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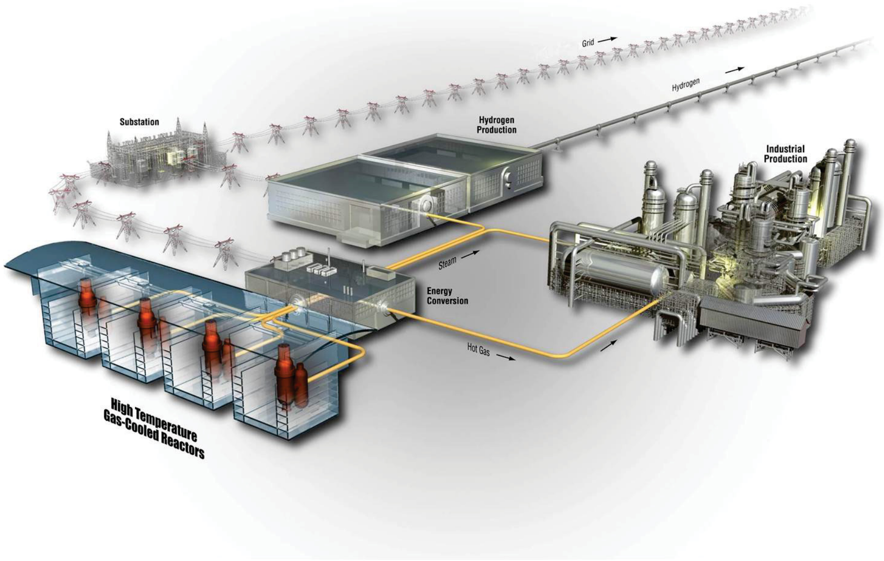
Specification

Project No. 29412, 23841

AGR-5/6/7 Irradiation Test Specification



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FIGURES

ACRONYMS

AGR	Advanced Gas Reactor
AGR-5/6	fuel qualification irradiation for the AGR program
AGR-7	fuel margin irradiation experiment for the AGR program
ATR	Advanced Test Reactor
FIMA	fissions per initial metal atom
HTGR	high temperature gas cooled reactor
INL	Idaho National Laboratory
PIE	post irradiation examination
R/B	release rate to birth rate ratio
TRISO	tristructural-isotropic (coated fuel)
UCO	uranium oxycarbide

1. BACKGROUND

Several fuel and material irradiation experiments are planned for the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program which supports the qualification of coated particle fuel for use in high temperature gas cooled reactors (HTGR). The goals of these experiments are to (a) provide irradiation performance data to support fuel process development, (b) qualify fuel for normal operating conditions, (c) support development and validation of fuel performance and fission product transport models and codes, and (d) provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing. Originally planned and named as separate fuel experiments but subsequently combined into a single test train, AGR-5/6/7 will test a single type of tristructural-isotropic (TRISO) coated particle, low enriched uranium, oxycarbide (UCO) fuel. The AGR-5/6 portion of the experiment will provide data to support qualification of the selected reference fuel design, while the AGR-7 portion will serve as a margin test, irradiating the fuel under extreme conditions.

2. INTRODUCTION

As defined in the Technical Program Plan for INL Advanced Reactor Technologies Technology Development Office/Advanced Gas Reactor Fuel Development and Qualification Program (Simonds 2015), the objectives of the AGR-5/6/7 experiment are to:

1. Irradiate reference design fuel that will provide data to support fuel qualification
2. Test fuel under margin conditions, and possibly assess the effects of sweep gas impurities, such as CO, H_2O, and H_2 typically found in the primary circuit of HTGRs, on fuel performance and subsequent fission product transport
3. Provide irradiated fuel and material samples for post irradiation examination (PIE) and safety testing
4. Support the refinement of fuel performance and fission product transport models with on-line, PIE and safety test data.

The purpose of this document is to define the requirements for the irradiation phase of the AGR-5/6/7 experiment. How these requirements will be met and predictive fuel exposure histories will be presented in the AGR-5/6/7 Test Plan. Requirements pertaining to fuel fabrication, PIE, safety testing, data management, and the irradiation test train design, fabrication, and disassembly are or will be presented elsewhere.

This specification is presented in nine different sections and an appendix. Sections 3 through 8 present requirements for the irradiation test capsules, irradiation test articles, irradiation test conditions, test operations, test measurements, and documentation. The requirements are presented in terms of a specification, highlighted in italics, followed by a brief technical justification. For ease of use, the specifications are listed in a table at the end of each section. References are listed in Section 9, and the strategy for the AGR-5/6/7 design approach is presented in Appendix A.

3. TEST CAPSULE REQUIREMENTS

- *The AGR-5/6/7 test train shall be a multi-capsule, instrumented-lead design.*
- *The test train shall be designed for irradiation in one of the four corner flux traps (without a safety rod position) of the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL).*
- *The test train shall contain up to 12 independent capsules. AGR-5/6 capsules shall be separate from AGR-7 capsule(s).*
- *Each capsule shall be independently controlled for temperature and independently monitored for fission product gas release.*
- *Each capsule shall have at least five thermocouples initially installed.*
- *Pending availability, each capsule may have advanced thermal monitors initially installed.*
- *Each capsule shall have a sufficient number of neutron monitors to determine end-of-irradiation thermal and fast (E>0.18 MeV) neutron fluences at the measurement location.*
- *Other than graphite holders (including grafoil spacers), and sweep gas, no capsule component (such as thermocouples, advanced thermal monitors, gas lines, neutron monitors or pressure barriers) shall come in contact with the irradiation test fuel compacts.*
- *Test fuel compacts shall not make radial contact with each other but are allowed to make axial contact with each other.*

3.1 Test Capsule Technical Justification

A multi-capsule, instrumented lead test train that allows each capsule to be independently controlled for temperature and monitored for fission product gas release provides flexibility in testing and gathering meaningful data under multiple test conditions during a single irradiation experiment. However, the test reactor's axial flux distribution and space considerations within the test train impose a practical limit of 12 independently controlled and monitored capsules per test train. Fewer than 12 capsules may be used for AGR-5/6/7 as long as test objectives can be met.

