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## Advanced Gas Reactor (AGR)-5/6/7 Fuel Irradiation Experiments in the Advanced Test Reactor

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**Abstract** – *The United States Department of Energy's Very High Temperature Reactor (VHTR) Advanced Gas Reactor (AGR) Fuel Development and Qualification Program will be irradiating up to seven separate low enriched uranium (LEU) tri-isotopic (TRISO) particle fuel (in compact form) experiments in the Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL). These irradiations and fuel development are being accomplished to support development of next generation reactors in the United States. The goals of the experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing. The experiments, which each consist of at least five separate capsules, are being irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gases also have on-line fission product monitoring of the effluent from each capsule to track performance of the fuel during irradiation. The first two experiments (designated AGR-1 and AGR-2), have been completed. The third and fourth experiments have been combined into a single experiment designated AGR-3/4, which started its irradiation in December 2011 and is currently scheduled to be completed in April 2014. The design of the fuel qualification experiment, designated AGR-5/6/7, is well underway and incorporates lessons learned from the three previous experiments. Various design issues will be discussed with particular details related to selection of thermometry.*

### I. INTRODUCTION

Fuel development and irradiations are being performed to support development of the next generation high temperature gas reactors in the United States. The AGR Fuel Development and Qualification Program, which is part of the Very High Temperature Reactor (VHTR) Program, will complete the balance of the irradiation experiments over the next four to five years to demonstrate and qualify new Low Enriched Uranium (LEU) TRISO particle fuel for use in high temperature gas cooled reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product

transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing [1]. The experiments each consist of multiple separate capsules, and are irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas also has on-line fission product monitoring of its effluent to track performance of the fuel in each individual capsule during irradiation.

Originally seven separate experiments were envisioned to meet various program objectives. The first experiment (AGR-1) was designated as a capsule shakedown test and incorporated a variety coating variants. The second experiment (AGR-2) was the first to use coated particle fuel from a

commercial particle coater. It also incorporated some non-US  $\text{UO}_2$  fuel and had one high temperature capsule. The third and fourth tests were combined (AGR-3/4), and the purpose of this test is to determine establish fission product retention in graphitic materials from failed fuel. The last three tests are also being combined into a single irradiation (AGR-5/6/7). These tests serve as the formal fuel qualification irradiations (AGR-5/6) and the margin test (AGR-7). The purpose of the margin test is to demonstrate that there is a substantial margin between the highest fuel temperature in an operating VHTR and the temperature at which fuel particle failure rate becomes unacceptable.

The experiments are specifically designed for the irradiation position location and size, as well as the specific irradiation parameters (e.g., temperature, fluence, etc.). The experiments employ an umbilical tube to house and protect the instrumentation and gas lines from the individual capsules to their connections at the reactor vessel wall. The overall capsule design concept and sweep gas systems used to control the capsule temperatures and monitor for fission gas release will be common to all of the AGR fuel experiments. The experiment capsule design, which was identical for the first two experiments (AGR-1 and AGR-2), was extensively modified for the third irradiation (AGR-3/4). The test train modification was performed primarily to support the specific purpose of the third irradiation, but it was also done to accommodate the different type of irradiation position to be used, i.e., flux trap versus large B. The temperature control system for the third irradiation included an additional feature to inject the typical gas impurities anticipated in the helium coolant of a VHTR into the gas stream of one of the 12 capsules. This feature will also be available for the AGR-5/6/7 experiment.

## II. EXPERIMENT TYPE, MISSION AND IRRADIATION POSITION

The following subsections detail the experiment type, mission, design requirements and irradiation position within the ATR core selected for the AGR-5/6/7 experiment.

### *II.A. Experiment Type*

AGR-5/6/7 will be an instrumented lead type experiment with on-line active temperature control and fission product monitoring of the effluent gas. The other major type of irradiation experiment commonly performed in the ATR is a static capsule

experiment, which has only passive temperature control, and the experimental results are determined after the irradiation by examination in a hot cell. The overall concept for temperature control of the experiment capsules, the temperature control system design, and the fission product monitoring system design are all essentially identical to those used on AGR-1, AGR-2, and AGR-3/4. The experiment capsules utilize an insulating gas jacket with variable mixing of helium and neon sweep gases to control temperature of the fuel during irradiation. AGR-5/6/7 will incorporate a large number of thermocouples in an attempt to provide the best temperature measurements possible.

