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Capabilities and Facilities Available at the Advanced Test Reactor to Support Development of the Next Generation Reactors

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ABSTRACT: The ATR is one of the world's premiere test reactors for performing long term, high flux, and/or large volume irradiation test programs. It 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 Irradiation Test Vehicle (ITV) installed in 1999 enhanced these capabilities by providing a built in experiment monitoring and control system for instrumented and/or temperature controlled experiments. This built in control system significantly reduces the cost for an actively monitored/temperature controlled experiments by providing the thermocouple connections, temperature control system, and temperature control gas supply and exhaust systems already in place at the irradiation position. Although the ITV in-core hardware was removed from the ATR during the last core replacement completed in early 2005, it (or a similar facility) could be re-installed for an irradiation program when the need arises. The proposed Gas Test Loop currently being designed for installation in the ATR will provide additional capability for testing of not only gas reactor materials and fuels but will also include enhanced fast flux rates for testing of materials and fuels for other next generation reactors including preliminary testing for fast reactor fuels and materials. This paper discusses the different irradiation capabilities available and the cost benefit issues related to each capability.

KEYWORDS: *Advanced Test Reactor, Idaho National Laboratory, Gas Test Loop*

I. INTRODUCTION

The Advanced Test Reactor (ATR) located at the newly formed 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 new United States Department of Energy's lead laboratory for nuclear energy development.

The ATR is the third generation of test reactors built at the Reactor Technology Complex (RTC), located in the INL, to study the effects of intense neutron and gamma radiation on reactor materials and fuels. The first generation was the Materials Test Reactor which had a maximum power level of 40 MW and operated from the early 1950s until 1970. The Engineering Test Reactor was the second generation with a maximum power level of 175 MW, and it was operated from 1957 to 1981. The third (and current) generation is the ATR, which began operation in 1967, and is still in operation today. 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 250MW and can provide maximum thermal neutron fluxes of $1E15$ neutrons per square centimeter per second and maximum fast ($E > 1.0$ MeV) neutron fluxes of $5E14$ neutrons per square centimeter per 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.

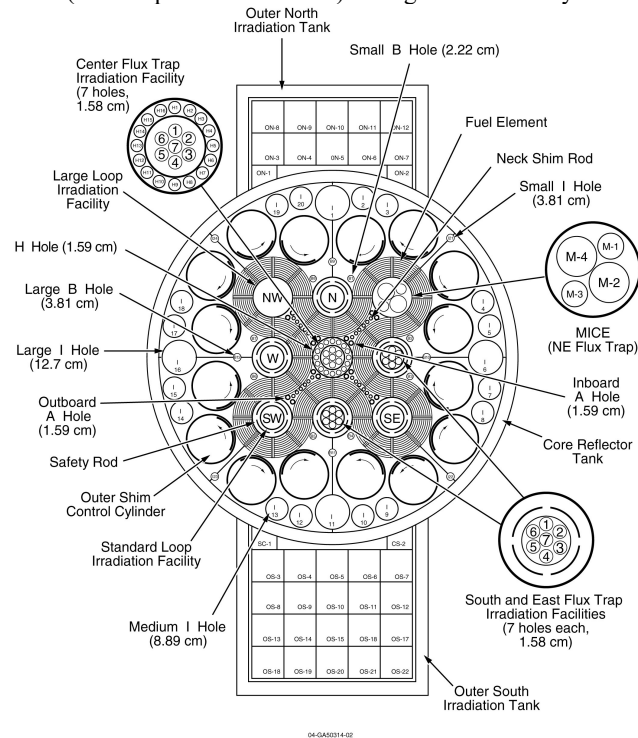


Figure 1 - ATR Core Cross Section

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.

II. STATIC CAPSULE EXPERIMENTS

Static capsules (shown in Figure 2) 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.

