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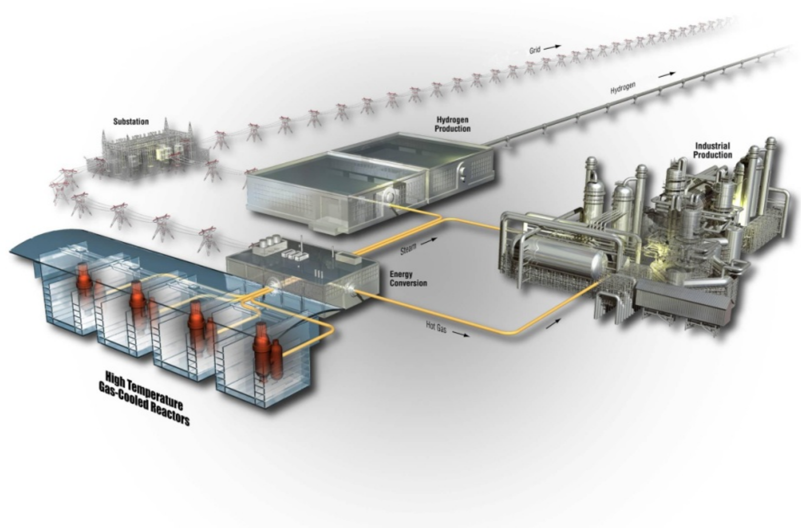
Plan

Project No. 23841

AGR-5/6/7 Irradiation Experiment Test Plan



Idaho National Laboratory

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SUMMARY

This document presents the test plan for the AGR-5/6/7 irradiation experiment, the combined fifth, sixth, and seventh irradiations of the U.S. Department of Energy Advanced Gas Reactor (AGR) Fuel Development and Qualification Program. The combined irradiation tests will consist of fuel qualification tests (AGR-5/6) and a margin test (AGR-7) for the industrially-produced uranium oxycarbide (UCO) tristructural isotropic (TRISO) coated particle fuel developed by the AGR program. The objective of the AGR-5/6/7 irradiation experiment is to establish the performance of UCO TRISO fuel fabricated using engineering-scale equipment in a production environment under and beyond normal operating conditions. Specifically, the goals of the AGR-5/6/7 irradiation experiment are:

1. Irradiate reference design fuel containing low-enriched UCO TRISO fuel particles to support fuel qualification.
2. Establish the operating margins for the fuel beyond normal operating conditions.
3. Provide irradiated fuel performance data and irradiated fuel samples for post-irradiation examination and safety testing.

In order to achieve the test objectives, the AGR-5/6/7 experiment will be irradiated in the northeast flux trap position of the Advanced Test Reactor at Idaho National Laboratory. The larger diameter of the northeast flux trap provides greater flexibility for test train design compared to the large B positions used for the AGR-1 and AGR-2 experiments, significantly enhancing the capability for the combined irradiations. The test train contains five separate and independently-controlled and -monitored capsules. The middle capsule constitutes the AGR-7 test, while the two bottom and two top capsules constitute the AGR-5/6 test. The capsules are filled with fuel compacts containing UCO TRISO particles, using two different packing fractions (nominally 25 and 40%).

The irradiation is planned for approximately 500 effective full power days (corresponding to about two and one-half calendar years) with peak fuel temperatures ranging between 750 and 1350°C depending on the specific AGR-5/6 capsule and between 1350 and 1500°C in the AGR-7 capsule. The AGR-5/6 irradiation temperatures are designed to envelope the range of operational temperatures in a high-temperature gas-cooled reactor core. The AGR-7 capsule will experience higher temperatures as part of the margin test because of the importance of time at temperature in TRISO fuel performance. The AGR-7 experiment was designed so that some measurable level of fuel failure and/or fission product release is expected to occur, allowing assessment of fuel performance beyond normal operating conditions and demonstration of safety margin between normal operating conditions and the temperatures at which fuel particle failure rate becomes unacceptable.

