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Preliminary Results of the Combined Third and Fourth Very High Temperature Gas-Cooled Reactor Irradiation in the Advanced Test Reactor

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Abstract – *The United States Department of Energy's Very High Temperature Reactor Technology Development Office (VHTR-TDO) Advanced Gas Reactor (AGR) Fuel Development and Qualification Program is irradiating up to seven 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 the next generation high temperature gas-cooled reactors in the United States. The experiments will be irradiated over the next several years to demonstrate and qualify new TRISO coated particle fuel for use in high temperature gas reactors. 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 will each consist of several independent capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation.*

The first experiment (designated AGR-1) started irradiation in December 2006 and was completed in November 2009. The second experiment (AGR-2) started irradiation in June 2010 and completed in October 2013. The third and fourth experiments were combined into a single experiment designated (AGR-3/4), which started its irradiation in December 2011 and completed in April 2014. Since the purpose of this combined experiment was to provide data on fission product migration and retention in a high temperature gas-cooled reactor (HTGR), the design of this experiment was significantly different from the first two experiments, though the control and monitoring systems are extremely similar. The design of the experiment will be discussed followed by its progress and status to date.

I. INTRODUCTION

The fuel development and irradiations are being performed to support development of the next generation reactors in the United States. The AGR Fuel Development and Qualification Program will complete the irradiation of the experiments over the next four to five years to demonstrate and qualify new 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 will each consist of multiple separate capsules, and will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation.

The experiments are specially designed for the exact irradiation position (e.g. 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 the monitoring, control and data collection system connections at the reactor vessel wall. The overall 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. However, the experiment capsule design, which was identical for the first two experiments (AGR-1 and AGR-2), was extensively modified for the third irradiation, which is a combination of the third and fourth experiments (designated 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 (e.g. flux trap versus large B) to be used. The temperature control system for the third irradiation also included an additional feature to inject the typical gas impurities anticipated in the coolant gas of the HTGR into the gas stream of selected experiment capsules. The mission, capsule design and support systems for the AGR-3/4 experiment will be discussed followed by the status and the irradiation results to date. Due to the large number of acronyms used, a list of the acronyms and their definitions has been included at the end of this paper.

II. EXPERIMENT DESCRIPTION AND MISSION

AGR-3/4 was an instrumented lead type experiment with on-line active temperature control and fission product monitoring of the effluent gas. The other major types of irradiation experiments commonly performed in the ATR are pressurized water loop experiments and static capsule experiments. The pressurized water loop experiments also have active monitoring and control systems, but the static capsule experiment have only passive monitoring and control so 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 and AGR-2. 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. New gas temperature control and fission product monitoring systems were installed for AGR-3/4 since the existing systems were being used to irradiate AGR-2 in parallel with the AGR-3/4 irradiation. The new systems are essentially duplicates of the previous systems. Since AGR-3/4 was a combination of the third and fourth experiments, the new system required twice as many temperature control channels and fission product monitors as the previous systems used for the irradiation of AGR-1 and AGR-2.

The primary mission for AGR-3/4 is to determine the retention behavior of metallic fission products in the fuel compact matrix material (used to form the fuel particles into fuel compacts) and the graphite materials planned for use in a prismatic HTGR. To complete this mission, design-to-fail (DTF) particles were included in the AGR-3/4 fuel. The DTF fuel particles provide the fission product source necessary to measure the retention behavior of the fuel compact matrix material as well as the nuclear grade graphite core components in a HTGR. This irradiation will also provide: a) fuel performance data on fission gas release from failed fuel particles; and b) irradiated fuel specimens for safety testing and PIE. In this role, the AGR-3/4 irradiation will provide valuable data for the development of improved fuel performance and fission product transport models to support source term analysis for a HTGR.

AGR-3/4 was 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.

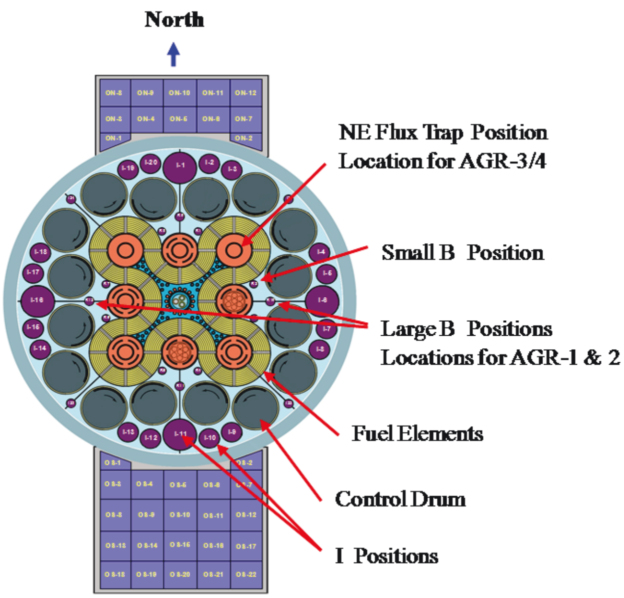

Fig. 1: ATR core cross-section showing the AGR fuel irradiation locations.

The next six AGR experiments (AGR-3 through AGR-8) have tentatively been scheduled for irradiation in the much larger (133mm) ATR north east flux trap (NEFT) position.

The NEFT has higher fast (4.4 x 10^{14} versus 2.5 x 10^{14} n/cm^2-s) and thermal (1.1 x 10^{14} versus 1.61 x 10^{13} n/cm^2-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 position. The increased fast to thermal neutron flux ratio in the NEFT also required tailoring of the neutron flux spectrum to prevent exceeding the maximum fast fluence limit before the fuel burnup goals were achieved. However, the acceleration factor between these ATR experiments and the HTGR 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 the other later experiments will be much larger in size and different in shape compared to AGR-1 and AGR-2. This much larger diameter irradiation position also supports irradiating two experiments simultaneously (as previously planned) by doubling them up into irradiations with essentially twice as many capsules and/or twice as many fuel stacks in each capsule. The doubling process 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. The schedule advantage of using the NEFT position is demonstrated in the irradiation schedules for AGR-2 versus AGR-3/4. The irradiation of AGR-2 was started in June 2010, and the irradiation of AGR-3/4 was started approximately 18 months later in December 2011. However, the irradiation of these two experiments completed in October 2013 for AGR-2 and only six months later for AGR-3/4 in April 2014.