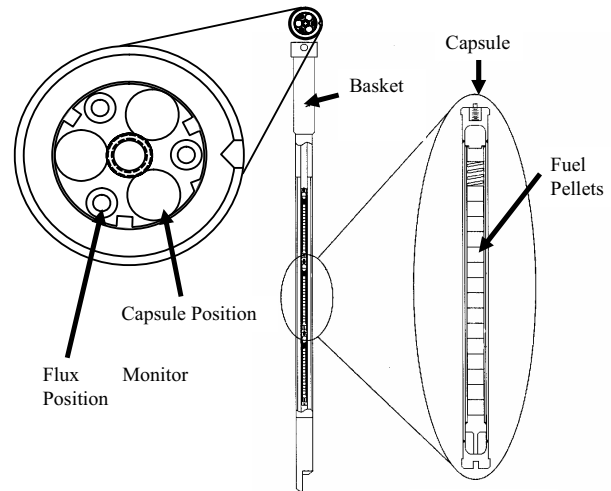


Figure 2 - Static Capsule and Basket Assembly Utilized for MOX Fuel Testing

The static capsules may vary in length from several centimeters, as shown in Figure 2 for the MOX irradiation, 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).

Static capsule testing has been utilized for experiments in both domestic programs as well as testing fuels and materials in collaboration with France and Japan for Generation IV systems and life extension of existing reactor plants.

III. 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. This level of testing can be broken into two types, the first category being a standard instrumented lead and the second being an Irradiation Test Vehicle experiment. The difference between these two types of experiments lies mainly in the method that is utilized in providing the pressure boundary between the experiment specimens and the ATR primary coolant. These two types of instrumented experiments, the difference between them, and their common method of operation are all discussed in the following sub-sections.

1. Standard Instrumented Lead Experiments

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 (see Figure 3). 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.

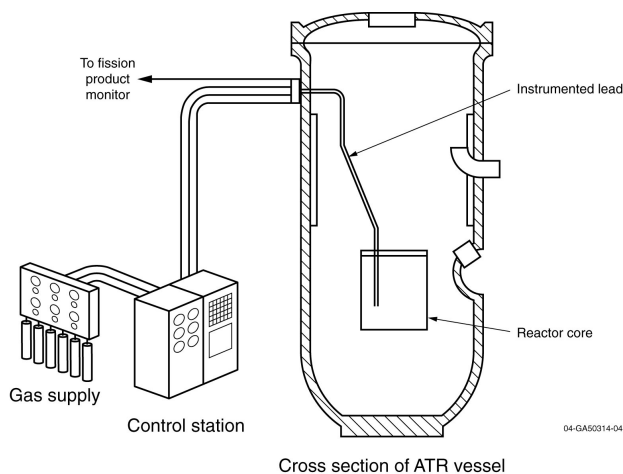


Figure 3 – Typical Instrumented Lead Experiment Configuration

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 this function 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.

Instrumented lead experiments have been conducted on various different materials and for different programs, mainly in support of various U. S. Department of Energy programs. However, there has been a significant amount of recent interest in performing lead experiments in the ATR by countries other than the U. S., including South Africa, France and Japan, for purposes ranging from life extension of existing reactor facilities to development of Generation IV or other reactors.

2. Irradiation Test Vehicle

The Irradiation Test Vehicle (ITV) utilizes the same instrument leads, gas control technique and exhaust gas monitoring as described above for a standard lead experiments. In fact the ITV is really only a sub-type of lead experiment. The concept for the ITV was to provide a permanent ATR in-core facility that included the reactor coolant pressure boundary, gas jacket, and the umbilical tube needed for instrumented lead experiments. The in-core facility was installed in the ATR center flux trap and connected to a permanent temperature control gas system to complete the ITV experiment facility in 1999. The in-core hardware was removed in the last ATR core replacement completed in January 2005, but could be re-installed or replaced with a similar facility in a different core position when the need arises. By utilizing this type of facility, an experimenter could avoid the cost of design and fabrication of the umbilical tube required to house the instrument leads and

temperature control gas lines to experiment, as well as reducing the cost of the experiment capsule since the pressure boundary between the experiment and the reactor primary coolant was already in place. Since this facility was located in the center flux trap (at the very center of the ATR core), the ITV provided new opportunities to perform temperature controlled material irradiations in high flux regions at reasonable cost to users.