The burnup and fast neutron fluence specifications are identical for the AGR-5/6 and AGR-7 tests. In each test, compact average fuel burnup will be greater than 6% fissions per initial metal atom for all compacts and greater than 18% fissions per initial metal atom for at least one compact. The fuel will experience fast neutron fluences between approximately 1.5 and 7.5×10^{25} n/m^2 (E>0.18 MeV) and at least one compact in each test will experience a fast neutron fluence > 5.0×10^{25} n/m^2 (E>0.18 MeV).

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ACRONYMS

AGR	Advanced Gas Reactor
ASME	American Society of Mechanical Engineers
ATR	Advanced Test Reactor
AWS	American Welding Society
BOL	beginning of life
BWXT	BWX Technologies
CIC	core internals changeout
EFPD	effective full power day
EOL	end of life
FIMA	fissions per initial (heavy) metal atom
FPMS	fission product monitoring system
HPGe	high-purity germanium
HTGR	high-temperature gas-cooled reactor
HTIR	high-temperature irradiation resistant
INL	Idaho National Laboratory
IPyC	inner pyrolytic carbon
MPFD	micropocket fission detector
NaI(Tl)	sodium iodide activated/doped with thallium
NDMAS	Nuclear Data Management and Analysis System
NEFT	northeast flux trap
OPTAF	optical anisotropy factor
OPyC	outer pyrolytic carbon
PALM	powered axial locator mechanism
PIE	post-irradiation examination
R/B	release rate to birth rate
RTC	reactor technology complex
SiC	silicon carbide
S/N	serial number
SPND	self-powered neutron detector
TC	thermocouple
TDO	Technology Development Office
TRISO	tristructural isotropic
UCO	uranium oxycarbide

1. INTRODUCTION

Several fuel and material irradiation experiments have been planned for the U.S. Department of Energy Advanced Gas Reactor (AGR) Fuel Development and Qualification Program, which supports the development and qualification of tristructural isotropic (TRISO) coated particle fuel for use in high-temperature gas-cooled reactors (HTGRs). The goals of these experiments are to provide irradiation performance data to support fuel process development, qualify fuel for normal operating conditions, support development of fuel performance models and codes, and provide irradiated fuel and materials for post-irradiation examination (PIE) and safety testing (INL, 2017a). Originally planned and named as separate fuel experiments, but subsequently combined into a single test train, AGR-5/6/7 will test low-enriched uranium oxycarbide (UCO – a heterogeneous mixture of uranium oxide and uranium carbide) TRISO 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 beyond normal operating conditions.

This test plan presents the conceptual planning to implement requirements from the AGR Technical Program Plan (INL, 2017a) and the Irradiation Test Specification (Maki, 2015) for the AGR-5/6/7 experiment. Following this introduction, the test objectives and experimental approach are outlined in Section 2; descriptions of the test articles, test train, and fission product monitoring system (FPMS) are presented in Section 3; anticipated irradiation conditions, including temperature, burnup, and fast neutron fluence are presented in Section 4; measurements associated with test conduct are described in Section 5; significant operational procedures that apply to AGR-5/6/7 are briefly described in Section 6; safety and quality assurance issues are outlined in Section 7; program constraints and test schedule are listed in Section 8; and references are presented in Section 9. Requirements and planning associated with PIE and safety testing of the AGR-5/6/7 test articles will be presented elsewhere.

2. BACKGROUND

2.1 Test Objectives

As defined in the AGR Technical Program Plan (INL, 2017a), the objectives of the AGR-5/6/7 experiment are to:

1. Irradiate reference design fuel containing low-enriched UCO TRISO fuel particles to support fuel qualification.
2. Establish the operating margins for the fuel beyond normal operating conditions.
3. Provide irradiated fuel performance data and irradiated fuel samples for PIE and safety testing.

The primary objective of the AGR-5/6 test is to verify successful performance of the reference design fuel by demonstrating compliance with statistical performance requirements under normal operating and potential accident conditions. As fuel performance is dependent on time at temperature and many degradation modes of TRISO fuel (e.g., palladium attack and fission product corrosion of the silicon carbide (SiC) layer, SiC thermal decomposition), as well as fission product transport, are enhanced at higher temperatures, the AGR-7 test was designed to explore fuel performance at higher fuel temperatures. Its primary objective is to demonstrate the capability of the fuel to withstand conditions beyond AGR-5/6 normal operating conditions in support of plant design and licensing.