III. FUEL TYPES AND DETAILS

The AGR-3/4 fuel is comprised of two different types of fuel particles [2]. The majority of the fuel particles being used to create the fuel compacts will provide the irradiation temperatures and conditions for the experiment. These particles are typically called ‘driver’ particles, since they serve similar functions to the driver fuel elements used in the core of a test reactor. The driver particles were made from uranium oxycarbide (UCO) type LEU fuel kernels originally fabricated for AGR-1 with an enrichment level of 19.7%. The individual fuel particles are comprised of fuel kernels, which are covered with a layer of silicon carbide, sandwiched between two pyrolytic carbon layers to make up the TRISO-coated fuel particles. The fuel particles are over-coated with a mixture of graphite powder and thermo-set resin, and pressed into fuel compacts that are then sintered to remove the volatile compounds in the resin. After being covered with the TRISO coatings, the 350 µm nominal diameter fuel kernels result in approximate 820 µm nominal diameter fuel particles.

The second type of fuel particles in the AGR-3/4 fuel compacts are the DTF particles mentioned earlier. The DTF particles were made using UCO type LEU fuel kernels from the same batch used for the driver particles. However, the DTF particles only contain a thin carbon buffer layer and a single highly anisotropic pyrolytic carbon layer resulting in an approximate overall particle diameter of 425 µm. Since the DTF particles do not contain a silicon carbide layer or the second pyrolytic carbon layer, these particles were anticipated to fail the single pyrolytic carbon layer and release fission products to the fuel compact and graphitic materials in the experiment capsule early in the irradiation. The puff of released fission gases was detected by the gross gamma detectors in the fission product monitors indicating when the particle failures occurred, and subsequent PIE analysis of the capsule contents will provide the fission product retention data desired from the experiment.

The height of the AGR-3/4 fuel compacts was reduced to increase the number of fuel compacts available for the planned PIE tests and measurements and to minimize the neutron fluence gradients within each compact. The nominal height of 25 mm used in the previous AGR-1 and AGR-2 experiments was decreased to 12.5 mm. However, the diameter of the AGR-3/4 fuel compacts was maintained at the same nominal 12.4 mm value used in the earlier experiments. Since the compact height was reduced, the number of fuel particles in each compact was also reduced from the approximate 4,150 fuel particles in AGR-1 to approximately 1,910 fuel particles total, including 20 DTF particles. The mean total uranium content of in an AGR-3/4 fuel compact from both driver and DTF particles is approximately 0.45 grams.

IV. IRRADIATION REQUIREMENTS

The twelve capsules in AGR-3/4 experiment will provide data in different combinations of irradiation temperature, fuel burnup, and material types/configurations. Six of the capsules were selected to be controlled based on time average peak fuel temperatures with one capsule at < 900°C, one capsule at < 1000°C, one capsule at < 1150°C, two capsules at < 1250°C, and one capsule at < 1400°C. The other six capsules were controlled based on time average peak graphite material temperatures ranging from 750°C to 1050°C. Controlling fuel temperatures alone would result in significant temperature variations over the life of the irradiation in the surrounding materials. Therefore, utilizing a temperature control strategy in both fuel and surrounding materials provided data under both conditions to help separate the effects of fuel versus material temperatures on fission product migration.

AGR-3/4 utilized the full 1.2 meter active core height in ATR to provide the desired broad range of fuel burn-up and temperature combinations. The initial fuel compact burnup goals were a minimum of 6% Fissions per Initial Metal Atom (FIMA) and a maximum of less than 19% FIMA. The as-run calculated burnup ranges from 4.78% FIMA for the compact furthest from core center and experiencing the lowest neutron flux to 15.3% FIMA burnup for the compacts at the peak neutron flux at the mid-plane of the ATR core. The as-run calculated results have been evaluated against the initial goals and have been found to satisfy programmatic requirements.

V. EXPERIMENT CAPSULE DESIGN

The overall concept for the AGR experiment capsules is very similar for all of the irradiations. However, the design of the experiment capsules, which was essentially identical for the first two irradiations (AGR-1 and AGR-2), was significantly modified for AGR-3/4. The change was needed primarily to support the different mission and purpose of AGR-3/4 as well as to accommodate the new type of irradiation position that will be utilized. As indicated earlier, the AGR-3/4 irradiation was performed in the much larger NEFT irradiation position in the ATR to reduce the overall irradiation schedule of the AGR experiments. A horizontal cross-section of the AGR-3/4 experiment capsule is shown in Figure 2 below.