Initial INL physics calculations (Chang and Parry 2011) have shown that the best ATR position to achieve significant end-of-irradiation conditions (compact burnup and fast neutron fluence) for a test train of sufficient size to accommodate an amount of fuel required for qualification testing, is obtained from irradiation in the northeast flux trap. Further INL physics calculations (Sterbentz 2015) have shown that by extrapolating to 500 effective full-power days of irradiation in this position, fuel compact burnups will exceed 18% fissions per initial metal atom (FIMA) with fast neutron fluences of about 7.3 x 10^{25} n/m^2, E>0.18 MeV. While the fast neutron fluence is higher than expected for a prismatic HTGR, test train design refinements are possible to reduce the fast neutron fluence. In addition, the rate of burnup and fast fluence accumulation, or acceleration, in this position is less than three times that expected in the HTGR. Past U.S. and German experience indicates that by keeping the acceleration factor under three, an irradiation test is more prototypic of an actual reactor irradiation.

Each capsule requires at least one thermocouple for thermal control, and in the case of thermocouple failure, each capsule should have at least two additional thermocouples to provide backup for the greatest extent of irradiation possible. Given the physical size of the test train, two additional thermocouples are being required to provide the highest possible redundancy in the experiment.

Fluences measured by the neutron monitors will be used to benchmark the analytical process used to determine compact burnups and fluences. These values will be compared to calculated results and possibly to other PIE measurements.

To prevent unwanted test article interactions and possible unwanted failures, no object or material other than specifically designed compact matrix, graphite test articles and holders, and sweep gas should come into contact with the irradiation test fuel. Fuel compacts should only be permitted to touch each other in the axial direction. This form of contact arises from stacking compacts one on top of another and simulates actual reactor use. Radial compact to compact contact is not allowed because this may lead to localized hot spots and possible deleterious particle-to-particle interactions.

Table 1. AGR-5/6/7 irradiation test capsule requirements.

Parameter	Specification
Test train design	Multi-capsule, instrumented lead
Location test train to be sized and configured	One of the four corner flux trap positions without a safety rod in the ATR at INL
Number of independent capsules	Up to and including 12 capsules, AGR-5/6 capsules separate from AGR-7 capsule(s)
Mode for temperature control and fission gas monitoring	Each capsule is independently controlled for temperature and monitored for fission gas release
Number of thermocouples initially installed per capsule	At least five
Advanced thermal monitors allowed	Pending availability, may be initially installed
Number of neutron monitors per capsule	A sufficient number to determine end-of-irradiation thermal and fast (E>0.18 MeV) neutron fluences
Allowable material contact with test fuel	Only graphite holders (including grafoil spacers), and sweep gas may contact the irradiation test fuel
Allowable fuel compact to fuel compact contact	Compact to compact contact only in the axial direction

4. TEST ARTICLE REQUIREMENTS

- *Each AGR-5/6 capsule shall contain the same reference design UCO fuel particles.*
- *The goal for the total number of AGR-5/6 fuel particles should be ≥ 500,000.*
- *Each AGR-7 capsule shall contain only one fuel type or variant. This fuel type may be the same as the reference design fuel to be used in AGR-5/6.*
- *The goal for the total number of AGR-7 fuel particles should be ≥ 50,000 per capsule.*

4.1 Test Article Technical Justification

The primary objective of AGR-5/6 is to irradiate reference design UCO fuel. This fuel will consist of 425 µm nominal diameter UCO kernels, enriched to about 15.5 wt% U-235. Each fuel compact will be nominally 12.3 mm in diameter by 25.5 mm long. It is currently planned that AGR-5/6/7 fuel compacts will be fabricated with at least two different particle loadings. The highest loaded compact may contain up to approximately 3500 fuel particles. Other design parameters and requirements for the reference design fuel are documented in the AGR-5/6/7 fuel specification (Marshall 2014).

Qualification of the reference design fuel requires that the particle failure fraction be determined, at a 95% confidence level, under prototypic reactor conditions. Statistics dictate that a larger population allows a lower 95% confidence level to be established for a given observation. As an example, for no failures in a population of 100,000 particles, the failure fraction at 95% confidence is about 3×10^{-5}, while for no failures in a population of 500,000 particles, the failure fraction at 95% confidence is about 6×10^{-6}. Since the failure fraction for the reference design fuel is expected to be very small, and some margin is desired in the resulting 95% confidence value, a population of 500,000 particles would provide adequate statistics for the qualification irradiation. Statistics of population size is discussed further in Appendix A.

AGR-7 will margin test UCO fuel. It is anticipated that this test will consist of one capsule containing the same reference design fuel as used in AGR-5/6. However, owing to fuel availability and other possible project needs, another UCO fuel type or variant may be substituted for the reference fuel and more than one capsule may be used for margin testing. Requiring each capsule to contain only one fuel type or fuel variant ensures that the fission gas release measurements and possible particle failure indicators are attributed to an identifiable source. As discussed in Appendix A, testing 50,000 particles per AGR-7 capsule should ensure good statistics for determining failure fractions.

Table 2. AGR-5/6/7 test article requirements.

Parameter	Specification
AGR-5/6 fuel type	Each AGR-5/6 capsule shall contain the same reference design UCO fuel particles
Total number of AGR-5/6 fuel particles goal	≥ 500,000 fuel particles total
AGR-7 fuel type	One fuel type per capsule, may be the same as the AGR-5/6 reference design fuel
Total number of AGR-7 fuel particles per capsule goal	≥ 50,000 fuel particles per capsule

5. IRRADIATION TEST CONDITION REQUIREMENTS

AGR-5/6 Requirements

- *The instantaneous peak temperature for each capsule shall be ≤1800°C.*
- *The time average temperature distribution goals should be:*
  - *≥600°C and <900°C for about 30% of the fuel,*
  - *≥900°C and <1050°C for about 30% of the fuel,*
  - *≥1050°C and <1250°C for about 30% of the fuel, and*
  - *≥1250°C and <1400°C for about 10% of the fuel.*
- *The time average, peak temperature goal should be 1350 ± 50°C.*
- *The time average, minimum temperature goal should be ≤700°C.*
- *The minimum fuel compact average burnup shall be >6% FIMA for all compacts.*
- *The maximum fuel compact average burnup shall be >18% FIMA for at least one compact.*
- *The minimum average fast neutron fluence for each fuel compact shall be* $>1.5 \times 10^{25}$ *n/m*^{2}*, E>0.18 MeV.*
- *The maximum average fast neutron fluence shall and* $\leq 7.5 \times 10^{25}$ *n/m*^{2}*, E>0.18 MeV, for all compacts and* $\geq 5.0 \times 10^{25}$ *n/m*^{2}*, E>0.18 MeV, for at least one compact.*
- *The instantaneous peak power per particle shall be ≤400 mW/particle.*