### *II.B. Mission*

The mission of AGR-5/6/7 is to serve as the primary fuel qualification experiment for TRISO coated fuel developed under the VHTR program. The test conditions will envelop those expected VHTR operating parameters in terms of burnup, fast fluence, and temperature. Since there are many additional details of the fuel (e.g., fuel kernel and particle size, fuel compact dimensions, enrichment levels, etc.) as well as irradiation requirements (e.g., burnup levels, temperatures, etc.), the fuel will be discussed further in a separate section.

### *II.C. Irradiation Position*

Like AGR-3/4, AGR-5/6/7 will be irradiated in the north east flux trap position in the ATR in contrast to the large B positions used to irradiate AGR-1 (B-10) and AGR-2 (B-12). These different irradiation positions are shown in Figure 1 below. The large B positions (38 mm diameter) were initially chosen for the AGR fuel irradiations since the rate of fuel burnup and fast neutron fluence accumulation in these positions would provide an acceleration factor of between one and three times that expected in the Very High Temperature Reactor (VHTR). This acceleration factor was high enough to accomplish the irradiation within a reasonable time, but yet low enough to avoid possible premature fuel particle failures similar to those experienced in past highly accelerated particle fuel tests. AGR-1 was irradiated in the east large B position (B-10) and AGR-2 was irradiated in the west large B position (B-12). The later experiments were also originally planned to be irradiated in pairs using the B-10 and B-12 irradiation positions concurrently to minimize the schedule necessary to complete the irradiations. However, it later became apparent that in order to achieve the fuel irradiations

in the time required to support the VHTR Program schedule, the irradiations would have to be somewhat accelerated. Therefore, all experiments beyond AGR-2 have been scheduled for irradiation in the much larger (133 mm) ATR north east flux trap (NEFT) position.

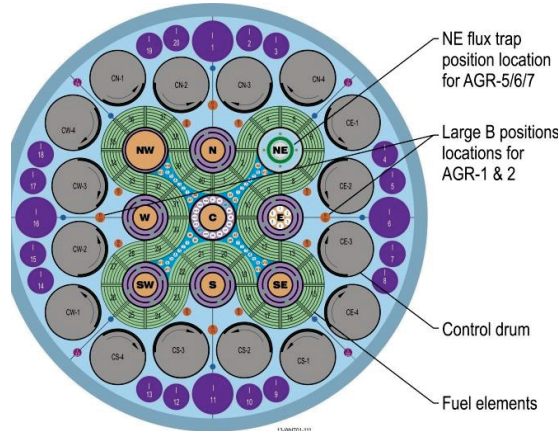


Fig. 1: ATR core cross-section showing the AGR fuel irradiation locations.

The NEFT has higher fast ( $4.4 \times 10^{14}$  versus  $2.5 \times 10^{14}$  n/cm<sup>2</sup>-s) and thermal ( $1.1 \times 10^{14}$  versus  $1.61 \times 10^{13}$  n/cm<sup>2</sup>-s) neutron fluxes that will allow the irradiations to achieve the burnup and fast fluence requirements in a shorter period of time, approximately 20 – 24 months versus 30 – 36 months in a large B positions. The increased thermal neutron flux in the NEFT provides the opportunity to accelerate the burnup rate. However, the acceleration factor between these ATR experiments and the VHTR for fuel burnup and fast neutron fluence accumulation will remain at or below three to prevent premature fuel particle failures. Since the NEFT position is almost four times the diameter of the large B positions, AGR-3/4 and AGR-5/6/7 experiments are much larger in size compared to AGR-1 and AGR-2. This much larger irradiation position also supports irradiating two experiments and even three (AGR-5/6/7) simultaneously. This combining of experiments will most effectively use the larger position to reduce the irradiation time required and therefore obtain the necessary fuel burnup and fast fluence levels as early as practical.

### III. FUEL AND IRRADIATION DETAILS

The following subsections describe the fuel used in the AGR-5/6/7 experiment as well as the irradiation requirements.