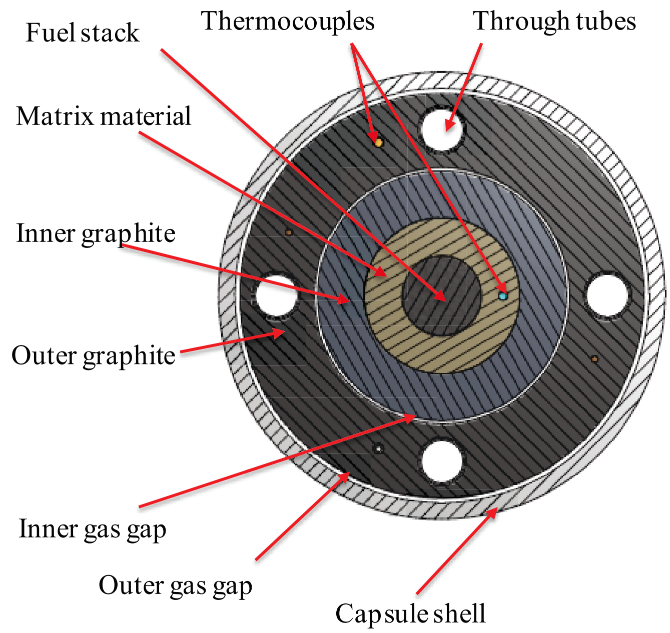

Fig. 2: AGR-3/4 capsule cross-section

Each AGR-3/4 capsule contains four right circular cylindrical fuel compacts nominally 12.4 mm in diameter and 12.5 mm long. The fuel compacts are arranged in a single stack in the center of the capsule, surrounded by a solid ring of fuel matrix material. The next ring is made of one of two nuclear grade graphites being considered for use in a prismatic HTGR core. An inner insulating gas gap separates the inner graphite from an outer ring of the same nuclear grade graphite, which operated at relatively cool temperatures from approximately 550°C to 750°C to collect any fission products that migrate completely through the matrix material and inner graphite rings. The outside diameter of the outer graphite forms the inside boundary of the outer insulating gas gap and provided the primary temperature control during irradiation. Both the inner and outer graphite components have spacer nubs machined on their outside diameters to space them and to form the applicable gas gap for temperature control. The thickness of the outer gas gap varies among the capsules from approximately 0.25 mm to slightly over 2.0 mm depending on the neutron flux at the vertical location of the capsules within the ATR core. The thickness variation in the outer gas gap was accomplished by varying the outside diameter of the outer graphite.

As in the other AGR experiments, no metal could touch the fuel particles so the thermocouples had to be placed within one of the graphite or matrix material rings within the experiment capsules. Thermocouple selection and placement was ultimately based on four criteria. First, the temperatures in the outer graphite are relatively low, which would significantly increase the longevity of the thermocouples and allow use of smaller (1 mm) diameter (type N) thermocouples. Second, if the smaller size thermocouples were used there was enough room within the through tubes to accommodate nominally two thermocouples in addition to the inlet and outlet gas lines for each capsule. Third, the smaller size thermocouples are much more flexible, which was very beneficial in making the relatively tight bends within the very limited space of the gas plenums between capsules. The final and fourth reason was the smaller thermocouples provided enough room for three capsules (nominally designed for fuel centerline temperatures of 900°C, 1150°C and 1250°C) to have a third thermocouple located in the matrix material next to the fuel compacts. These additional thermocouples in the matrix layer provided measured temperature data inside of the inner gas gap. The temperature data from these three thermocouples has been used to more accurately reconcile the thermal analysis model and improve the accuracy of the model predictions for the fuel, matrix material and inner graphite temperatures for the other capsules.

The through tubes (pathways for thermocouples and gas lines from the lower capsules to pass through the upper capsules) were positioned in the middle of the outer graphite to minimize their effect on the sorption of the fission products. Melt wires were included in each capsule for passive temperature verification in the relatively unlikely event that all thermocouples within a capsule were to fail during irradiation. Flux wires were also installed in the graphite to measure both the thermal and fast neutron fluence.

VI. TEST TRAIN DESIGN

The AGR-3/4 experiment test train was very similar to AGR-1 and AGR-2, and included twelve separate stacked capsules welded together to form the core section of the test train. The core section was welded to an umbilical tube (termed a leadout at ATR) that houses and protects the gas lines and thermocouple leads. The leadout was 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 were connected to their facility counterparts in the temperature monitoring, control and data collection systems similar to the other AGR experiments. The lead-out also vertically located the experiment within the NEFT (shown in Figure 1) in the ATR core. A vertical section of the AGR-3/4 test train is shown in Figure 3 below.

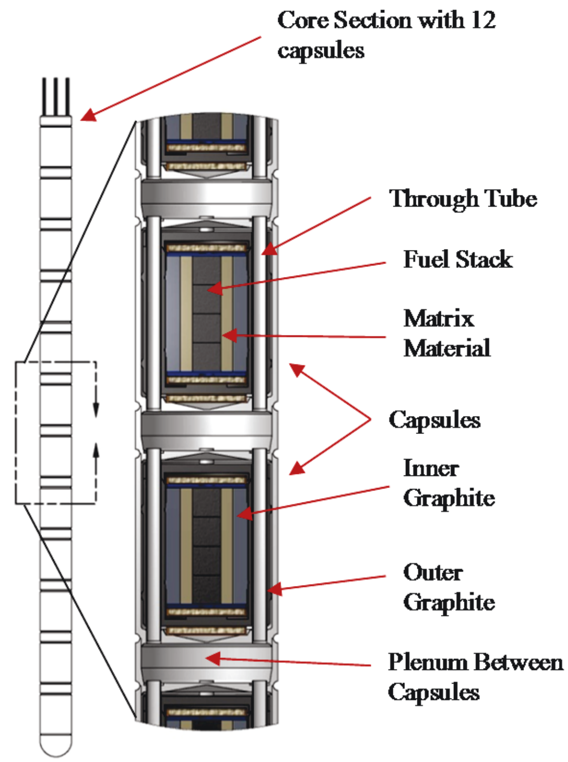

Fig. 3: AGR-3/4 test train vertical section

The original AGR-3 and AGR-4 experiments were both necessary to obtain data at the different combinations of irradiation conditions necessary to support development of the fission product transport models. Therefore, the desired number of capsules for this irradiation was twice the nominal six capsules originally envisioned for each irradiation. Doubling the number of capsules required use of the full 1.2 meter ATR active core height (versus 0.9 meters used in AGR-1 and AGR-2). In addition, the overall capsule height (with gas plenums between capsules) was reduced from 150 mm in AGR-1 and AGR-2 to approximately 110 mm. Capsules towards the top and bottom of the core (as well as the fuel compacts within these capsules) in this arrangement had increased vertical neutron flux gradients, which was also a major factor in the decision to reduce the height of the fuel compacts for AGR-3/4.