AGR-5/6/7 will also provide irradiated fuel performance data on fission product gas release from failed particles during irradiation and provide irradiated fuel samples for safety testing and PIE. The in-pile gas release, PIE, and safety testing data on fission gas and metal release from kernels will be used in the development of improved fuel performance and fission product transport models.

2.2 Experiment Approach

To achieve the test objectives outlined above, AGR-5/6/7 will be irradiated in the northeast flux trap (NEFT) position of the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL). A core cross section indicating this location is displayed in Figure 1.

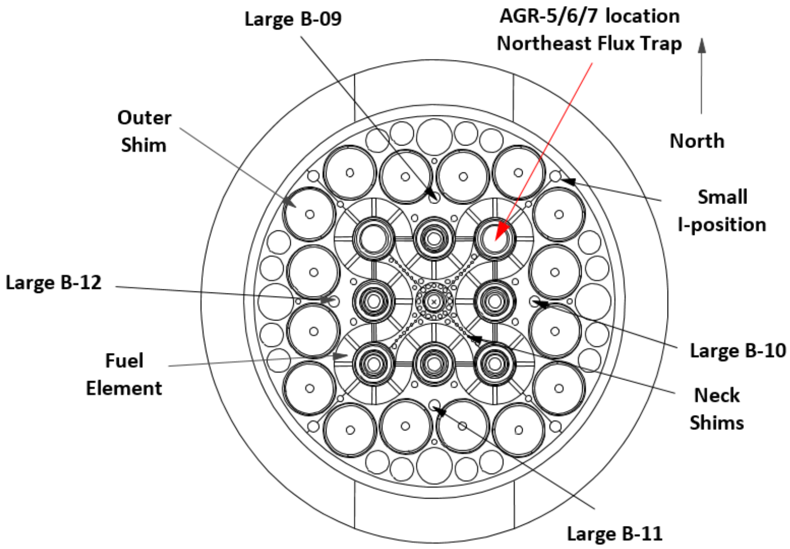

Figure 1. ATR core cross section displaying the NEFT position.

Initial physics calculations (Chang and Parry, 2013) have shown that the NEFT is 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 the amount of fuel required for qualification testing. Further physics calculations (Sterbentz, 2017) have shown that by extrapolating to 500 effective full power days (EFPDs) of irradiation in this position, fuel compact burnups will exceed 18% fissions per initial metal atom (FIMA) with fast neutron fluences of about 7.3×10^{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 were made to reduce the fast neutron fluence by use of neutron filters. Contrary to the Large B positions used for AGR-1 and AGR-2, the larger diameter of the NEFT also provides greater flexibility for test train design, significantly enhancing the capability for the combined irradiations. Specifically, the AGR-5/6/7 irradiation in the NEFT position:

- Efficiently utilizes the ample space afforded by the NEFT to accommodate enough fuel for the needs of qualification and margin tests
- Reduces the irradiation time due to the higher achievable flux levels relative to other ATR irradiation locations
- Allows the use of neutron filters to maintain more consistent compact power as the fuel burns out
- Allows power level control (corner lobes controlled independently).

In addition, the rate of burnup and fast fluence accumulation, or acceleration, in this position is less than three times that expected in an 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 (Petti et al., 2002).

The AGR-5/6/7 test train is based on the experience gained from previous irradiations in ATR, using instrumented lead experiments. Instrumented lead experiments are used for irradiations requiring a controlled environment and monitored parameters. The AGR-5/6/7 test train contains five separate capsules and will use the full 1.2-m active core height in ATR to maximize the amount of irradiated fuel (~500,000 particles in AGR-5/6 and ~50,000 particles in AGR-7) and span the desired broad range of fuel burnup and temperature combinations expected in a modular HTGR. This will provide more representative data on TRISO fuel performance. Each capsule is filled with fuel compacts containing UCO TRISO particles. The capsules will be irradiated in an inert sweep gas atmosphere with individual online temperature monitoring and control. The sweep gas also has online fission product monitoring of its effluent to track performance of the fuel in each individual capsule during irradiation.