#### III.A. Fuel Details

The AGR-5/6/7 fuel is comprised of uranium oxycarbide (UCO) type LEU fuel kernels with a kernel diameter of 430  $\mu$ m and an enrichment level of 15.5%. The fuel particles are comprised of LEU fuel kernels and a 100  $\mu$ m porous buffer, which is covered with a layer of silicon carbide, sandwiched between two pyrolytic carbon layers to make up the TRISO-coated fuel particles. After being covered with the TRISO coatings, the fuel particles reach a diameter of approximately 860  $\mu$ m.

The fuel particles are over-coated with a mixture of graphite powder and thermo-set resin, and then pressed into fuel compacts that are then sintered to remove the volatile compounds in the resin. The fuel compacts are right circular cylinders with the same nominal dimensions as the AGR-1 and AGR-2 experiments, i.e., approximately 25.4 mm tall by 12.4 mm diameter. The total number of fuel particles in a compact will be approximately 3450 with a total uranium content of 1.37 grams.

#### III.B. Irradiation Details

The AGR-5/6 portion of the experiment will consist of four capsules operating at different combinations of irradiation temperature, fuel burnup, and fast fluence. The AGR-7 experiment will consist of a single capsule designed to irradiate fuel at temperatures above any expected VHTR fuel operating temperature. The temperature ranges with minimum numbers of particles in each range are shown in Table 1.

For the AGR-1 experiment, 50% of the fuel was above 1025-1100°C on a time average basis, while for typical reactor designs the value is closer to 900-950°C. While the success of the AGR-1 experiment suggested that these high temperatures may not be deleterious, it is also not representative enough for a fuel qualification irradiation. Less fuel should be at the high temperature end of the distribution and more fuel near the median and lower quartile of the distribution. Furthermore, fuel performance code calculations suggest that fuel irradiated at lower temperature has a higher probability of failure (because of less irradiation induced creep of PyC at lower temperatures). While this effect is not large, it needs to be considered in the fuel particle temperature distribution plan.



TABLE I

AGR-5/6/7 Fuel Particle Temperature Distribution

AGR-5/6	
Desired Fraction of Particles per Temperature Range	Minimum Number of Particles Based on 500,000 total
30% <900C	150,000
30% 900C - 1050C	150,000
30% 1050C - 1250C	150,000
10% 1250C - 1350C	50,000
Total	500,000
AGR-7	
Temperature Range	Minimum Number of Particles
1350C - 1500C	50,000

To increase the chances of irradiating the minimum number of particles in each temperature range, the AGR-5/6/7 experiment is being designed to accommodate 650,000 – 700,000 particles. To irradiate such a large number of particles while keeping the experiment linear heat rate manageable, it will be necessary to utilize nearly the full 1.2 meter active core height in ATR.

The burnup goals are a peak compact averaged burnup of greater than 14% Fissions per Initial Metallic Atom (FIMA) and a minimum burnup of at least 6% FIMA. The fast fluence goals are a maximum fluence of between 5.5 and 7.0 E+21 n/cm<sup>2</sup> (E>0.18 MeV) and a minimum fluence of at least 2.4 E+21 n/cm<sup>2</sup>. The burnup and fluence levels peak at the core mid-plane and drop off at the top and bottom of the active fuel zone. A certain amount of thermal flux tailoring can be done axially to increase the burnup at the top and bottom of the active fuel zone.

#### IV. CAPSULE AND CONTROL AND MONITORING SYSTEM DESIGNS

The following subsections provide details of the irradiation capsule and test train design as well as the monitoring and control systems design and function.

#### IV.A. Capsule Design

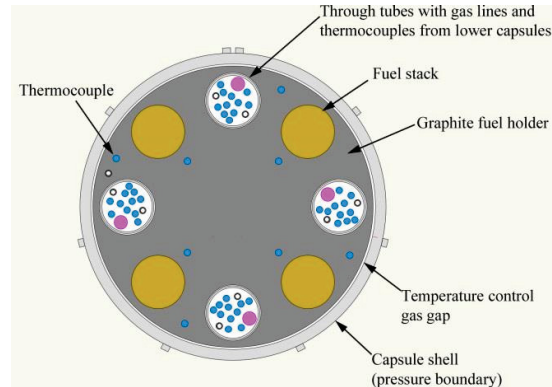


Fig. 2: AGR-5/6 capsule cross-section

A typical AGR-5/6 capsule cross section is shown in Figure 2. Four stacks of fuel, each 150 to 250 mm tall (six to ten compacts), will be placed around the periphery of the graphite fuel holder. Four through tubes, 12.7 mm diameter, are interspersed between the compacts.

