/monitoring equipment. An instrumented lead experiment may contain several vertically stacked capsules, and is specifically designed to meet the experimenter’s needs. This is accomplished by selecting a suitable irradiation position, which will provide the necessary gamma and/or reaction heating as well as the total neutron fluence within the available schedule, and then designing the umbilical tube routing necessary to connect the experiment to the reactor vessel wall.

The most common parameter to be monitored and controlled in an instrumented lead experiment during irradiation is the specimen temperature. The temperature of each experiment capsule is independently controlled by varying the thermal conductivity of a gas mixture in a very small insulating gas jacket between the specimens and the experiment containment. This is accomplished by blending a conductor gas with an insulator gas. Helium is used as the conductor gas and neon is typically used as the insulator gas. However argon has also been used as an insulator gas (with helium as the conductor) when a larger temperature control band is needed and the activity from the by-product Ar-41 does not affect the experiment data collection (i.e. monitoring of the experiment temperature control exhaust gas for fission gases, etc.). During normal operation, the gases are blended automatically to control the specimen capsule temperature based upon feedback from the thermocouples. The computer controlled gas blending system permits a blend range of 98% of one gas to 2% of the other to maximize the temperature control range for the experiments.

Temperature measurements are typically taken with at least two thermocouples per capsule to provide assurance against an errant thermocouple and to also provide redundancy in the event of a thermocouple failure. The control system also provides automatic gas verification to assure the correct gas is connected to the supply ports in the system to prevent an uncontrollable temperature excursion resulting from a gas supply mix-up (i.e. insulator gas connected to a conductor gas port or vice versa). Monitoring of the temperature control exhaust gas is quite common to sense for different materials as a measure of the experiment performance or conditions. There are several options available for monitoring that have been employed on previous experiments conducted in the ATR. The most common monitoring has been for fission gases in fueled experiments to monitor fuel performance during irradiation. However, other monitors have also been utilized such as a gas chromatograph to monitor for chemical changes in an experiment cover gas due to oxidation of the specimens, and monitoring for supplemental gases to detect leakage through a test barrier during irradiation. Alarm functions are provided to call attention to circumstances such as temperature excursions or valve position errors. Helium purges to each individual specimen capsules are automatically actuated in the unlikely event of the ability to measure or control the temperature is lost. In order to minimize response time between a gas mixture change and a change in temperature in the experiment specimens, the gas system maintains a continuous flow to the experiment through very small internal diameter tubing. Manual control capability is provided at the gas blending panels to provide a helium purge of the experiment capsules in the event of a computer failure. Data acquisition and archive are also included as part of the control system function. Real time displays of all temperatures, gas mixtures, and alarm conditions are provided at the operator control station. All data are archived to removable media, with the data being time stamped and recorded once every ten minutes to as often as 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 benefits of performing an instrumented lead experiment are more precise monitoring and control of the experiment parameters during irradiation as well as monitoring the temperature control exhaust gas to establish specimen performance during the irradiation. However, this type of experiment has the detriments of higher total experiment costs and a longer lead time to get an experiment into the reactor than a static capsule. There are also higher costs and risks associated with removal and re-installation of an instrumented lead experiment in the reactor for specimen replacements or to avoid a short high power ATR operating cycle.

2.3. Pressurized Water Loops

Five of the ATR flux traps contain In-Pile Tubes (IPT), which are connected to pressurized water loops. The other four flux trap positions currently contain capsule irradiation facilities, and have also contained the ITV as mentioned above. An IPT is the reactor in-vessel component of a pressurized water loop, and it provides a barrier between the reactor coolant system water and the pressurized water loop coolant (see Fig. 2 below). Although the experiment is isolated from the reactor coolant system by the IPT, the test specimens within the IPT are still subjected to the high intensity neutron and gamma flux environment of the reactor. The IPT extends completely through the reactor vessel with closure plugs and seals at the reactor's top and bottom heads. This allows the top seals to be opened and each experiment to be independently inserted or removed. The experiments are suspended from the top closure plugs using a hanger rod. The hanger rod vertically positions the experiment within the reactor core and provides a pathway for test instrumentation. Anything from scaled-down reactor fuel rod bundles to core structural materials can be irradiated in these pressurized water loops. Each IPT is connected to a separate pressurized water loop, which allows material or fuel testing at different pressures, temperatures, flow rates, water chemistry, and neutron flux (dependent of the location within the ATR core) with only one reactor.