Figure 2 shows an axial schematic of the AGR-5/6/7 test train with the four AGR-5/6 capsules (Capsules 1, 2, 4, and 5) and the AGR-7 capsule (Capsule 3). For AGR-5/6, 30% of the ~500,000 particles will operate at <900°C, 30% will operate at 900 to 1050°C, 30% will operate at 1050 to 1250°C, and the remaining 10% will operate at 1250 to 1350°C[a]. For the margin test, AGR-7, all ~50,000 particles will operate at 1350 to 1500°C. The burnup and fast neutron fluence specifications are identical for the AGR-5/6 and AGR-7 tests. In each test, compact average fuel burnup will be greater than 6% for all compacts and greater than 18% FIMA for at least one compact. The fuel will experience fast neutron fluences between approximately 1.5 and 7.5 × 10^{25} n/m^2 (E>0.18 MeV) and at least one compact in each test will experience a fast neutron fluence greater than 5.0 × 10^{25} n/m^2 (E>0.18 MeV). To attain these goals and still be able to control the temperature in the capsules, two packing fractions of compacts are used in the test train. Compacts with a 40% nominal packing fraction are used in Capsules 1 and 5, and compacts with a 25% nominal packing fraction are used in Capsules 2, 3, and 4.

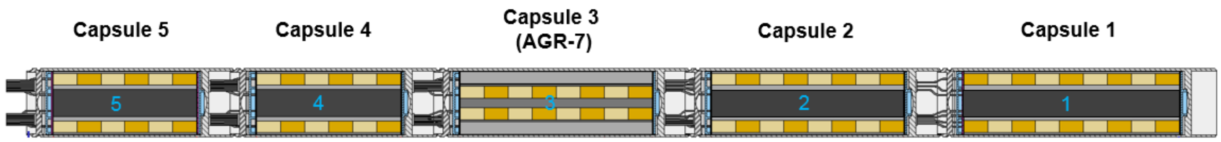

Figure 2. Axial schematic of the AGR-5/6/7 test train.

2.3 Experiment Schedule

The initially-proposed schedule for the AGR-5/6/7 irradiation experiment is presented in Table 1. The physics and thermal pre-test predictions (see Section 2.2 and Section 4) were performed using this schedule. It consists of nine regular ATR power cycles and four intermittent high-power powered axial locator mechanism (PALM) cycles. Altogether, the thirteen cycles were estimated to bring the total irradiation duration of the AGR-5/6/7 test train over the required 500 EFPDs.

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[a] The AGR-5/6/7 Irradiation Test Specification (Maki, 2015) indicates an upper temperature of 1400°C. It was later decided to reduce this temperature to 1350°C to better separate the thermal ranges of AGR-5/6 and AGR-7.

Table 1. Initially-proposed AGR-5/6/7 irradiation schedule.

Cycle	Cycle Type	Cycle Length (EFPD)	Northeast Lobe Power (MW)
1	Regular	50	14
2	Regular	50	14
3	PALM	15	20
4	Regular	50	14
5	Regular	50	14
6	PALM	15	20
7	Regular	50	14
8	Regular	50	16
9	PALM	15	20
10	Regular	50	18
11	Regular	50	18
12	PALM	15	20
13	Regular	50	18
	Total	510	—

Refinement of the ATR schedule and delay in the fabrication of the AGR-5/6/7 fuel shifted the insertion of the test train in the reactor and the beginning of its irradiation by one cycle. With the current estimated schedule, only 476 EFPDs of irradiation will be accumulated before the planned core internals changeout (CIC). CIC consists of the replacement of ATR internal components that fatigue and weaken over time because of high neutron flux exposure. Periodic changeout of these components allows the ATR facility's safety to be ensured, and safe and continued operation to be maintained. During the currently planned 9-month CIC outage, the AGR-5/6/7 test train will be transferred and stored in the large ATR canal adjacent to the reactor vessel. The test train will then be re-inserted in the NEFT for another ATR power cycle to reach its target irradiation length of 500 EFPDs, which will ensure the required burnup and fast neutron fluence levels are achieved.

Table 2 summarizes the current estimated AGR-5/6/7 irradiation schedule.