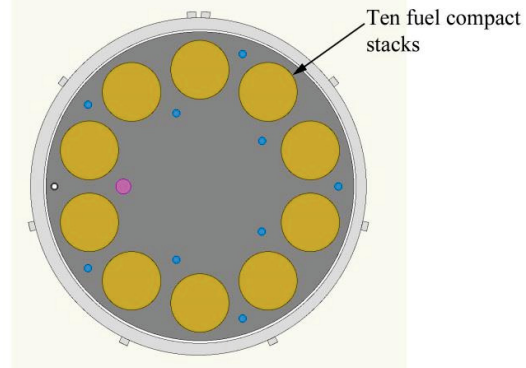


Fig. 3: AGR-5/6 bottom capsule cross-section

The design for the bottom capsule of the test train is shown in Figure 3. It is different from the capsules above it. Because it is the bottom capsule, no through tubes are required to bring thermocouples or gas lines from lower capsules. More fuel stacks are feasible for this capsule because it is near the bottom of the active fuel zone where the heat rate is lower. Also, without the thermal breaks created by the through tubes, the perimeter for heat conduction is greater.

As shown in Figure 4, the design of the AGR-7 capsule is also unique. This is the hottest capsule and will be placed near the core mid-plane. Since the through tubes must accommodate thermocouples from capsules below it, it is desirable to keep the

temperatures inside the through tubes below  $1000^{\circ}\text{C}$  and preferably below  $800^{\circ}\text{C}$ . To accomplish this, the graphite holder is made from inner and outer segments with a small gas gap, called the inner gap, between the two. This allows the inner segment of the graphite holder to run much hotter than the outer segment, and will keep the through tubes at a temperature less than  $800^{\circ}\text{C}$ .

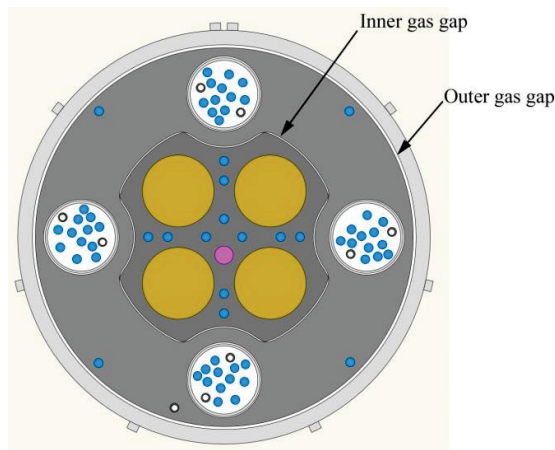


Fig. 4: AGR-7 capsule cross-section

For each of the three capsule cross sections, the outside diameter of the graphite fuel holder forms the inside boundary of the insulating gas gap that provides the primary temperature control during irradiation. The thickness of the outer gas gap varies among the capsules from approximately 0.25 mm to 0.40 mm thick depending on the neutron flux at the vertical location of the capsules within the ATR core. The thickness variation in the outer gas gap will be accomplished by varying the outside diameter of the graphite fuel holder.

The thickness of this insulating gap, also known as the temperature control gas gap, is the limiting factor for the number of fuel stacks that can be placed in a cross section. The nuclear grade graphite that will be used to make the fuel holder is subject to 0.5% to 1% or more diametral shrinkage during the irradiation period. If the initial gas gap width is too small at the beginning of irradiation, the relative growth of the gap will be so large at the end of irradiation that it will not be possible to maintain the target irradiation temperature for a given capsule.

#### IV.B. Instrumentation Considerations

As mentioned previously, the AGR-5/6 experiment will serve as the formal fuel qualification experiment for the VHTR program. As such, every

effort is being made to select temperature instrumentation that will provide the best possible performance during the irradiation period.

This selection process involves a three pronged approach. First, experience gained from the AGR-1, AGR-2, and AGR-3/4 experiments will be applied to the thermocouple selection process; second, experience from other reactor experiments at similar conditions will be applied; and third, results from out-of-pile furnace testing at INL will help guide selection.