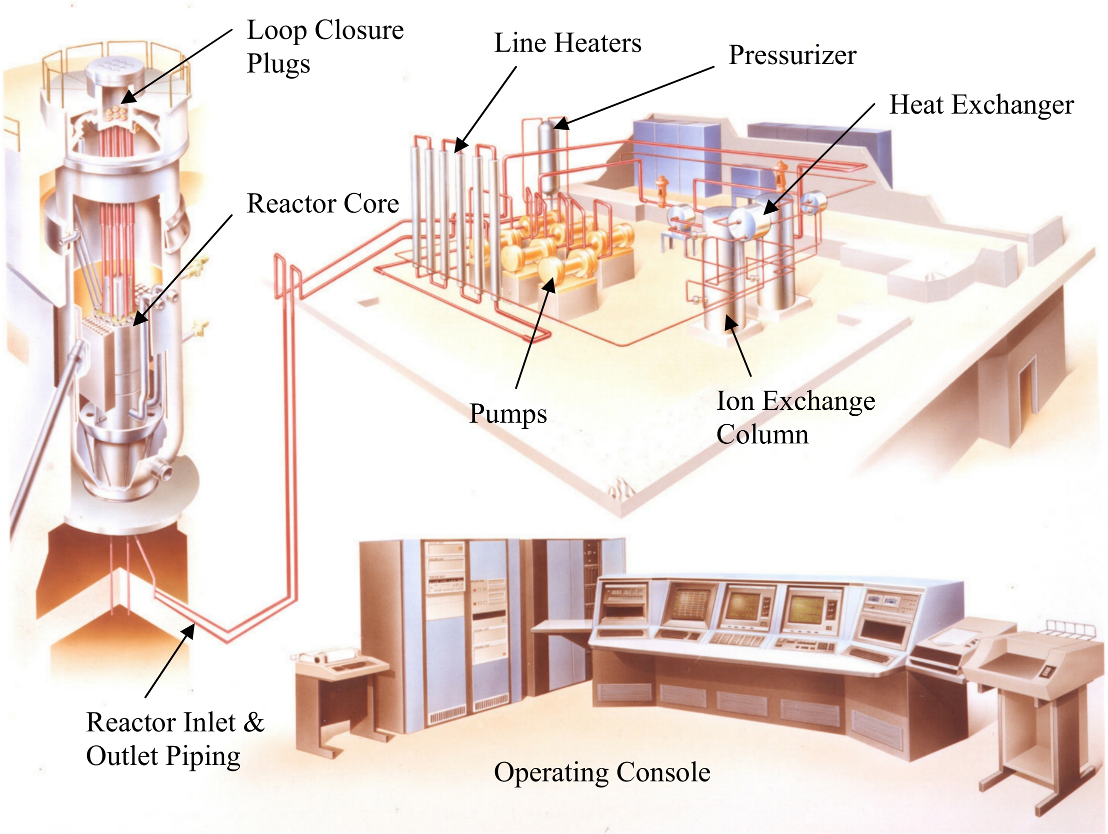

Figure 2 - Pressurized Water Loop Configuration

The loops are connected to a state-of-the-art computer control system. This system controls, monitors, and provides emergency functions and alarms for each loop. The experiment designers, though constrained by ATR's unique operating and safety requirements, are free to develop a test with specific operating conditions within the space and operating envelope created by the IPT and loop. A loop experiment can contain a variety of instrumentation including flow, temperature, fluence, pressure, differential pressure, fission product monitoring, and water chemistry. All of these parameters can be monitored by the Loop Operating Control System (LOCS) and controlled by the LOCS reactor control system, or by operator intervention. The LOCS is a state-of-the-art computer system designed specifically for the ATR loops. The system controls all aspects of loop operations (flow, pressure, and temperature) for all five loops simultaneously. This information is displayed on the Loop Operating Console and interfaces with the reactor control system. Loop Operators are stationed at the controls to operate and monitor the systems to meet the experiment sponsors requirements. Typical operations include setting, monitoring and maintaining flow rates, temperatures, pressure, and water chemistry.

There are two Powered Axial Locator Mechanism (PALM) drive units that can be connected to specially configured tests in the loop facilities so that complex transient testing can be performed. The PALM drive units move a small test section from above the reactor core region into the core region and back out again either very quickly, approximately 2 seconds, or slowly depending on test requirements. This process simulates multiple startup and shutdown cycles of test fuels and materials. Thousands of cycles can be simulated during a normal ATR operating cycle. The PALM drive units are also used to precisely position a test within the neutron flux of the reactor and change this position slightly as the reactor fuel burns.