AGR-7 Requirements

- *The instantaneous peak temperature for each capsule shall be ≤1800°C.*
- *The time average, peak temperature goal should be 1500 ± 50°C for at least one capsule.*
- *The minimum fuel compact average burnup shall be >6% FIMA for all compacts.*
- *The maximum fuel compact average burnup shall be >18% FIMA for at least one compact.*
- *The minimum average fast neutron fluence for each fuel compact shall be* $>1.5 \times 10^{25}$ *n/m*^{2}*, E>0.18 MeV.*
- *The maximum average fast neutron fluence shall be* $\leq 7.5 \times 10^{25}$ *n/m*^{2}*, E>0.18 MeV, for all compacts and* $\geq 5.0 \times 10^{25}$ *n/m*^{2}*, E>0.18 MeV, for at least one compact.*
- *The instantaneous peak power per particle shall be ≤400 mW/particle.*

5.1 Irradiation Test Condition Technical Justification

The goal for AGR-5/6 is to adequately bound the irradiation conditions expected in a HTGR. As discussed in Appendix A, specifying time average irradiation temperatures from less than 900°C to over 1250°C will conservatively span a range expected in a prismatic reactor. An instantaneous peak temperature specification of ≤1800°C will provide an operational limit to minimize over heating of the test fuel.

The specified maximum compact average burnups for both AGR-5/6 and AGR-7 ensure that the tests approach, or exceed, what may be considered full burnup in a HTGR for 15.5 wt% enriched fuel. The specified minimum compact average burnups ensures that a level of significant irradiation is achieved. Based upon a preliminary analysis of a multi-capsule test train in the northeast flux trap position of the

ATR (Sterbentz 2015), these burnups are calculated to take about 500 effective full power days to accumulate. Greater burnups may be achieved by extending the irradiation. However, the irradiation duration will likely be restrained by the fast neutron fluence limit requirement.

The specified maximum AGR-5/6 fast neutron fluence of ≥5.0 × 10^{25} n/m^2, E >0.18 MeV, bounds expected HTGR service conditions. Minimum fast neutron fluences of >1.5 × 10^{25} n/m^2, E >0.18 MeV, ensure that the fuel pyrocarbon experiences the transition from creep-dominated strain to swelling-dominated strain (at 1250°C) for all compacts.

The instantaneous peak power per the particle requirement of ≤400 mW/particle is the same as the value adopted by General Atomics for the irradiation of their compacts in the High Flux Reactor EU-2 experiment (Conrad et al. 2002). This specification limits the peak kernel temperature and the temperature gradient across the particle, which reduces fission product diffusion and potential fission product/silicon carbide interactions.

The primary goal of AGR-7 is to margin test UCO fuel. A dominant fuel performance parameter is time at temperature. Since AGR-2 tested UCO fuel at a peak time average temperature of 1360°C with on-line data indicating no deleterious effects, AGR-7 will be tested at a higher peak temperature of 1500°C. In order to achieve full burnup, it is anticipated that fast neutron fluences (near the mid-plane of the proposed test train in the northeast flux trap position of the ATR) will approach 7.3 × 10^{25} n/m^2, E>0.18 MeV. This fast neutron fluence exceeds expected HTGR conditions and will serve as another AGR-7 margin test parameter.

Table 3. AGR-5/6/7 fuel irradiation test condition requirements.

Parameter	AGR-5/6 Specification	AGR-7 Specification
Instantaneous peak temperature for each capsule (°C)	≤1800	≤1800
Time average temperature distribution goals (°C)	≥600 and <900 for~30% of the fuel ≥900 and <1050 for~30% of the fuel ≥1050 and <1250 for~30% of the fuel ≥1250 and <1400 for~10% of the fuel	Not specified
Time average, peak temperature goal (°C)	1350 ± 50	1500 ± 50 for at least one capsule
Time average, minimum temperature goal (°C)	≤700	Not specified
Minimum compact average burnup (% FIMA)	>6 for all compacts	>6 for all compacts
Maximum fuel compact average burnup (% FIMA)	>18 for at least one compact	>18 for at least one compact
Minimum fuel compact fast neutron fluence (10^{25} n/m^2, E > 0.18 MeV)	>1.5 for all compacts	>1.5 for all compacts
Maximum fuel compact fast neutron fluence (10^{25} n/m^2, E > 0.18 MeV)	≤7.5 for all compacts and ≥5.0 for at least one compact	≤7.5 for all compacts and ≥5.0 for at least one compact
Instantaneous peak power per particle (mW/particle)	≤400	≤400

6. TEST OPERATION REQUIREMENTS

- *Sweep gas shall consist of low neutron activation, inert gases.*
- *Each sweep gas supply cylinder shall have a gas purity of ≥99.99% by volume.*
- *For capsules not injected with impure gas, moisture content of the inlet sweep gas shall be measured at least once after each gas cylinder change on the inlet side of the capsule and shall be <5 ppm H_2O at a dew point of – 100 ± 2.5°C.*
- *Should gaseous impurity injection be used, the sweep gas shall contain gaseous impurities typical of those found in the primary coolant circuit of HTGRs.*
- *Sensitivity of the fission product monitoring system shall be able to detect every individual particle failure, up to and including the first 250 failures, from each identifiable capsule.*
- *Transit time of the sweep gas from each capsule to the fission product monitoring system shall be <25 minutes.*
- *AGR-5/6/7 experiment operation shall be conducted in accordance with the approved ATR NQA-1 Quality Assurance Program.*

6.1 Test Operation Technical Justification

Inert gas will be swept through each capsule to provide temperature control and carry any released fission product gases to a detection system. Low neutron activation inert gases are specified for this sweep gas to minimize background activity in the fission product monitoring system. Historically, sweep gas has consisted of mixtures of helium and neon or helium and argon with purities of ≥99.99% by volume for each gas. This level of purity limits the amount of contamination to the test articles and limits background activity. Also, moisture content of under 5 ppm H_2O within the sweep gas reduces possible reactions with the graphite contained in the test capsule.

The AGR program will determine if one or more AGR-5/6/7 capsules will be injected with gaseous impurities, such as CO, H_2O and H_2 that are typically found in the primary coolant circuit of HTGRs. This will allow for an assessment of the effects of these impurities on fuel performance and fission product transport.

As an indicator of fuel performance, the fission product monitoring system needs to be able to detect each particle failure and must have the ability to identify the capsule where the failure had occurred. The limit value of 250 particle failures is a compromise between detection sensitivity (which decreases as more particles fail) and programmatic need to identify the timing of each failure.