Fig. 5 is a summary of the thermocouple failure trends during the three AGR experiments irradiated in ATR. The AGR-1 experiment saw a thermocouple failure rate of about 53% by the end of the irradiation period (approx 620 full power days). Three different thermocouple types were used in this experiment. An INL-developed doped Mo/Nb-alloy thermocouple design, designated High Temperature Irradiation Resistant-thermocouple (HTIR-TC) [2] were installed in 11 locations. Eight HTIR-TCs, 1.5 mm diameter, operated successfully at startup, and five HTIR-TCs survived the entire irradiation period. The HTIR-TC thermocouples operated within a temperature range of ( $900^{\circ}\text{C} - 1200^{\circ}\text{C}$ ).

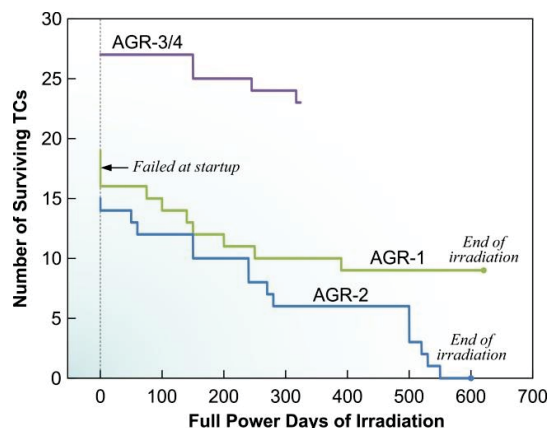


Figure 5. Thermocouple Failure Chart for AGR-1, AGR-2, and AGR-3/4.

The second thermocouple type used in AGR-1 was a standard 1.5 mm diameter, Type N, crushed MgO insulation, Inconel 600 sheath design. This design was used in five locations, and only one survived the entire irradiation period. The operating temperature range was  $750^{\circ}\text{C} - 900^{\circ}\text{C}$ .

The third thermocouple type used in AGR-1 was a 2.3 mm diameter, Type N, molybdenum sheath design with hard fired, loose-pack alumina

insulation. This design was used in three places, all in the top capsule, and all three survived the entire irradiation period. These thermocouples operated within a temperature range of 750°C – 800°C. These thermocouples exhibited very good performance, but it may have been due to the lower operating temperature, larger size, and shorter heated length; rather than an inherently superior design.

Fig. 5 also shows the overall performance of the thermocouples used in AGR-2. In this case there were a total of 15 thermocouples and by the end of irradiation (600 days) all of them had failed. For AGR-2 all of the thermocouples were of the same design, 2.0 mm diameter, Type N, crushed MgO insulation, niobium sheath. It was anticipated that the thicker thermoelements would result in better survivability than in AGR-1. However, this was not the case.

The reasons for the comparatively poor performance of the AGR-2 thermocouples are not clear. This experiment was subjected to substantial handling stress as the entire experiment test train was removed from its irradiation position and reinstalled two different times – once at about 200 days of irradiation, and a second time at about 500 days of irradiation. The failures of the last six thermocouples seem to be directly correlated to the second handling sequence. Another reason for the high failure rate may have been due to the brittle nature of the niobium sheath. Even very minute quantities of oxygen or moisture present in the sweep gas, integrated over thousands of hours, may have served to embrittle the sheaths and make the thermocouples more subject to failure when subjected to thermal expansion or handling.

The performance of the AGR-3/4 thermocouples is also illustrated in Fig. 5. After approximately 325 days of irradiation, only four of the 27 thermocouples installed in the experiment have failed. These thermocouples are all standard 1.0 mm diameter, Type N, crushed MgO, in an Inconel 600 sheath. These thermocouples have operated in a temperature range of 550°C – 1000°C with the great majority operating at 550°C – 700°C. The relatively good performance of this thermocouple set is probably due to the lower operating temperatures of most of the thermocouples.