The benefits of performing a pressurized water loop experiment are (as with the instrumented lead experiments) more precise monitoring and control of the experiment parameters during irradiation as well as monitoring the loop water chemistry to establish specimen performance during the irradiation. However, this type of experiment has the detriments of the highest total experiment costs and the longest lead time to get an experiment into the reactor.

3. Experiments

The following sections provide several examples of the different types of experiments conducted in the ATR. Unfortunately, an example of a pressurized water loop experiment was not available; however examples of a static capsule and a lead experiment are provided.

3.1 Advanced Gas Reactor Fuel Experiments

The design of the first experiment test train assembly, control gas system modifications, and fission product monitors for the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program have all been completed and the experiment was inserted in the ATR core in December 2006. [1, 2] A horizontal cross-section of one of the six capsules in the experiment test train is shown in Figure 3 and a vertical section is shown in Figure 4.

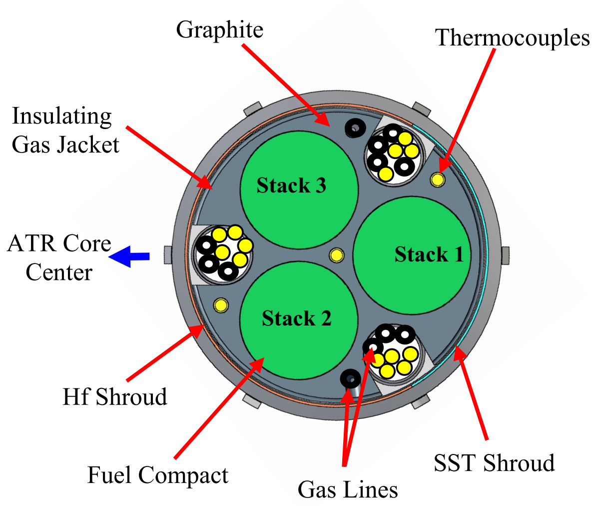

Figure 3 - AGR Capsule Cross-Section

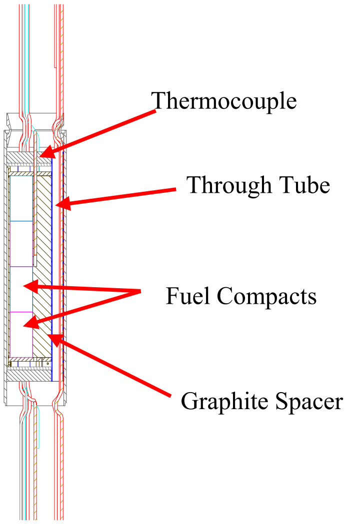

Figure 4 - AGR Capsule Vertical Section

Eight different fuel irradiations are planned for the program, with the first (AGR-1) currently being irradiated in the east large (38.1 mm diameter) B position (B-10). The test train for AGR-1 consists of six separate capsules vertically centered in the ATR core, each with its own custom blended gas supply and exhaust for independent temperature control. Each of the six capsules is 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 780 µm diameter TRISO-coated fuel particles, graphite and a binder to hold the compacts together. 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 also contains 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. In addition to the boron carbide in the graphite, a thin hafnium shroud is located around the outside of the graphite to provide additional neutron absorption and provide more control of the experiment fission rate. 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 and somewhat flattening the fission rate in the early portion of the irradiation provided better control of the temperatures in the fuel over the duration and especially at the end of the long irradiation.

The Large B positions were chosen for the AGR fuel irradiations to provide a flux rate with an acceleration factor of approximately 1.5. 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 burn-up 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 with 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 three tubes containing gas lines and thermocouples for adjacent capsules. In addition to providing a pathway for the gas lines and thermocouples from adjacent capsules, the placement of the three tubes was utilized to space the graphite at the proper distance from the capsule wall thereby providing the necessary gas jacket for temperature control. There area a total of three thermocouples in each capsule, located in the top, middle, and bottom of the graphite holder measuring temperatures in the graphite during irradiation. The thermocouples could not have direct contact the fuel since attaching or touching the fuel with thermocouples could induce fuel particle failures. Therefore, the thermocouples will measure the graphite temperature, and the corresponding fuel temperatures will be calculated. Flux wires were also installed in the capsules to measure both the thermal and fast neutron fluence.