To limit the amount of decay from released, short-lived isotopes and to increase detectability, the transit time of the sweep gas from each capsule to the fission product monitoring system is kept under 25 minutes.

The approved ATR NQA-1 Quality Assurance Program applies to AGR-5/6/7 experiment operation.

Table 4. AGR-5/6/7 operation requirements.

Parameter	Specification
Sweep gas composition	Low neutron activation, inert gases
Sweep gas purity	Each supply cylinder with sweep gas ≥99.99% by volume
Moisture content of inlet sweep gas on inlet side of capsule for capsules not injected with impure gas	<5 ppm H_2O measured at least once after each gas cylinder change at a dew point of – 100 ± 2.5°C
Sweep gas impurity injection if used	Gaseous impurities, typical of those found in the primary coolant circuit of HTGRs, injected into capsule sweep gas
Sensitivity of fission product monitoring system	Able to detect every individual particle failure from each capsule, up to and including the first 250 failures, and able to identify in which capsule each failure had occurred
Transit time of sweep gas	<25 minutes from each capsule to the fission product monitoring system
Experiment operation	Conducted in accordance with the approved ATR NQA-1 Quality Assurance Program

7. TEST MEASUREMENT REQUIREMENTS

- *Flow rate of each sweep gas constituent shall be measured with an accuracy of ±2% and shall be recorded at least every hour during irradiation and continuing for at least 2 days after each reactor shut down.*
- *Moisture content of the sweep gas shall be measured on the outlet side of each capsule at a dew point of – 100 ± 2.5°C and shall be recorded at least every hour during irradiation.*
- *For each capsule injected with gaseous impurities, the concentration of each injected gaseous impurity in the sweep gas shall be measured on the inlet side and outlet side of the capsule at least every week during initial irradiation. Pending results of the initial injected gaseous impurity measurements, the Program may change the frequency of measurement.*
- *Total radiation level of the sweep gas from each capsule shall be measured and recorded continuously during irradiation.*
- *Concentrations of at least Kr-85m, Kr-87, Kr-88, Xe-131m, Xe-133, and Xe-135 shall be measured in the sweep gas from each capsule and recorded at least daily during irradiation. If possible, the concentrations of Kr-89, Kr-90, Xe-135m, Xe-137, Xe-138, and Xe-139 should also be measured in the sweep gas from each capsule and recorded at least daily during irradiation.*
- *Concentrations of at least Xe-133, Xe-135, and Xe-135m shall be measured in the sweep gas from each capsule and recorded at least daily for at least 2 days following each reactor shutdown.*
- *Readings from each thermocouple shall be recorded at least every 5 minutes during irradiation and each thermocouple shall have an as-installed accuracy of ±2% of reading.*
- *ATR lobe powers shall be provided by ATR Engineering within 5 working days of the end of each reactor cycle of irradiation.*
- *During abnormal events, the flow rate of each sweep gas constituent and the readings from each thermocouple shall be measured and recorded at least every minute.*
- *End of irradiation neutron fluences shall be determined from each neutron monitor with a monitor counting uncertainty within ±10%.*
- *All test data shall be backed up and stored in separate facilities at least daily.*

7.1 Test Measurement Technical Justification

Measurement values for each sweep gas constituent flow rate, thermocouple readings, and reported ATR lobe powers are needed as input for thermal calculations. ATR lobe powers are also needed for physics calculations. The measurement values will be electronically processed and are specified to be recorded at intervals deemed reasonable for their expected rate of change. During abnormal events, data will be recorded at least every minute to capture possible rapid data changes. Abnormal events are defined in the latest revision of the Technical and Functional Requirements document TFR-630 and will be discussed in the Experiment Safety Assurance package (to be completed prior to test insertion).

Moisture content of the sweep gas, measured on the outlet side of the capsule, and compared to the inlet value, provides an indicator of capsule integrity. Past experience indicates that the outlet moisture monitor will detect any water leak within the capsule.

Continuously measuring and recording total radiation levels (as from an in-line ion chamber or NaI detector) of the sweep gas from each capsule provides an indicator of particle failure. A failure is evident by a sharp rise and fall, or spike, in the detected activity level. However, at sufficiently high radiation levels, the activity contribution (or spike) from a single particle failure cannot be resolved. Overall fuel performance is also indicated by release-to-birth (R/B) ratios of fission product gases released from the fuel. These R/B ratios are calculated from the measured concentrations of the isotopes in the sweep gas. Fuel performance information is also gained by measuring xenon in the sweep gas immediately after reactor shutdown.

End of irradiation fluences measured by the neutron monitors and appropriately adjusted to prescribed energy levels, will be compared to physics calculations. The measured neutron fluences, together with other necessary input parameters, will be used to determine compact average burnups and will also be compared to physics calculations.

To avoid irretrievable loss of information, all test data will be backed up.

Table 5. AGR-5/6/7 measurement requirements

Measurement	Specified frequency of measurement recordings during irradiation
Flow rate of each sweep gas constituent with an accuracy of ±2%	At least every hour during irradiation and continuing for at least 2 days after each reactor shutdown
Moisture content of sweep gas on outlet side of capsule at a dew point of – 100 ± 2.5°C	At least every hour
Concentration of each injected gaseous impurity on inlet and outlet side of each injected capsule	Initially, at least every week, afterwards, subject to change by the Program
Total radiation level of the sweep gas from each capsule	Continuously
Concentrations of at least Kr-85m, Kr-87, Kr-88, Xe-131m, Xe-133, and Xe-135 in the sweep gas from each capsule. Optional isotopes to also measure include Kr-89, Kr-90, Xe-135m, Xe-137, Xe-138, and Xe-139	At least daily
Concentrations of at least Xe-133, Xe-135, and Xe-135m in the sweep gas from each capsule	At least daily for at least 2 days after each reactor shutdown
Readings from each thermocouple with an as-installed accuracy of ±2% of reading	At least every 5 minutes
ATR lobe powers	Provided by ATR Engineering within 5 working days of the end of each reactor operating cycle
Flow rate of each sweep gas constituent and readings from each thermocouple during abnormal events	At least every minute
Neutron fluence from each neutron monitor with a monitor counting uncertainty within ±10%	At end of irradiation
Backup of all test data	At least daily in separate facilities

8. DOCUMENTATION REQUIREMENTS

- *Status reports highlighting experiment progress shall be distributed at least monthly.*
- *A Final Irradiation Test Results report shall be issued within 9 months of test completion.*
- *As-run data reports and the Final Irradiation Test Results report shall contain at least the following calculated values with their associated uncertainties:*
  - *Time-average peak fuel temperature for each capsule*
  - *Time-average, volume average fuel temperature for each capsule*
  - *Histories of minimum, average and peak fuel temperatures for each compact*
  - *Average fast neutron fluence (E>0.18 MeV) for each compact*
  - *Average burnup for each compact*
  - *R/B values for at least Kr-85m, Kr-87, Kr-88, Xe-131m, Xe-133, and Xe-135 for each capsule*
  - *Estimated number of particle failures within each capsule.*

8.1 Documentation Technical Justification

The specified issuance of documents ensures timely and sufficient dissemination of test information.