Table 2. Current estimated AGR-5/6/7 irradiation schedule.

Cycle	Cycle Type	Cycle Length (EFPD)	Northeast Lobe Power (MW)
1	Regular	38	14 ± 1
2	PALM	7 [(a)]	11 ± 3 and 20 ± 2
3	Regular	54	14 ± 1
4	Regular	59	14 ± 1
5	PALM	14	20 ± 2
6	Regular	59	14 ± 1
7	Regular	56	14 ± 1
8	PALM	7 [(a)]	11 ± 3 and 20 ± 2
9	Regular	56	16 ± 1

Table 2. (continued).

Cycle	Cycle Type	Cycle Length (EFPD)	Northeast Lobe Power (MW)
10	Regular	56	18 ± 1
11	PALM	14	20 ± 2
12	Regular	56	18 ± 1
	Subtotal	476	—
Core Internals Changeout (274 days)			
13	Regular	45	18 ± 1
	Total	521	—

(a) The 7-day PALM cycles will be run 5 days at 11 MW and 2 days at 20 MW.

3. EXPERIMENT DESCRIPTION

3.1 Fuel Particles

Fuel for AGR-5/6/7 consists of reference design UCO TRISO-coated particles that are slightly less than 1 mm in diameter. Each particle has a central kernel containing the fuel material, a porous carbon buffer layer, an inner pyrolytic carbon (IPyC) layer, an SiC barrier coating, and an outer pyrolytic carbon (OPyC) layer. AGR-5/6 and AGR-7 use the same reference design fuel. This fuel design is illustrated in Figure 3. The functions of each coating layer are listed in Table 3.

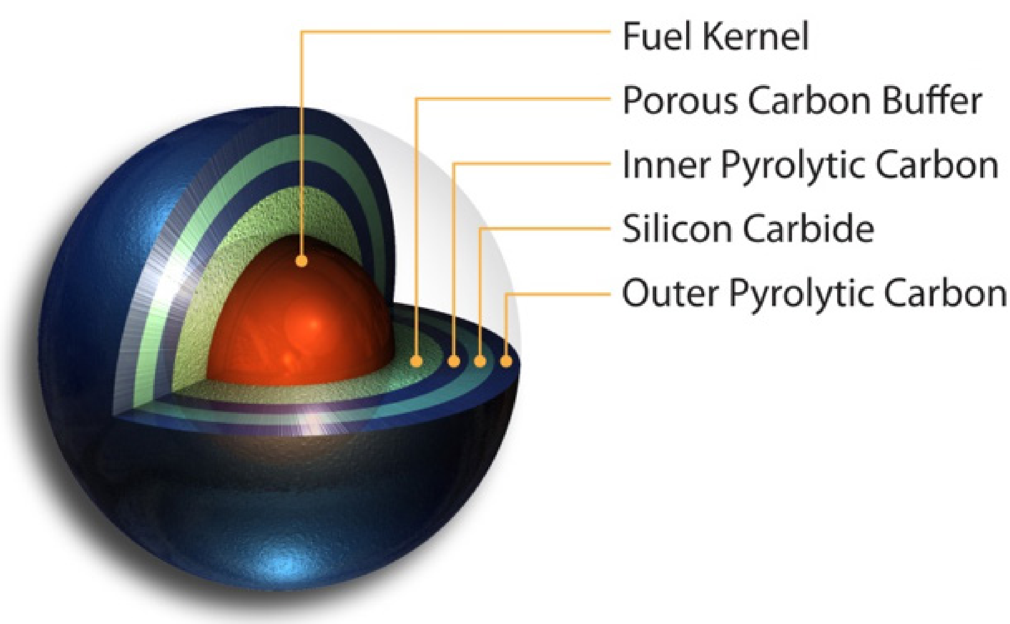


Figure 3. Graphic of a typical TRISO-coated fuel particle.

Table 3. Primary functions of particle fuel components.