To maximize the irradiation space available and meet the fluence and burnup requirements, a new flux trap irradiation housing was designed for this specific experiment and is shown in Figure 4. The irradiation housing interfaced with the ATR core structure that supports the ATR fuel elements surrounding the NEFT, and the housing also located the AGR-3/4 test train in the center of the NEFT. The neutron flux was moderated to reduce the fast to thermal neutron flux ratio to prevent excessive fast neutron damage while achieving the desired fuel burnup. The housing also helped lower the overall thermal neutron flux rate to keep the irradiation acceleration factor to less than three and prevent possible premature fuel particle failures. Furthermore the NEFT 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. The irradiation program utilizing the NEFT has the ability to determine the power level (within specified limits) in the northeast quadrant, which was a very key parameter in limiting the irradiation acceleration factor. Controlling the power level was also crucial in maintaining a relative flat heat generation rate within the AGR-3/4 fuel compacts to achieve the constant desired irradiation temperatures in the experiment.

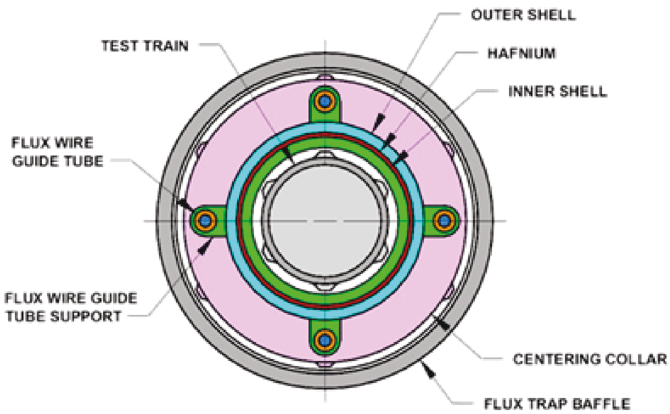

Fig. 4: AGR-3/4 irradiation housing cross-section

The irradiation housing consisted of inner and outer stainless steel shells with a hafnium filter sandwiched between them. The outer shell had 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 channel between it and the ATR core structure. In the same manner, spacer nubs on the AGR-3/4 test train ensured a uniform reactor coolant channel between the test train and the irradiation housing. The center section of the irradiation housing located within the active core height of ATR contained a very wide coolant channel located vertically between the centering collars that are shown in pink in Figure 4. In addition to its cooling function, the reason this water coolant channel was exceptionally wide was 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 helped reduce the thermal neutron flux along with the power level adjustments to maintain the low irradiation acceleration factor. It should be noted that a consumable neutron poison (e.g. boron carbide used in AGR-1 and AGR-2) could not be used in the graphite in this irradiation since it might affect the fission product retention behavior of the graphite. The design of the irradiation housing required a very close coordinated effort between its design, the test train design, and the reactor physics and thermal analyses. Meeting the neutron flux requirements was one of the biggest challenges in the design of the AGR-3/4 experiment. Of course there were many other design challenges in providing the relatively large number of capsules with widely different irradiation temperatures combined within a single test train.

VII. CONTROL AND MONITORING SYSTEMS

Since most of the AGR-3/4 irradiation was concurrent with the AGR-2 irradiation, a second temperature control system was needed. The new system has fourteen temperature control channels (one for each capsule, one for the leadout, and an installed spare). The new system is essentially a duplicate version of the original AGR-1 system, and is shown in Figure 5.

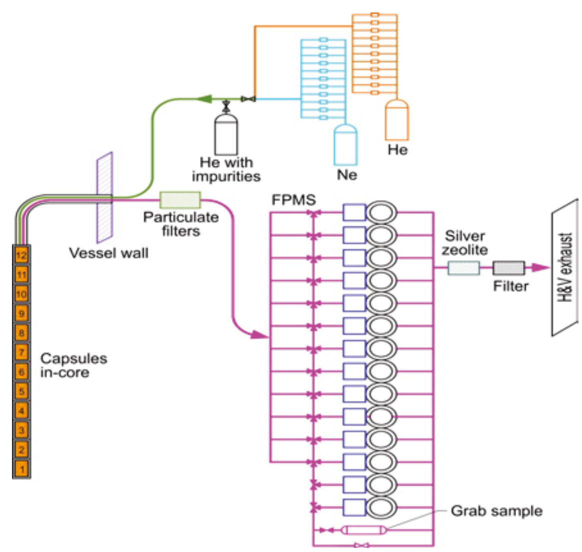

Fig. 5: AGR experiment gas flow path

Each AGR-3/4 capsule had its own custom blended gas supply and exhaust for independent temperature control and fission product monitoring. The desired temperatures in the experiment capsules were achieved by adjusting the mixture ratio of two different gases with opposing thermal conductivities to control the heat transfer across the two insulating gas gaps 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 (52ºC). 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. For AGR-3/4, two thermocouples were located in the outer graphite (shown in Figure 2) inside each experiment capsule, and one thermocouple was designated for primary control of the capsule temperature. In the event the control thermocouple failed open, temperature control for the capsules was switched over to the designated back-up thermocouple, which then became the new control thermocouple. As indicated earlier, a third thermocouple was included in three select capsules to help reconcile the thermal analysis model by providing temperature data across the inner gas gap in the capsules. A more detailed description of the AGR temperature control system design and functions can be found in Reference [3].

An additional requirement imposed on the AGR-3/4 gas system was to incorporate the capability of injecting the anticipated types and levels of gas impurities anticipated in the HTGR into the temperature control sweep gas of up to six experiment capsules. The purpose of this requirement is to determine the possible effects of the gas impurities on the fuel and other capsule materials. In practice these impurities were injected into only one AGR-3/4 capsule's gas supply. The results from this capsule will be compared to other capsules operating at similar temperatures without the gas impurities. 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 flow rate of the impurity injection system is a very low percentage of the temperature control gas (e.g. 0.5 sccm of 30 sccm) to minimize the effect of the additional helium and impurities on the temperature control of the capsules. The carrier gas and impurity concentrations are mixed to provide the desired levels of 10 ppmv H_2O, 50 ppmv CO, and 50 ppmv H_2 in the total 30 sccm temperature control gas supply to the affected capsules. The capability to obtain weekly grab samples upstream of the experiment capsules was provided to verify the correct impurity levels are being supplied to the capsules. In addition, the capability to take grab samples downstream of the capsules, which has been included on all AGR experiment capsules, can be used to measure the change in impurities in the exhaust gas from the capsules. The impurity injection system is anticipated to also be utilized on the later AGR irradiations including AGR-5/6/7.