Table 6. AGR-5/6/7 documentation requirements.

Document for AGR-3/4 irradiation test	Specified issuance
Status report highlighting experiment progress	Monthly
Final Irradiation Test Results report	Nine months after test completion
Calculated values with associated uncertainties: • Time-average peak fuel temperature for each capsule • Time-average, volume average fuel temperature for each capsule • Histories of minimum, average and peak fuel temperatures for each compact • Average fast neutron fluence (E>0.18 MeV) for each compact • Average burnup for each compact • R/B values for at least Kr-85m, Kr-87, Kr-88, Xe-131m, Xe-133, and Xe-135 for each capsule • Estimated number of particle failures within each capsule	Documented in as-run data reports and Final Irradiation Test Results report

9. REFERENCES

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D. W. Marshall, “AGR-5/6/7 Fuel Specification,” SPC-1352, Revision 4, January 8, 2014.

J. Simonds, “Technical Program Plan for INL Advanced Reactor Technologies Technology Development Office/Advanced Gas Reactor Fuel Development and Qualification Program,” PLN-3636, Revision 4, May 7, 2015.

J. W. Sterbentz, “Physics Evaluations for the AGR-5/6/7 Experiment Irradiated in the ATR NEFT in Support of Preliminary Design Activities,” Draft ECAR, expected to be issued September 2015.

Appendix A

Strategy for Design Approach to AGR 5/6/7 Fuel Qualification

D. A. Petti

1. SERVICE CONDITIONS (BURNUP, FLUENCE, TEMPERATURE)

The anticipated service envelope for NGNP fuel is shown in Figure A-1. Of all these conditions, the ones of greatest concern in establishing the configuration of the AGR-5/6/7 test train are fast fluence and burnup. While calculations have not yet been done for irradiation in the ATR Northeast Flux Trap, the maximum fast fluence may need to be increased relative to that expected in a reactor core to accommodate the greater fast flux in that position.[a] The peak burnup may also be difficult to achieve with an enrichment of 15.5% and still hold temperature in the capsule. I recommend 40-41% packing fraction and the power density will be determined by the power established in the Northeast Flux Trap. For compacts that are nominally 0.5 inches in diameter and one inch long, this packing fraction corresponds to ~ 3300 particles.

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[a] Available analysis results for prismatic modular HTGR cores indicate fast fluence would not exceed ~5×10^{25} n/m^2. However, achieving the projected maximum burnup in the northeast flux trap location would likely exceed this value for fast fluence. Prior irradiations of high quality LEU UO_2 TRISO German fuel in the HFR reactor reached fast fluences of 8×10^{25} n/m^2 with no apparent detrimental effect.

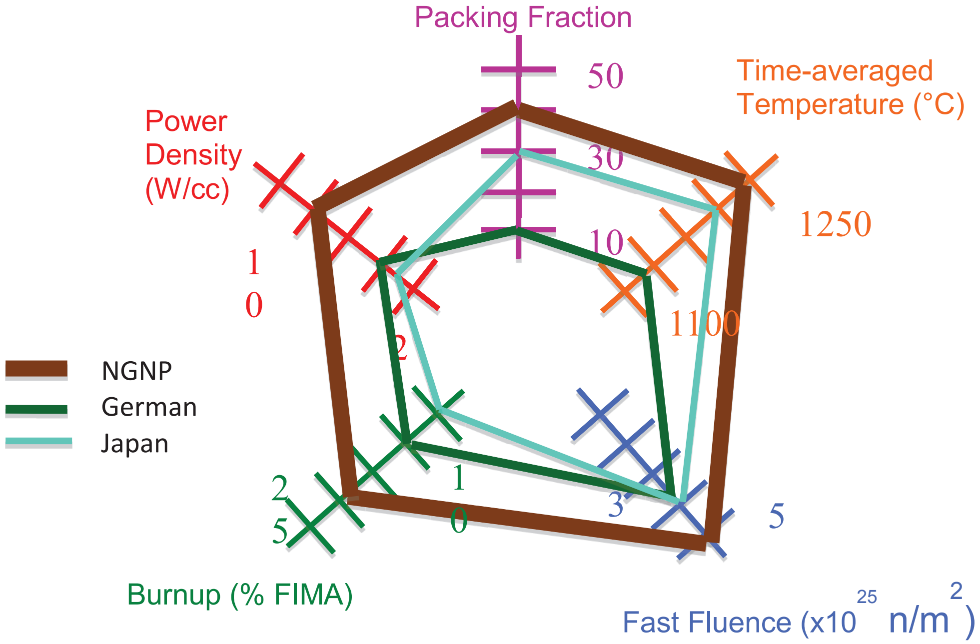

Figure A-1. Radar plot of key parameters for TRISO fuel.

2. TEMPERATURE DISTRIBUTION CONSIDERATIONS

The goal for the AGR-5/6 fuel qualification irradiation is to develop a temperature distribution that adequately bounds that expected in the NGNP. Figure A-2 compares the temperature census for each capsule in AGR-1 with the SC-MHR (AREVA design), and the conceptual design by GA for the NGNP (Fuel loads 1, 2, and 3). While AGR-1 is very conservative relative to the SC-MHR (750°C outlet), it appears that additional work is needed in terms of capsule design to ensure we bound the high temperature tail of the GA conceptual design in AGR-5/6. If AGR-5/6 were similar to AGR-1, the irradiation capsule would not have enough fuel at the middle to lower range of operating temperature of the reactor. The AGR-1 temperature distribution results in too much of the fuel being near the higher end of the temperature range and not enough fuel at the average or low temperature end of the operational range in a VHTR. As we design the capsules, we will have to set temperature ranges that ensure we bound the reactor values. A key aspect of setting these ranges is how high in temperature do we need to irradiate fuel to ensure that the fuel envelope that we qualify accounts in some way for (a) uncertainties in calculated fuel temperatures in the reactor, (b) overpower events and (c) anticipated operating occurrences during which fuel temperatures may increase above nominal design levels.