Gaseous fission products are the most common isotopes monitored in lead experiment temperature control exhaust gases, and these experiments are no exception. The outlet gas from each capsule is routed to its individual fission product monitor with the capability to be rerouted to an online spare if any monitors experience detector or other failures. There is also the capability to take a grab sample of the effluent gas from each capsule. The fission product monitors consist of a High Purity Germanium (HPGe) spectrometer for identifying specific fission gases and a gross gamma (sodium iodide crystal scintillation) 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 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.

3.2. Advanced Fuel Cycle Initiative and Gen IV Gas Fast Reactor Irradiations

The Advanced Fuel Cycle Initiative is currently irradiating different fuel types in the East Flux Trap of the ATR, and plans to continue to irradiate fuel in the same position for at least several more years. The fuel is being irradiated in static capsule type experiments, consisting of short internal capsules (called rodlets – shown in Figure 5) containing the fuel specimens. The rodlets are filled with sodium to provide good heat transfer and temperature equalization within the capsule and fuel. An inert cover gas plenum is also included in the top of the rodlet to provide room for swelling and collection fission gas releases. Several rodlets are then loaded in an outer capsule with a precisely designed gas gap between the rodlet and the capsule wall and filled with a suitable cover gas to control the heat transfer from the rodlet to the capsule wall and therefore to the ATR primary coolant. The capsules are loaded into an open top basket that positions the capsules in the proper vertical location within the selected position within the East Flux Trap in ATR. Since the experiments are being conducted in one of the high thermal flux positions of ATR and have a maximum linear heat generation rate similar to existing power reactors, a cadmium lined basket is utilized to reduce the thermal flux and therefore reduce the fission rate in the fuel. This approach also increases the fast to thermal flux ratio to a more representative value of future fast reactors.

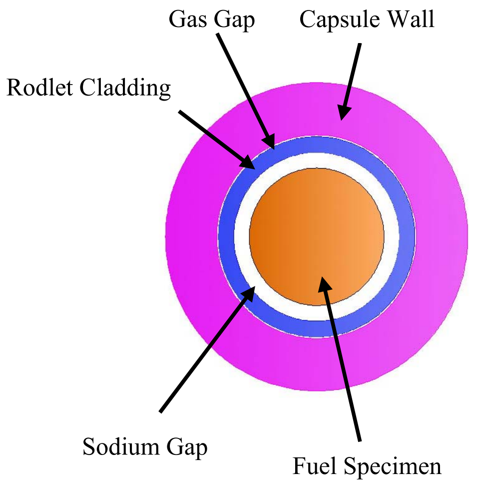

Figure 5 – AFCI Capsule Cross Section

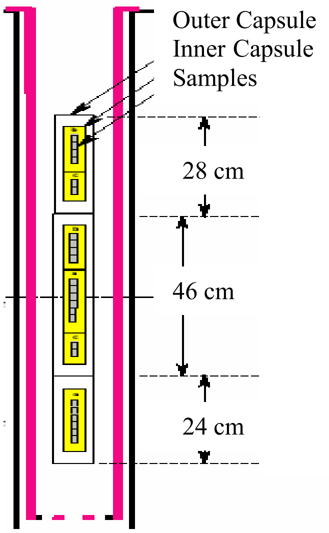

Figure 6 – GFR Basket Elevation

The Generation IV Gas Fast Reactor (GFR) program has utilized the same hardware and approach used in the AFCI irradiations to irradiate materials being considered for the GFR type reactors. The major differences between the AFCI and the GFR experiments are the heat source and heat transfer medium in the capsules. Since the GFR capsules only contain structural materials and no fuel, the main heat source in the GFR is gamma heating of the materials in contrast to the AFCI irradiations where the main heats source is the reaction heating in the fuel. Therefore, the GFR irradiations utilize a gas or gas mixture inside the rodlet instead of sodium as a heat transfer medium in order to attain the desired temperature in the specimens. The GFR irradiations share not only the experimental hardware configuration, but they are also irradiated in the ATR East Flux Trap irradiation position. Future GFR fuel irradiations are also planned for the ATR along with future AFCI irradiations.

4. Conclusion

The ATR has a long history in fuel and material irradiations, and will be fulfilling a critical role in the future fuel and material testing necessary to develop the next generation reactor systems and advanced fuel cycles. The capabilities and experience at the ATR, as well as the other test reactors throughout the world, will be vitally important for the development of these new systems to provide the world with clean safe energy supplies in the future.

Acknowledgements

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