The ITV in-core hardware is made up of three irradiation positions (called mini-in-pile tubes [MIPTs]) consisting of a pressure tube with an internal concentric gas channel tube. The pressure tube provides the pressure boundary between the reactor coolant and the specimen holders. The gas channel tube is machined to incorporate axial passageways (or channels) in its external surface to route gas to each vertical experiment chamber or temperature control zone. Each MIPT has a total of five temperature control zones that can each house a separate experiment capsule. Although there are five separate zones in each MIPT, an experimenter may elect to have any number of one to five capsules within an MIPT simply by combining more than one temperature control zones on a single capsule. The gas channel tube was installed into the pressure tube with an interference shrink fit to assure a seal between each gas channel. The pressure tube and the gas channel tubes were assembled as a unit and all three units were installed into the reactor surrounded by an aluminum filler sleeve to maintain the standard primary coolant flow through the center flux trap. Thermal neutron filtering materials can be included as part of the experiment assembly inside the MIPT or they can also be located in a channel outside of the aluminum filler specifically provided for this purpose. The outside filler material is replaceable during reactor outages, whereas any internal capsule filters are not. By using external filters, high neutron absorption can be retained for long durations by simply replacing filters during reactor outages as their neutron poison depletes. The ITV could provide up to 650 cc of instrumented irradiation volume in the 15 capsule positions (within the three MIPTs), each capable of being independently controlled at $\pm 5^\circ\text{C}$ of its selected temperature. The largest specimen that can be irradiated in the ITV is approximately 22-mm in diameter. Depending on the specific vertical position in the core, the temperature of each specimen capsule may be controlled up to 800°C or possibly higher depending on the internal heating and heat transfer properties of the materials used in the experiment. This facility provides a test platform that permits experimenters to subject a broad range of material specimens to varying ranges of temperatures and neutronic conditions. The ITV facility also permits changing of specimens with as little imposition on reactor operations as possible. Experiment handling takes place within the standard 7 or 14 day outages between the normal 40 to 50 day operating cycles. Temperature measurement and control is accomplished in the same manner as the lead experiments discussed in the previous section, and the temperature control gas can also be monitored by the same systems as the standard lead experiments. An experimenters monitoring station was included with the ITV control system to allow an experimenter to observe the conditions of their experiment

during initial start-up or other critical times during their experiment operation. A second gas system, completely separate from the temperature control gas system but using similar equipment, has also been installed to provide a controlled gas atmosphere surrounding the irradiation specimens within the ITV experiment capsules.

The benefits of performing an ITV experiment are identical to those of a standard lead experiment, plus the added advantage of the reduced costs of design and fabrication identified earlier. An ITV experiment also has the detriments of a standard instrumented lead experiment of higher total experiment costs and a longer lead time to get an experiment into the reactor than a static capsule. However, the costs and risks associated with removal and re-installation of an ITV experiment in the reactor to avoid a short high power ATR operating cycle are less than a standard instrumented lead experiment because of the ability of ITV experiments to utilize the center flux trap top head penetration.

The ITV has been utilized to perform an irradiation for the UK to support life extension for some of the Magnox reactor power stations. The ITV has also been of interest for irradiation of different materials for other countries including Japan. Although the ITV was removed from the ATR during the last core replacement, it or a similar facility could be re-installed for an irradiation program when the need arises.

IV. 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. 4). 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.

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.