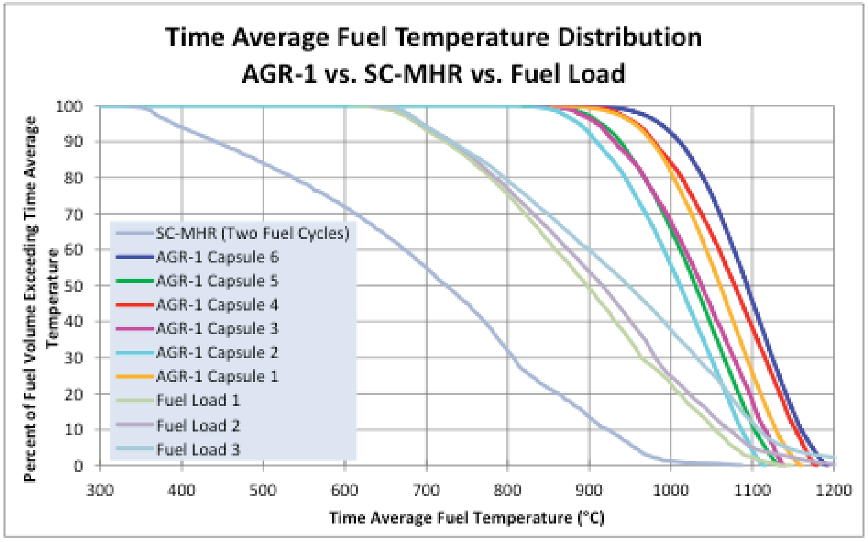

Figure A-2. Comparison of temperature distributions in AGR-1 with two VHTR designs, the AREVA SC-MHR and the GA conceptual design (Fuel loads 1, 2, 3).

In addition, detailed analysis of AGR-1 indicates that the fuel experienced significant time at high temperature. As indicated in Figure A-3, 10% of the AGR-1 fuel experienced temperatures of 1300°C for 100 to 200 days and a few percent experienced temperatures in excess of 1400°C for 50 days.

While the success of AGR-1 suggests that these times at high temperatures may not be deleterious, it is also not representative for a qualification irradiation, where the service conditions in the irradiation should try to better represent those anticipated in the reactor. In AGR-1, 50% of the fuel was above 1025-1100°C (depending on the capsule) on a time average basis, whereas for the GA reactor design that value is closer to 900-950°C. Less fuel should be at the high temperature end of the distribution and more fuel should be near the median and lower quartile of the distribution. Furthermore, our 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 I do not believe this effect is large we could be criticized for not incorporating this finding into our thinking about the irradiation.

As a design goal, I would recommend that 30% of the fuel be less than 900°C, 30% between 900 and 1050°C and 40% above 1050°C with less than 10% above 1250°C. This may be hard to accomplish in practice in a single capsule and should be discussed as part of our initial planning. The use of multiple capsules with different set points looks most practical at this point. (This does not include the high temperature capsules in the AGR-7 portion of the test train.)

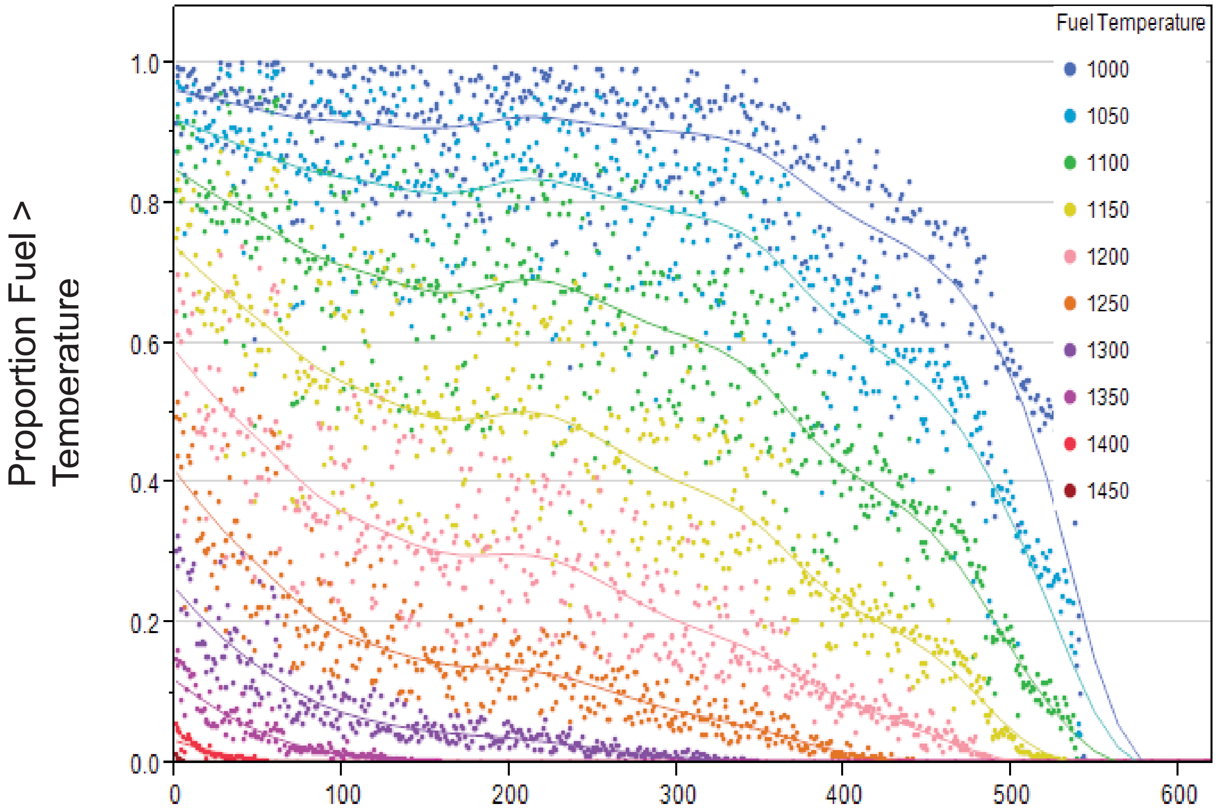

Figure A-3. Time at temperature plot for AGR-1 (proportion of fuel greater than a given temperature plotted versus effective fuel power days).