Component	Primary Function
Kernel	Contains fissile/fertile fuel
Buffer	Provides void space for fission product gases and accommodates differential changes in dimensions between coating layers and the kernel
IPyC	Structural layer and fission gas barrier that protects the kernel during SiC deposition and the SiC layer from most fission products during irradiation
SiC	Primary structural layer and primary fission product barrier
OPyC	Structural layer that also permits embedding the particles in graphitic matrix material

Kernels for AGR-5/6/7 consist of low-enriched UCO fuel. The kernels were fabricated by BWX Technologies (BWXT, 2016) in accordance with the AGR-5/6/7 Fuel Specification (Marshall, 2017). Several production batches were combined into a single composite: Lot J52R-16-69317. Complete characterization data for this kernel lot are compiled in the Data Certification Package (BWXT, 2016). Selected kernel composite properties and corresponding fuel product specifications are listed in Table 4.

Table 4. Selected properties for AGR-5/6/7 kernel Lot J52R-16-69317.

Property	Specified Range for Mean Value	Actual Mean Value ± Population Standard Deviation
Diameter (µm)	425 ± 10	425.78 ± 10.42
Density (g/cm^3)	≥10.4	11.048 ± 0.044
U-235 enrichment (wt%)	15.5 ± 0.1	15.477 ± 0.013
Carbon/uranium (atomic ratio)	0.40 ± 0.10	0.370 ± 0.000
Oxygen/uranium (atomic ratio)	1.50 ± 0.20	1.441 ± 0.004
[Carbon + oxygen]/uranium (atomic ratio)	≤2.0	1.811 ± 0.004
Total uranium (wt%)	≥88.5	89.684 ± 0.040
Sulfur impurity (ppm – wt)	≤1500	247 ± 14
Phosphorus impurity (ppm – wt)	≤1500	25 ± 8
All other impurities (ppm – wt)	≤100 each	≤31 each [(a)]
(a) Upper limit of the 95% confidence interval		

The UCO kernels were coated and characterized by BWXT (BWXT, 2017a). Coating was performed in accordance with the AGR-5/6/7 Fuel Specification (Marshall, 2017). Several production batches were combined into a single composite: Lot J52R-16-98005. A summary of selected properties and corresponding mean value specifications, where applicable, are listed in Table 5.

Table 5. Selected properties for AGR-5/6/7 coated particle Lot J52R-16-98005.

Property	Specified Range for Mean Value	Actual Mean Value ± Population Standard Deviation
Buffer thickness (µm)	100 ± 15	100.37 ± 5.55
IPyC thickness (µm)	40 ± 4	39.24 ± 1.26
SiC thickness (µm)	35 ± 3	36.15 ± 0.65
OPyC thickness (µm)	40 ± 4	35.03 ± 1.99 [(a)]

Table 5. (continued).

Property	Specified Range for Mean Value	Actual Mean Value ± Population Standard Deviation
Buffer density (g/cm^3)	1.05 ± 0.10	1.031 ± 0.022
IPyC density (g/cm^3)	1.90 ± 0.05	1.897 ± 0.010
SiC density (g/cm^3)	≥3.19	3.195 ± 0.002
OPyC density (g/cm^3)	1.90 ± 0.05	1.897 ± 0.004
IPyC diattenuation Optical anisotropy factor (OPTAF) [b, c]	≤0.0170 ≤1.045	0.0153 ± 0.0010 1.031 ± 0.002
OPyC diattenuation Optical anisotropy factor (OPTAF) [b, c]	≤0.0122 ≤1.035	0.0102 ± 0.0006 1.021 ± 0.001
IPyC OTPAF post compact anneal [c]	Not specified	1.0388
OPyC OPTAF compact anneal [c]	Not specified	1.0296
SiC aspect ratio [d]	Not specified [e]	1.053 ± 0.009
Particle mass (mg)	Not specified	1.02

(a) The OPyC thickness mean value is below its specified range. Online monitoring and post-irradiation feedback from previous AGR irradiation experiments suggests that the AGR-5/6/7 measured OPyC thickness on TRISO batches composing Lot J52R-16-98005 will not have a deleterious effect on in-pile performance. Therefore, Lot J52R-16-98005 was accepted for use as is.

(b) The optical anisotropy factor is obtained from the diattenuation N as: $\mathrm{OPTAF} = \frac{1+N}{1-N}$

(c) Measured values obtained from Helmreich et al. (2017).