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 indicated earlier, the AGR-3/4 test train contained twelve experiment capsules controlled by the twelve new temperature control channels discussed earlier. Therefore the new fission product monitoring system installed for AGR-3/4 contains twelve primary monitors plus two spare monitors. As shown in Figure 5, the outlet gas from each capsule was 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. The new monitors are duplicates of the original monitors that have performed exceptionally well on the AGR-1 and AGR-2 experiments. The new system has two on-line spare monitors so the ratio of spare monitors to prime monitors is the same as the previous systems (e.g. one spare for each six prime monitors). The new system also has the capability of re-routing the effluent of any capsule to either spare monitor to maximize the flexibility of the system.

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 DTF particle 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 relatively small TRISO particle fuel lots, 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 HGTR. 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 [3].

VIII. EXPERIMENT SCHEDULE, IRRADIATION, AND RESULTS

The final design of the test train and new temperature control, impurity injection and fission product monitoring systems was performed in early February 2011. Fabrication, assembly and testing of the test train and the control and monitoring systems installations were completed in November 2011. Insertion of the experiment into the ATR core was performed in early December and irradiation was initiated in mid December 2011. As previously stated, the irradiation completed in April 2014.

In order to prevent excessive stresses resulting from the very high temperature gradients experienced in the AGR irradiation capsule materials, the capsule design includes a very tight tolerance slip fit between the through tubes and the capsule bottom heads. This slip fit introduces a possible leakage path between capsules. However, leakage between capsules (e.g. cross-talk) is prevented by an inert gas overpressure in the leadout portion of the test train that ultimately flows into the plenums between capsules. The gas overpressure or flow rate into the leadout then results in gas leaking from the plenums into all of the capsules [3]. The in leakage of the gas from the plenums prevents gas out leakage from the capsules to the plenums that could result in capsule cross-talk. The gas supplied to the leadout can be either helium or neon, depending on the stage of the irradiation, since it will slightly down blend the temperature control gas mixture. In order to minimize the down blending effect of the leadout gas in leakage, the minimum flow rate required to prevent cross-talk between capsules must be determined. This minimum flow rate is accomplished by using the fission product monitors to detect leakage (or absence of leakage) of activated neon between capsules at different plenum flow rates in the very beginning of the experiment irradiation. The leadout minimum flow rate testing along with measuring the gas delivery time between the capsules and their fission product monitors for AGR-3/4 was completed in the first week or so of irradiation.

The experiment was then taken to temperature, which identified the need to increase the power in the NEFT by approximately 10% to achieve temperature in several of the capsules. After the power increase was completed in the second week of irradiation, there were only three capsules ranging from approximately 50°C to 140°C below their target temperatures, and nine of the capsules were within their target temperature ranges. Very early in the third week of irradiation, the DTF particles started to fail, and by January 2, 2012, DTF particle failures had been detected in all but four capsules. Once DTF particles failed the need to maintain constant temperatures in the capsules then became more important than necessarily achieving the initial temperature targets, so the decision was made to readjust the temperature ranges of the three low temperature capsules. In a similar vein, the impurity injection system was not activated until all DTF particles had failed and the fission product release had stabilized in the selected capsule, which was capsule 11.

The parameters for capsules 10 and 12 for the entire irradiation campaign are shown in Figures 6 and 7 below, and they indicate the typical, extremely flat temperature profile achieved in the AGR-3/4 irradiation. Capsules 10 and 12 both have a third thermocouple located in the matrix material (shown as the green line for TC3), which indicates the temperature differential between the outer graphite and the matrix material.