The control strategy taken in AGR-1 and AGR-2 was to set a peak temperature and control to that peak temperature based on calculations using a detailed 3-D thermal model. When thermocouples completely failed, control was based on calculation alone to set the gas mixture. This approach worked reasonably well. This was more difficult in AGR-1 because the control gap was shrinking due to swelling of the boronated graphite holders. For AGR-2, the control was much better as indicated by the flatness in the TC readings. The thermal model considers all modes of heat transfer and the degradation of the thermal conductivity of the carbonaceous fuel matrix and graphite with fluence. However, at times, it was difficult to control the peak temperature within our tight tolerance band given the changes in ATR operation and drift of TCs. Sometimes the fuel ended up running too cool relative to the peak and at other times near the end of the experiment when we were trying to keep temperatures high we overshot using the shim control cylinders. We anticipate much better thermal control in the NE flux trap than in the large B position. The 3-D thermal model we are using is also getting more sophisticated. For control in AGR-3/4, dimensional change of the graphite, which will affect gaps in the experiment, is being added as part of the as-run model explicitly (instead of only in the posttest analysis) to try to maintain temperatures as constant as possible. This capability can be used in AGR-5/6/7 as necessary.

3. STATISTICS

From a statistical standpoint, the more fuel that is irradiated the lower the 95% confidence bands will be on the estimated failure rate. In Figure A-4, using traditional binomial statistics a nominal population of 500,000 particles should give us adequate statistics even allowing for a few failures. The historical modular HTGR in-service failure rate core-wide is $2x10^{-4}$. I think we need to and can with the volume available in the flux trap do much better, on the order of $2x10^{-5}$. We can allow 5 failures over the entire test train to meet this failure level at 95% confidence.

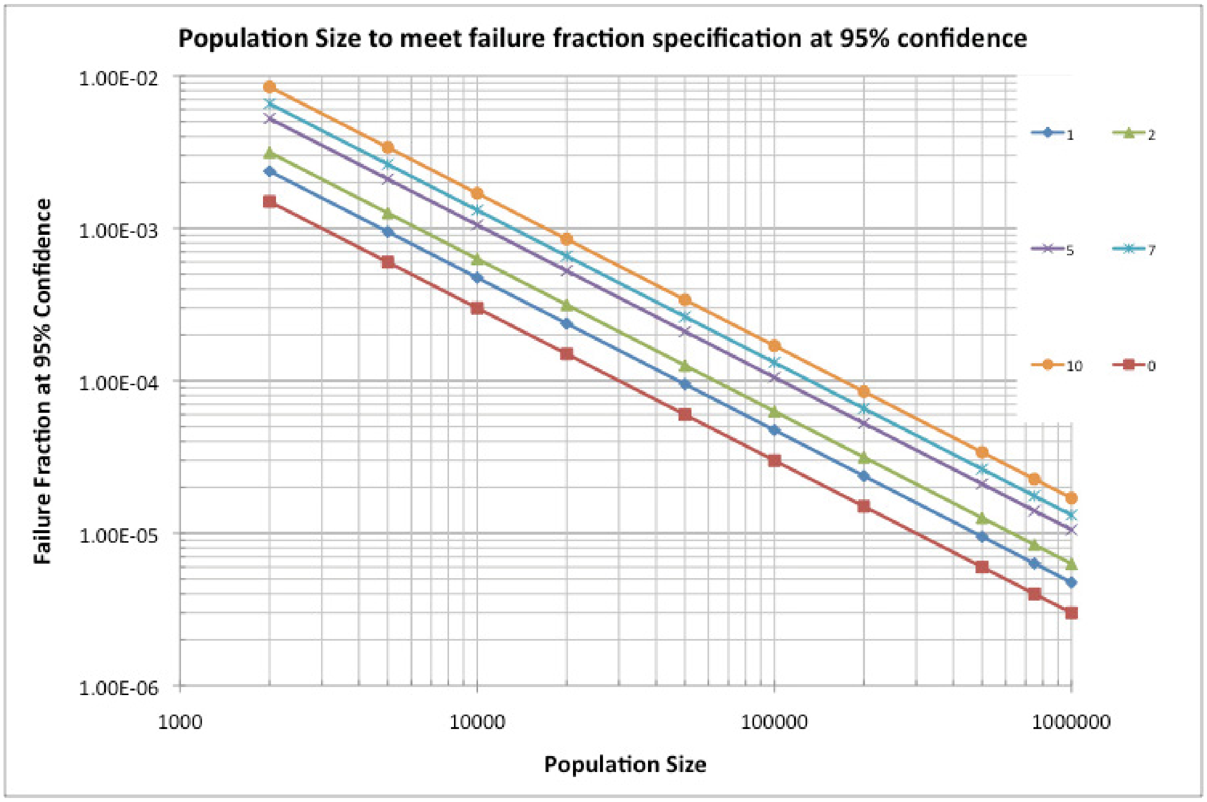

Figure A-4. Particle Failure Statistics.

Because we do not have a design yet, the qualification strategy must seek to reasonably bound the conditions in the anticipated reactor design with some margin to provide some flexibility to the designer. Thus, the strategy for the qualification testing is to use large enough subpopulation samples that one can build a failure rate versus irradiation temperature curve. At the same time, if the irradiation reasonably bounds the conditions expected in the reactor, then the reactor designer can use the failure statistics for the entire irradiation. If we can assure that only 10% of the agr-5/6 population is above 1250°C, that is 50,000 particles. Assuming 5 failures in that subpopulation would correspond to a failure fraction of $2x10^{-4}$, the core-wide reactor designer requirement for incremental failure. For other subpopulations, the failure fractions should be less than this value. This value of 50,000 particles should also be used in any of the margin tests to ensure good statistics.

A particle population of 500,000 should ensure plenty of compacts for safety testing. The historical reactor designer requirement for incremental failure under accident heatup conditions is $6x10^{-4}$, three times greater than the value under normal operation. Allowing for 5 failures with a particle population of 50,000 particles would result is a failure fraction of $2x10^{-4}$. This corresponds to 15 compacts that need to be heated at 1600°C (Note that the temperature might be 1650°C to account for uncertainties and would require some discussion before setting the exact value). Testing at higher temperatures, 1700 and 1800°C would use smaller populations, perhaps on the order of 20,000 particles (6 compacts) which would be still result in a 95% confidence value of $<6x10^{-4}$ for five or fewer failures. Under air or moisture ingress conditions, similar amounts of fuel would have to be tested because the allowable failure rate is the same. This strategy is captured in Figure A-5.