(d) Aspect ratio is defined as the ratio of maximum to minimum diameters of the coated particle and is measured on SiC-coated particles following burn back of the OPyC layer.

(e) Critical region is specified such that ≤1% of the particles must have an aspect ratio ≥1.14.

3.2 Fuel Compacts

After coating, AGR-5/6/7 fuel was formed into right cylindrical compacts. The compact matrix material is composed of natural and synthetic graphite powders and a thermosetting phenolic resin. Prior to compacting, the fuel particles were overcoated with thick layers of the resinated graphite matrix material. This overcoat is intended to prevent particle-to-particle contact and help achieve the desired packing fractions of fuel particles. The compacts were overcoated and compacted in four different batches: J52R-16-14154, J52R-16-14155, J52R-16-14156, and J52R-16-14157. For each batch, the compacts were separated in four series, labelled A to D, for heat treatment. The fourth furnace run (series D) did not have any compacts from batch J52R-16-14157 as the entire batch was treated in the first three furnace runs. The second furnace run (series B) was interrupted after resin carbonization to fix a problem establishing the desired vacuum in the furnace.

AGR-5/6/7 compacts are nominally 25.0 mm in length and 12.3 mm in diameter. The AGR-5/6/7 fuel compacts were fabricated with two different nominal particle loadings (packing fractions 25 and 40%). A summary of selected properties, based on actual characterization data (BWXT, 2017b) and derived from these data, is listed in Table 6 along with mean value specifications, where applicable, for comparison purposes. Data for compact mass, diameter, and length are based on averages of the 432 compacts sent to INL (batches J52R-16-14154A and J52R-16-14155A for 40% packing fraction and batches J52R-16-14156A and J52R-16-14157A for 25% packing fraction). Destructive chemical analyses to determine the other attributes in Table 6 were performed on batches J52R-16-14154C, J52R-16-14155C, J52R-16-14156C, J52R-16-14157C (series B was deemed unsuitable because of furnace interruption and series D did not represent all compact batches). For traceability, Table 7 and Table 8 list the compacts sent to INL. For each batch, Table 7 shows the number of compacts used in the AGR-5/6/7 capsules.

Table 6. Selected properties for AGR-5/6/7 compacts.

Property	Specified Range for Mean Value	Actual Mean Value ± Population Standard Deviation
Compact mass (g)		
Capsule 1	Not specified	6.676 ± 0.065
Capsule 2		6.182 ± 0.026
Capsule 3		6.187 ± 0.021
Capsule 4		6.100 ± 0.034
Capsule 5		6.603 ± 0.021
Mean uranium loading (g U/compact)		
Capsule 1	1.36 ± 0.10	1.362 ± 0.011
Capsule 2	0.90 ± 0.08	0.898 ± 0.007
Capsule 3	0.90 ± 0.08	0.898 ± 0.007
Capsule 4	0.90 ± 0.08	0.871 ± 0.009
Capsule 5	1.36 ± 0.10	1.346 ± 0.016
Diameter [(a)] (mm)		
Capsule 1	12.20–12.44	12.293 ± 0.007
Capsule 2		12.241 ± 0.007
Capsule 3		12.245 ± 0.006
Capsule 4		12.248 ± 0.006
Capsule 5		12.296 ± 0.006
Length [(a)] (mm)		
Capsule 1	24.40–25.30	24.947 ± 0.219
Capsule 2		24.991 ± 0.098
Capsule 3		25.000 ± 0.078
Capsule 4		24.770 ± 0.119
Capsule 5		24.675 ± 0.059
Number of particles per compact [(b)]		
Capsule 1	Not specified	3460
Capsule 2		2281
Capsule 3		2282
Capsule 4		2213
Capsule 5		3419
Particle volume packing fraction (%)		
Capsule 1	40	39.3
Capsule 2	25	26.1
Capsule 3	25	26.1
Capsule 4	25	26.0
Capsule 5	40	39.3
Effective overall compact density [(b)] (g/cm^3)		
Capsule 1	Not specified	2.26
Capsule 2		2.10
Capsule 3		2.10
Capsule 4		2.09
Capsule 5		2.25

Table 6. (continued).