The number of thermocouples in the previous three AGR experiments was limited by the space constraints of the through tubes. The design of the AGR-5/6/7 capsules permits much larger through

tubes. There will be room for at least 10 thermocouples per capsule. This fact alone will significantly increase the chances of retaining at least one operating thermocouple at the end of irradiation, in each capsule. Another favorable factor is that, similar to AGR-3/4, the irradiation period for AGR-5/6/7 will be on the order of 450 days vs the 600 day plus irradiation campaigns of AGR-1 and AGR-2.

Not only will there be more thermocouples per capsule in AGR-5/6/7, but every effort is being made to select the best types available, as discussed below.

During the initial design of the AGR-1 capsule (circa 2005) it was recognized that the combination of the high temperatures and high neutron flux environment would be a challenge for any commercial thermocouple design. At temperatures above 1000°C even the best base metal thermocouple type, Type N, is subject to drift and open circuit failure. At that time, several thermocouple vendors advertised versions of Type N thermocouples that were less subject to drift and survived for longer periods at high temperature. Also, at that time, the HTIR-TC thermocouples had shown some early success. A 4000 hour, 1200°C test program was commissioned [3]. The results from that effort include: the worst Type N thermocouples drifted downward as much as 100°C; the best drifted about 40°C, and the HTIR-TC thermocouples drifted only about 20°C. It was expected that several of the thermocouples would experience open circuit failure during the test, but not a single thermocouple failed completely.

As an aid to final thermocouple selection for AGR-5/6/7, a test similar to that conducted in 2005, although probably of shorter duration, is planned. The following variations on a standard Type N design are being considered for evaluation:

1. Spinel insulation ( $\text{MgAl}_2\text{O}_4$ ) rather than MgO insulation
2. Haynes 214 alloy sheath rather than Inconel 600
3. Low alloy nickel sheath developed at Cambridge University [4] rather than Inconel 600
4. Loose assembly with molybdenum sheath, similar to the design used in the AGR-1 top capsule, as described above.

Current versions of the HTIR-TC thermocouple design will also be evaluated in this test.

#### IV.C. Test Train Design

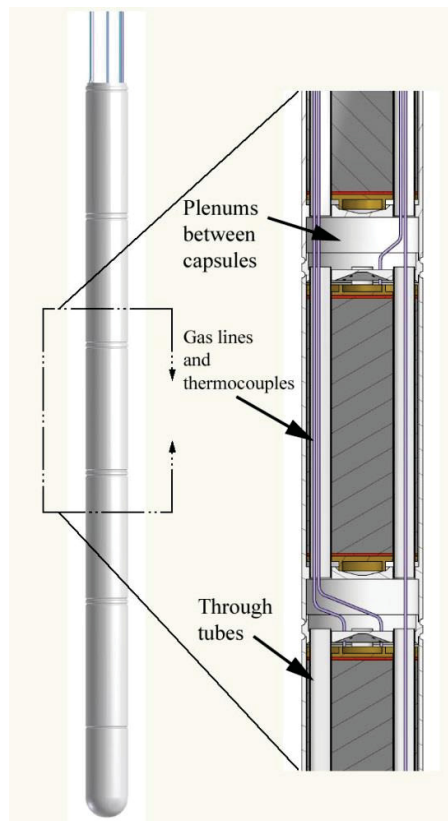


Fig. 6: AGR-5/6/7 test train vertical section

The overall design of AGR-5/6/7 experiment test train will be similar to the previous three AGR experiments. Five separate stacked capsules will be welded together to form the core section of the test train. The core section will be welded to an umbilical tube (termed a leadout at ATR) that houses and protects the gas lines and thermocouple leads. The leadout will be routed from the NEFT position straight up from the ATR core to the experiment penetration in the reactor vessel top head. Above the vessel top head, the gas lines and thermocouple leads will be connected to their facility counterparts in the temperature monitoring, control and data collection system similar to the other AGR experiments. The lead-out will also vertically locate the experiment within the NEFT in the ATR core. A

vertical section of the AGR-5/6/7 test train is shown in Figure 6.