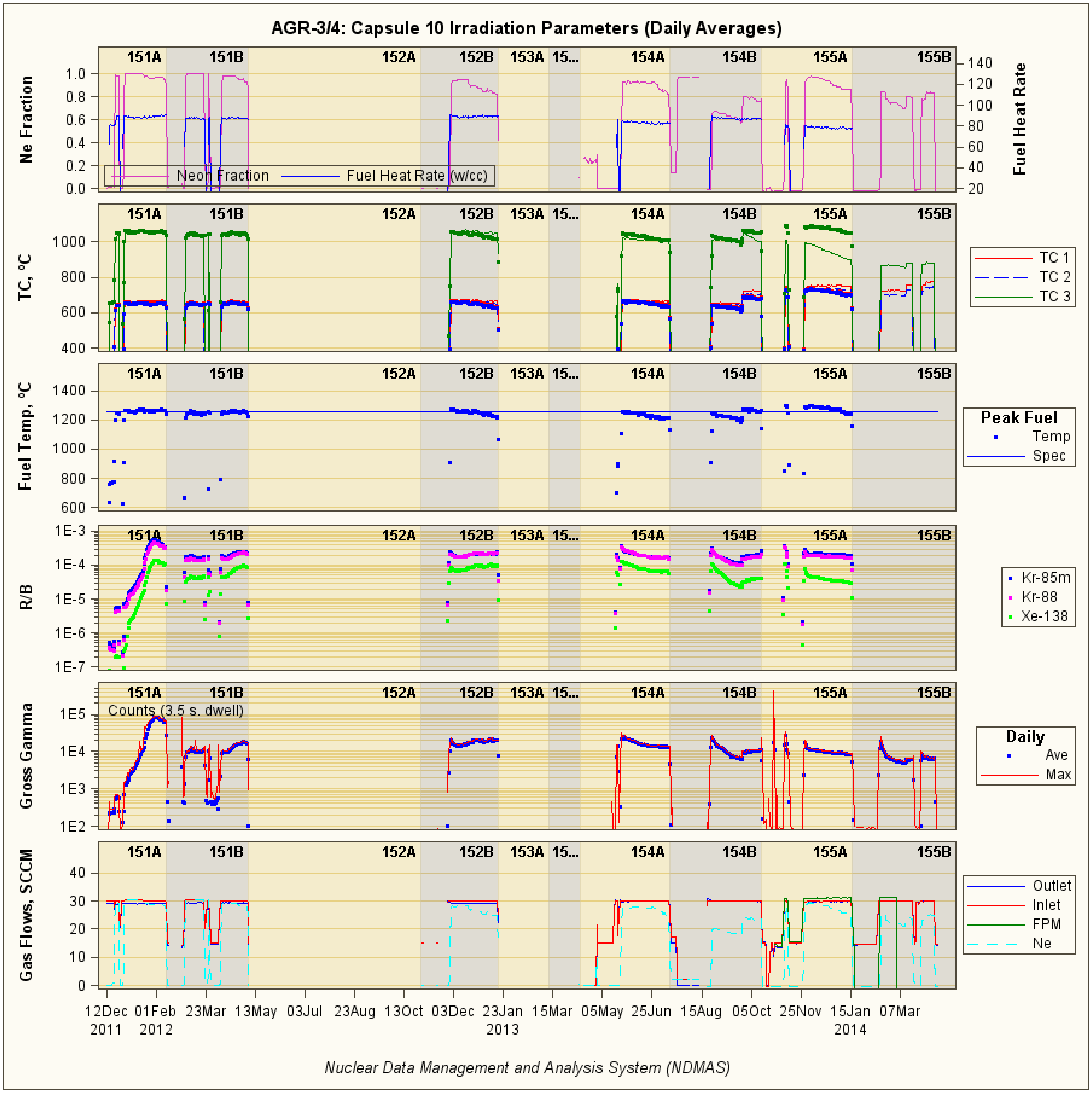

Fig. 6: AGR-3/4 Parameters for Capsule 10 over the Entire Experiment Irradiation Campaign

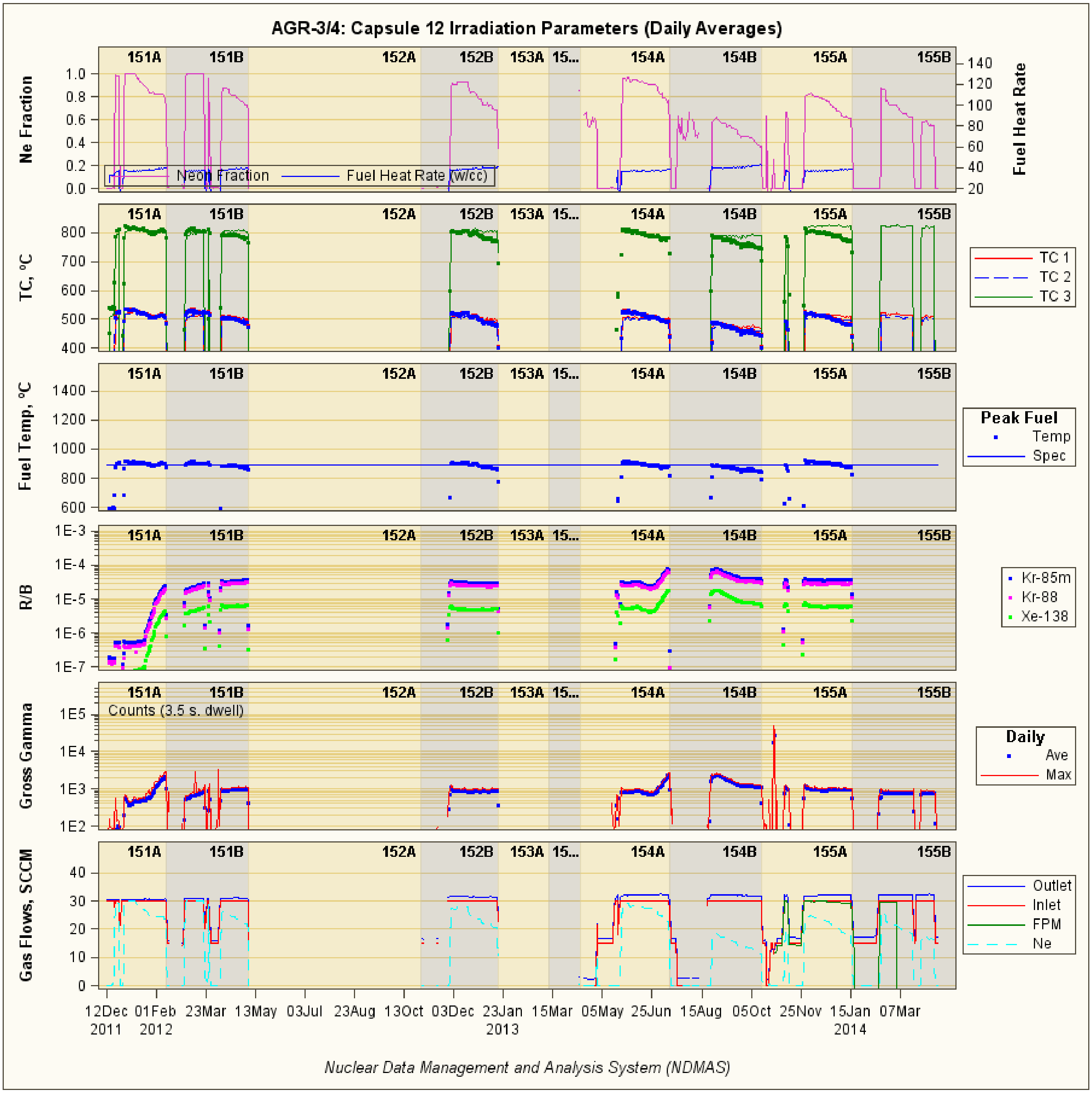

Fig. 7: AGR-3/4 Parameters for Capsule 12 over the Entire Experiment Irradiation Campaign

The DTF particle failures resulted in very high count rates in the fission product monitors, so the collimators were changed in the monitors to reduce the count rates. Overall the system performed very well and the performance and results of the irradiation have exceeded expectations.