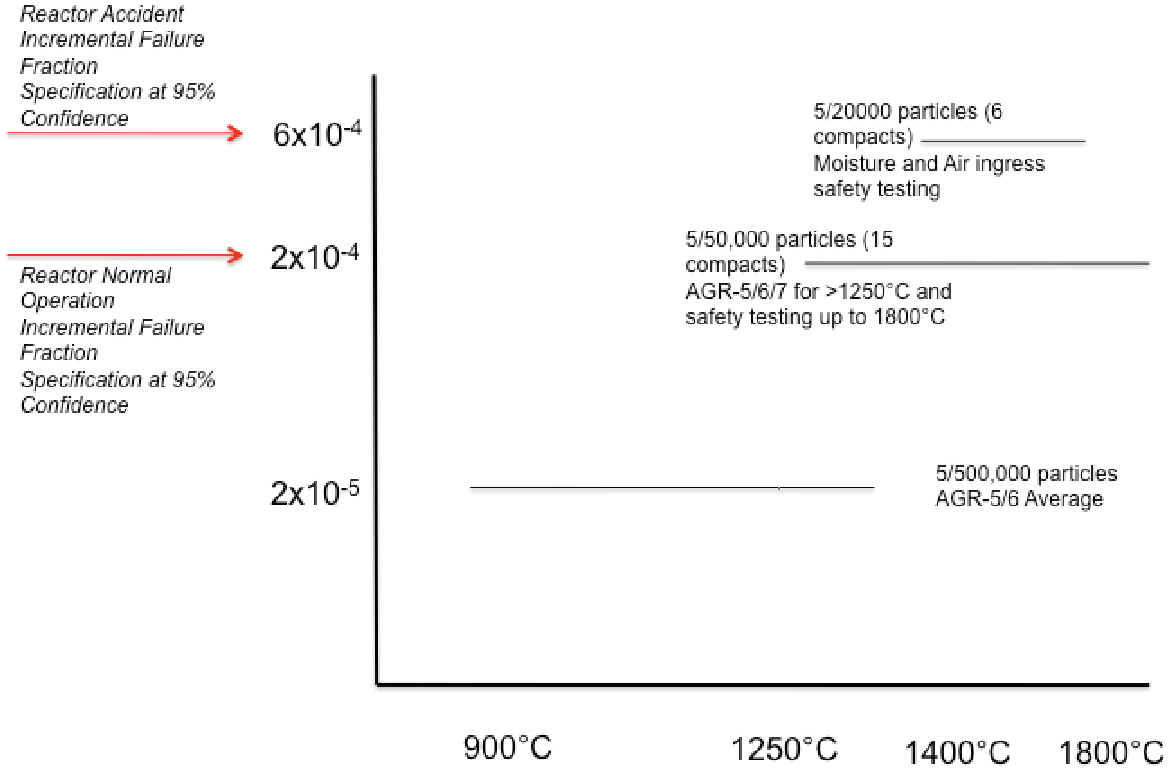

Figure A-5. Comparison of anticipated failure rates from irradiation and safety test compared to reactor specifications.

4. MARGIN TESTING

In the earliest versions of the AGR program plan, AGR-7 was to be a fuel performance validation experiment but as time evolved and discussions with NRC occurred it was clear that the concept of fuel margins needs to be explored as well. Additionally, our historic understanding of fuel performance and current PARFUME modeling suggests that time at temperature is really the dominant parameter that characterizes fuel performance because many of the potential degradation modes of TRISO fuel are Arrhenius temperature relationships (e.g., Pd attack, fission product corrosion, SiC thermal decomposition) as is fission product diffusion.

Of lesser importance are the remaining two primary variables, burnup and fast fluence. Burnup primarily affects the concentration of fission products, fuel kernel swelling, and transport behavior of fission products in the kernel. The burnup of AGR-1 will exceed that anticipated in AGR-5/6/7 and no deleterious affects associated with burnup have been observed. Fast fluence influences the shrinkage and swelling behavior of the PyC layers and radiation damage to the SiC. It is anticipated that the fast fluence in the ATR Northeast Flux Trap will be above that anticipated in a VHTR, perhaps as high as 6.5 to

8×10^{25} n/m^2, at the midpoint of the test train. While the database on PyC shrinkage and swelling is sparse beyond 5×10^{25} n/m^2 TRISO fuel should be capable of handling fast fluences at these slightly increased levels. Generally, the PyC stresses in particles peaks early due to shrinkage and irradiation induced creep slowly relaxes those stresses over time. Thus, if the PyC can survive the initial shrinkage it should be able to accept the slightly greater radiation damage up to a limit. There is also data, albeit limited, that suggests the IPyC reorients under the stress of irradiation causing it to become more anisotropic, which could induce greater stress during the reorientation. This effect is not incorporated in PARFUME given the paucity of data surrounding this effect but remains a concern at higher fluences.

Finally, the long times at high temperature experienced by some of the fuel in AGR-1 without failure coupled with NRC concerns about uncertainties in predictions of fuel temperatures in VHTRs (because of effects of bypass, thermal conductivity degradation of graphitic components etc.) suggests that exploration of higher fuel temperatures under irradiation is the proper objective for AGR-7. At this point, a peak time average temperature of about 1450°C is recommended, pending information from PIE of the AGR-2 1400°C hot capsule.

5. INSTRUMENTATION

Given the increased focus by NRC on in-pile temperature measurements in the AGR experiments and the lessons learned from our capsules to date, some redundancy and diversity of temperature measurement is recommended. Four different temperature measurements are envisioned:

a. INL high temperature thermocouples used in AGR-1

b. Conventional thermocouples that can be used in cooler spots in the capsules

c. SiC thermocouples (maybe RTDs) by Sporian

d. Thermoacoustic measurements by INL researcher.

The exact placement of the devices will await the availability of the sensors and design of the capsule. Given the two new measurement types in items (c) and (d), a mockup of a capsule with heater rods representing the fuel will be used to qualify the two measurements prior to use in the AGR-5/6/7. This mockup will include a gap in which we can change the gas composition. The INL thermal model can them be compared to the measurements. This should also increase NRC confidence in our use of the thermal model to predict fuel temperatures.

Beyond thermal measurements, the need to measure the neutron flux profile in real time is also under consideration. While such flux instruments (e.g., self-powered neutron detectors, micro fission chambers) will not survive long in the ATR environment, such a measurement if it could be incorporated into the design would be very valuable to confirm physics models.