The NEFT has a considerably larger diameter than the AGR-5/6/7 capsules. Thus, a means to center the experiment in the irradiation position is required. Also, there is a need to tailor the neutron flux spectrum to more closely approximate the neutron spectrum in a VHTR. Therefore, a flux trap irradiation housing will be designed for this experiment (see Figure 7). The irradiation housing interfaces with the ATR core structure that supports the ATR fuel elements surrounding the NEFT; hence, this housing will locate the AGR-5/6/7 test train in the center of the NEFT. The housing also helps lower the overall thermal neutron flux rate to keep fuel heating rate manageable, i.e., to allow a reasonably sized temperature control gas gap. A nice feature of the NEFT is that it is the primary irradiation position within the northeast quadrant of the ATR, and its power level is controlled by the four control drums (see Figure 1) on its north and east sides. This localized power level control provides an additional parameter for controlling heat rate and irradiation acceleration factor.

The irradiation housing consists of inner and outer stainless steel shells with a hafnium filter sandwiched between them. The outer shell has centering collars with spacer nubs on them located at the top and bottom of the housing (above and below the active core height of ATR) to provide a uniform reactor coolant water channel between it and the ATR core structure. In the same manner, there will be spacer nubs on the AGR-5/6/7 test train to ensure a uniform reactor coolant water channel between the test train and the irradiation housing. The center section of the irradiation housing located within the active core height of ATR contains a very wide water coolant channel shown in blue in Figure 7. In addition to its cooling function, the reason this channel is exceptionally wide is to moderate the neutrons coming from the ATR driver fuel and therefore reduce the fast to thermal neutron flux ratio. The hafnium filter in the housing next to the test train then helps reduce the thermal neutron flux along with the power level adjustments to maintain the low irradiation acceleration factor and manageable heat rates.



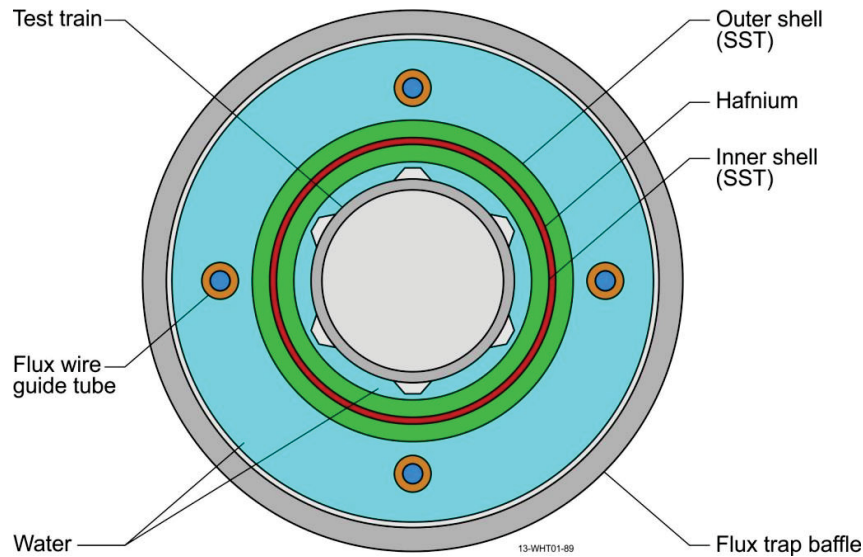


Fig. 7: AGR-5/6/7 test train inside irradiation housing

#### IV.D. Temperature Control System

Each capsule has its own custom blended gas supply and exhaust for independent temperature control and fission product monitoring. The desired temperatures in the experiment capsules are achieved by adjusting the mixture ratio of two different gases with opposing thermal conductivities to control the heat transfer across the insulating gas gap between the heat source (fuel fissions and gamma heating of capsule materials) and the capsule wall that is in direct contact with the relatively cold ATR primary coolant (52°C). Helium is used as the high (thermally) conductive gas, and neon is used as the insulating gas. Neon (versus argon that can provide a wider temperature control band) is typically used in fuel irradiations such as the AGR experiments for the insulating gas to prevent activated argon gas from overwhelming the fission product monitors. Computer controlled mass flow controllers are used to automatically blend the gases (based upon feedback from the experiment thermocouples) to control the thermocouple temperatures, which are analytically coupled to the fuel specimen temperatures.

It is expected that the AGR-5/6/7 test will have upwards of 10 thermocouples per capsule. These thermocouples will be embedded in the graphite fuel holder at locations near the fuel compacts. At the beginning of irradiation, one thermocouple will be designated for primary control of the capsule

temperature. In the event the control thermocouple fails open (as indicated by a significant increase in resistivity), temperature control for the capsule will be switched over to a designated back-up thermocouple, which will then be designated as the new control thermocouple. A more detailed description of the AGR temperature control system design and functions can be found in Reference [5].