AGR-3/4 completed its last irradiation cycle in April 2014 in the ATR achieving a total of 369 Effective Full Power Days (EFPDs) of irradiation and a peak fuel burnup of 15.3% FIMA. DTF fuel particle failures have been detected in all capsules to different degrees depending on location of the capsule with respect to the axial neutron flux profile of the ATR. By the end of March 2012, the highest burn-up capsules at the vertical center of the ATR core appeared to have experienced failure of essentially all DTF particles. At the same time, approximately 25% of the DTF particles had failed in the very top and bottom capsules at the edges of the ATR core, while the DTF particle failures in the intermediate capsules ranged from 60% to over 90%.

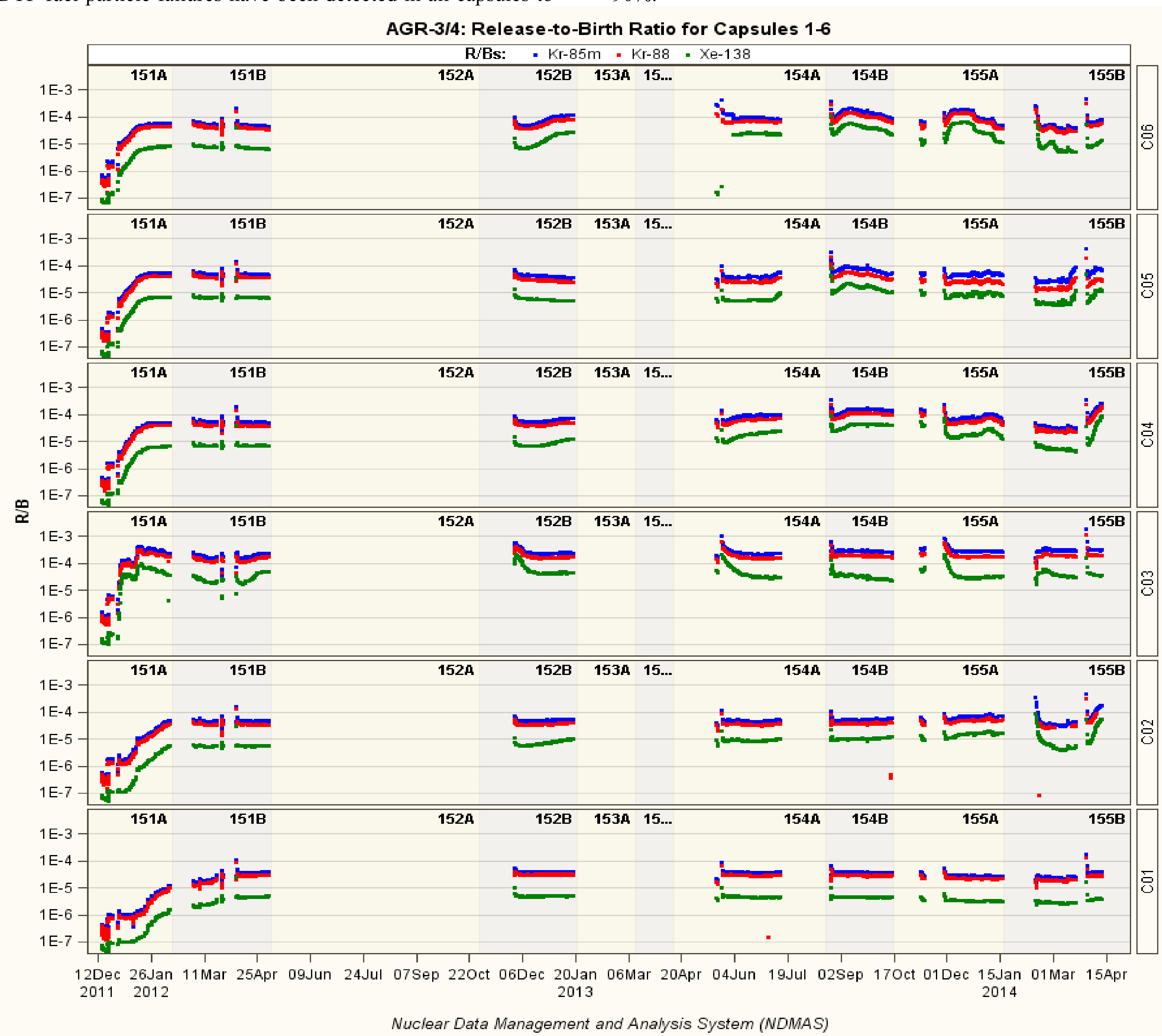

Fig. 8: Release-to-Birth Ratios in AGR-3/4 Capsules 1 through 6 over the Entire Irradiation Campaign