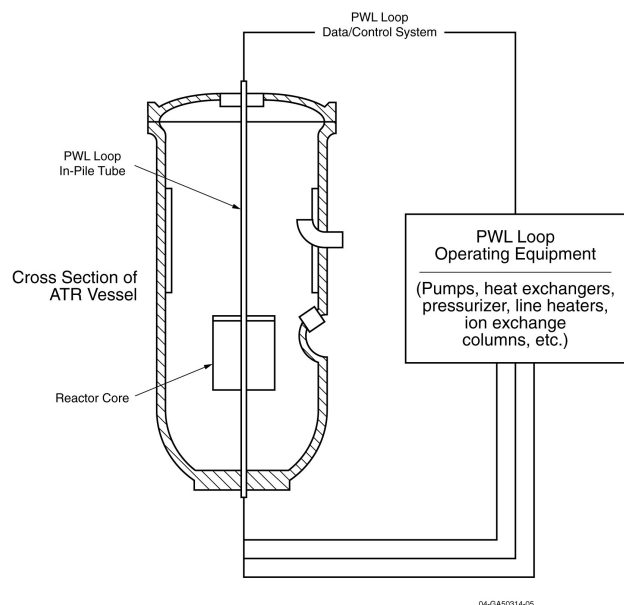


Figure 4 – Pressurized Water Loop Configuration

All test specific information from reactor power levels to test temperatures, pressures, flow rates, etc. is monitored and can be recorded. The data can be averaged daily, hourly or even every 2 to 3 seconds, and can be recorded and transferred to the test sponsors. The massive amount of information is typically averaged over longer periods of time before being permanently recorded and transferred to the sponsors. If desired, any off-normal event can be recorded on a shorter time period and the data provided.

Loop experiments are loaded into the IPT either from the ATR canal using the ATR Transfer Cask or directly from the shipping casks. These are 30-ton shielded casks specifically designed to interface with the ATR reactor top. The loop is depressurized and partially drained, the IPT closure seals are removed, and the cask is set over the IPT and the test lowered

down into the IPT. The cask is then removed, the closure seals are reinstalled, the instrumentation lines are connected and the loop refilled.

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.

Pressurized water loop experiments have historically been conducted mainly for U. S. Department of Energy programs, but could also be accomplished for other entities. In fact, there is a proposal to reactivate an existing unused water loop to support testing for other non-DOE programs. Interest in utilizing such a water loop for various different materials and fuel testing has been expressed by both U. S. and international customers, including Japan and France.

V. GAS TEST LOOP

A proposed Gas Test Loop (GTL) for ATR is in its conceptual design phase, and therefore the features are still being identified and developed. The system is currently being planned for installation in one of the large flux trap positions in ATR to maximize the flux rates and experiment size available to experimenters. In addition to use of a flux trap position, currently consideration is being given to 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, manufacturability, and increased capabilities.

The current gas testing facilities at ATR utilize either stagnant or very low control gas flows (50 cc/min) and therefore rely on conduction and/or radiation heat transfer mechanisms. However, the GTL is envisioned to utilize convection heat transfer for cooling of the irradiation positions, which would greatly expand the capability of the ATR for testing gas reactor fuels. Helium is the bulk coolant under consideration and the heat rejection capacity of the gas system is still under development.

The current concept includes three irradiation in-pile tubes similar to the one used in the ITV but slightly larger in diameter. In addition, there will be the capability to include several vertical positions in each in-pile tube similar to the ITV configuration. The individual experiment capsules will use helium/neon mixtures (or other inert gases) to provide fine temperature control for the experiment specimens within the in-pile tubes while the helium bulk coolant on the outside of the in-pile tube will provide the main heat rejection. The Gas Test Loop is anticipated to replace the ITV and have significantly increased capabilities. These features are currently being developed and will most likely be carried forward into the preliminary design phase of the project.

Interest in using the new GTL has been expressed by several countries involved in the Gen IV program, including Japan and France. This new capability at ATR for gas testing in conjunction with a higher fast neutron flux will be a definite boost to available testing options for the Gen IV community.

IV. CONCLUSIONS

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.

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