The AGR-3/4 irradiation had a new requirement to inject the types and levels of gas impurities anticipated in a VHTR into the temperature control sweep gas of some of the experiment capsules. The purpose of this requirement is to determine the possible effects of the gas impurities on the fuel and other capsule materials. The system was designed to utilize a helium carrier gas supply containing carbon monoxide, hydrogen and moisture impurities that could be injected into the temperature control gas of the selected capsules downstream of the neon and helium mixing tee. The carrier gas and impurity concentrations are mixed to provide the desired levels of 10 ppmv H<sub>2</sub>O, 50 ppmv CO, and 50 ppmv H<sub>2</sub> in the total 30 sccm temperature control gas supply to the affected capsule. The impurity injection system is anticipated to be utilized for one or more capsules in AGR-5/6/7 as well.

#### IV.D. Fission Product Monitoring System

In order to minimize temperature changes and maintain the temperature as constant as possible, the

temperature control gas system provides a continuous flow to each specimen capsule. Monitoring this continuous gas flow for fission gases provides valuable information on the fuel performance during irradiation. As shown in figure 8, the outlet gas from each capsule is routed to its individual fission product monitor, and the gas flows can be rerouted to an online spare monitor if any of the primary monitors experience detector or other failures.

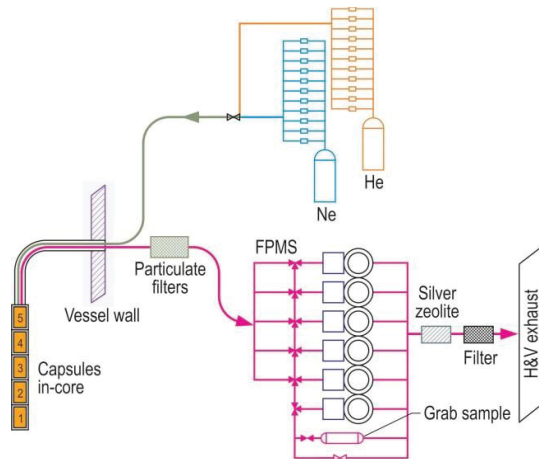


Fig. 8: AGR-5/6/7 experiment gas flow path

The fission product monitors consist of a high purity germanium spectrometer for identifying and quantifying the fission gas nuclides and a sodium iodide liquid scintillation gross gamma detector to provide indication when a puff release of fission gases passes through the monitor. The gross gamma detector also provides the release timing. 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 determine which portions of the voluminous spectrometer data need to be closely scrutinized. A puff release of fission gases typically indicates when a TRISO fuel coating failure may have occurred. Through identification and quantification (with uncertainties) of the isotopes, the spectrometer can be used to determine the isotopic release-to-birth ratio (with uncertainties) of the fission gases being detected. The determination of the release-to-birth ratios 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 uranium contamination on the outside surface of the fuel particles. These details can be very important in the testing of small TRISO particle fuels, where the particle failures need to be tallied very accurately to

support statistical qualification of the fuel or development of improved fuel performance and fission product transport models to support source term analysis for a VHTR. The fission product monitoring system was designed and response modeled to detect and quantify each individual fuel particle failure up to and including a very unlikely 250th fuel particle failure. A more comprehensive description of the AGR fission product monitoring system design and functions can be found in Reference [6].

## V. PROJECTED SCHEDULE AND STATUS

The AGR-3/4 irradiation experiment is scheduled to be completed in July 2014.

The AGR-5/6/7 irradiation experiment is currently in the conceptual design phase. Experiment assembly is expected to begin in June of 2015. Irradiation is scheduled to begin in January of 2016 and complete in February of 2018.

## VI. CONCLUSIONS

The insights and lessons learned from AGR-1, AGR-2, and AGR-3/4 have been incorporated into the conceptual design of AGR-5/6/7. The AGR-5/6/7 experiment will be heavily instrumented and is expected to provide data necessary to qualify the VHTR TRISO fuel design.

## VII. ACKNOWLEDGMENTS

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## VIII. REFERENCES

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