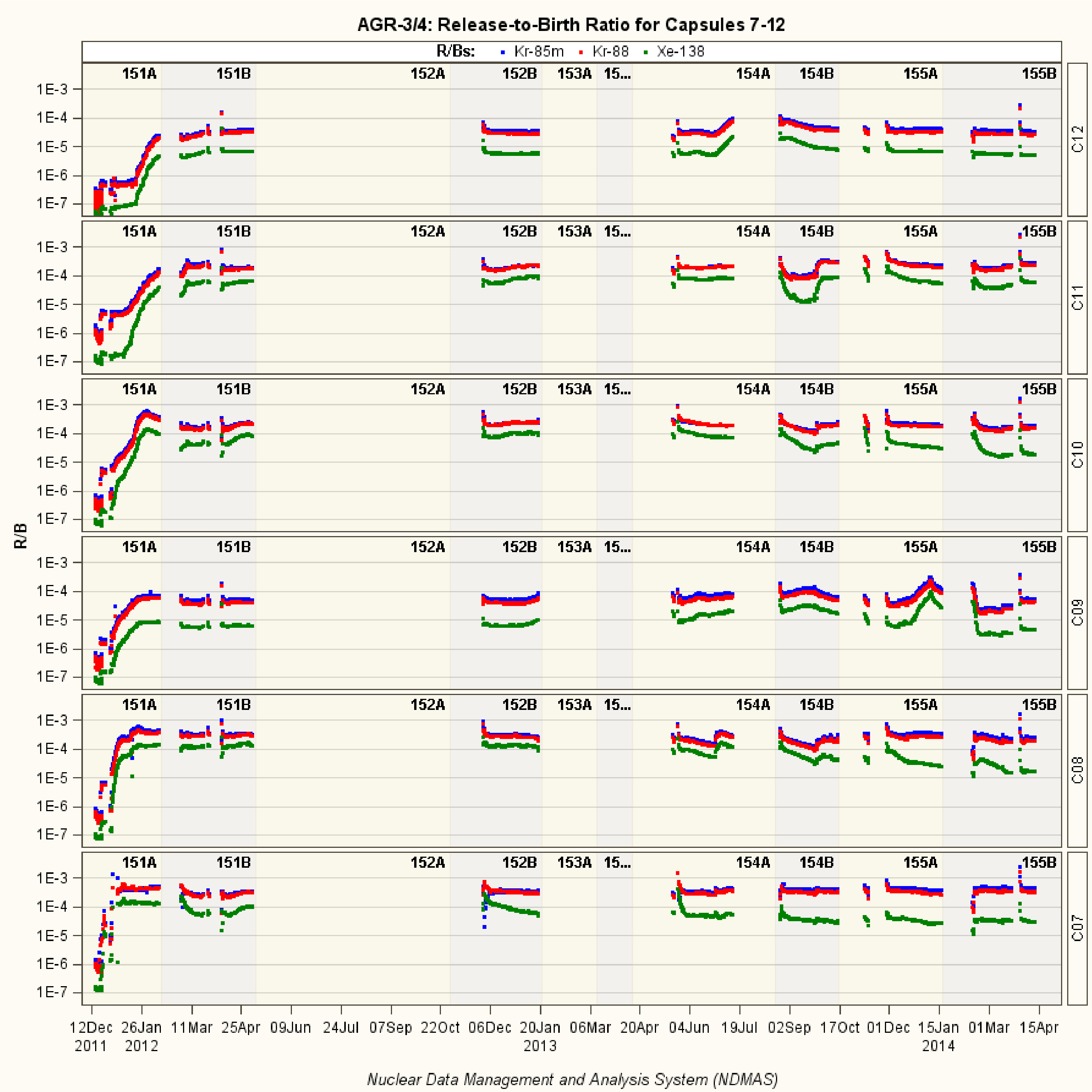

Fig. 9: Release-to-Birth Ratios in AGR-3/4 Capsules 7 through 12 over the Entire Irradiation Campaign

By the end of the irradiation in April 2014, all 80 DTF particles had failed in capsules 2, 3, and 9. The remaining capsule DTF failures ranged from 50% to 95%. The release-to-birth ratios (R/Bs) for all capsules over the entire irradiation are shown in Figures 8 and 9. The low initial R/Bs are typical for the AGR fuel, but as the DTF particles failed, which started in late December (as indicated earlier), the R/Bs increased rapidly and rose to much higher levels during the first and second irradiation cycles. These preliminary results indicate the fuel performed exactly as designed. Detailed analysis of the results is discussed in Reference 4.

IX. CONCLUSIONS

The insights and lessons learned from AGR-1 were incorporated into the design, assembly and early irradiation of AGR-2, and then rolled into the design of AGR-3/4. AGR-3/4 presented new design challenges, which were resolved with multiple new design features. An additional system to inject the anticipated HTGR coolant gas impurities into the AGR-3/4 irradiation sweep gas was included in the experiment requirements. Preliminary data shows that after 369 effective full power days of irradiation, AGR-3/4 achieved a peak burnup of 15.3% FIMA and a peak fast fluence of 5.43E25 n/m^2. This irradiation will provide valuable data for the qualification of gas reactor particle fuel by updating and improving the fission product transport and fuel performance models for the HTGR.

X. ACRONYMS

AGR - Advanced Gas Reactor
ATR – Advanced Test Reactor
DTF – Designed To Fail
EFPDs – Effective Full Power Days
FIMA – Fissions per Initial Metal Atom
HTGR- High Temperature Gas Reactor
INL – Idaho National Laboratory
LEU – Low Enriched Uranium
NEFT – North East Flux Trap
PIE – Post Irradiation Examination
R/Bs – Release-to-Birth ratios
TRISO – Tri-isotopic
UCO – Uranium Oxycarbide

XI. ACKNOWLEDGEMENTS

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XII. REFERENCES

[1] Petti, D. A., et al, “Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program”, Idaho National Laboratory Report INL/EXT-05-00465, Revision 1 (August 2005)

[2] Hunn, J. D., et al, “Fabrication and Characterization of Driver Fuel Particles, Designed-to-Fail Fuel Particles, and Fuel Compacts for the US AGR-3/4 Irradiation Test”, Proceedings of the HTR2012, Tokyo, Japan, October 28 – November 1, 2012, Paper HTR2012-3-026

[3] Grover, S. B., and Petti, D. A., “Initial Irradiation of the First Advanced Gas Reactor Fuel Development and Qualification Experiment in the Advanced Test Reactor”, Proceedings of Global 2007 Advanced Nuclear Fuel Cycles and Systems, Boise, ID, USA, September 9-13, 2007, Paper 177457

[4] Einerson, J. J., et al, “Analysis of Fission Gas Release-to-Birth Ratio Data from the AGR Irradiations”, Proceedings of the HTR2014, Weihai, China, October 27-31, Paper HTR2014-31102.