Property	Specified Range for Mean Value	Actual Mean Value ± Population Standard Deviation
Compact matrix density (g/cm^3)		
Capsule 1	≥1.65	1.729 ± 0.007
Capsule 2		1.761 ± 0.005
Capsule 3		1.761 ± 0.005
Capsule 4		1.748 ± 0.007
Capsule 5		1.727 ± 0.007
Compact weight% U [(b)]		
Capsule 1	Not specified	20.40
Capsule 2		14.52
Capsule 3		14.52
Capsule 4		14.28
Capsule 5		20.38
Compact weight% O [(b)]		
Capsule 1	Not specified	1.98
Capsule 2		1.41
Capsule 3		1.41
Capsule 4		1.39
Capsule 5		1.98
Compact weight% Si [(b)]		
Capsule 1	Not specified	7.18
Capsule 2		5.11
Capsule 3		5.11
Capsule 4		5.03
Capsule 5		7.18
Compact weight% C [(b)]		
Capsule 1	Not specified	70.44
Capsule 2		78.96
Capsule 3		78.96
Capsule 4		79.31
Capsule 5		70.47
Iron content (μg Fe outside of SiC/compact)	≤25	<5
Chromium content (μg Cr outside of SiC/compact)	≤50	<25
Manganese content (μg Mn outside of SiC/compact)	≤50	<10
Cobalt content (μg Co outside of SiC/compact)	≤50	<10
Nickel content (μg Ni outside of SiC/compact)	≤50	<10
Calcium content (μg Ca outside of SiC/compact)	≤50	<25
Aluminum content (μg Al outside of SiC/compact)	≤50	<25

Table 6. (continued).

Property	Specified Range for Mean Value	Actual Mean Value ± Population Standard Deviation
Titanium content (µg Ti outside of SiC/compact)	Note (c)	<10
Vanadium content (µg V outside of SiC/compact)	Note (c)	<10
Dispersed uranium fraction [d] (g leached U/g U in compact)		
Nominal 25% packing fraction	$\leq 1.0 \times 10^{-5}$	$\leq 2.95 \times 10^{-5}$ [e]
Nominal 40% packing fraction	$\leq 1.0 \times 10^{-5}$	$\leq 3.80 \times 10^{-5}$ [e]
Exposed kernel fraction [d] (kernel equivalent/particle count)		
Nominal 25% packing fraction	$\leq 5.0 \times 10^{-5}$	$\leq 1.48 \times 10^{-5}$
Nominal 40% packing fraction	$\leq 5.0 \times 10^{-5}$	$\leq 9.28 \times 10^{-5}$ [e]
Defective SiC coating fraction [d]		
Nominal 25% packing fraction	$\leq 1.0 \times 10^{-4}$	$\leq 1.22 \times 10^{-4}$ [e]
Nominal 40% packing fraction	$\leq 1.0 \times 10^{-4}$	$\leq 9.66 \times 10^{-5}$
Defective IPyC coating fraction [d]	$\leq 1.0 \times 10^{-4}$	$\leq 7.6 \times 10^{-5}$
Defective OPyC coating fraction [d]	$\leq 1.0 \times 10^{-2}$	$\leq 8.6 \times 10^{-5}$

(a) Allowable range corresponding to upper and lower critical limits specified with no compacts exceeding the limits, which require 100% inspection of all compacts.
(b) Calculated value derived from other characterized properties.
(c) Mean value specification of ≤240 µg Ti+V outside of SiC per compact.
(d) 95% confidence fraction.
(e) The 95% confidence fraction exceeds the specification. A Quality Control Deficiency Notice (No. J52-005) has been issued in the data certification package (BWXT, 2017b) with a disposition to use as is.

Table 7. AGR-5/6/7 compact batches.

Batch	Nominal Packing Fraction	Compact Serial Number (S/N) Range	Capsule	Number of Compacts
J52R-16-14154A	40%	0001 to 0108	1	55
J52R-16-14155A	40%	0109 to 0216	1 5	35 24
J52R-16-14156A	25%	0217 to 0324	2 3	32 24
J52R-16-14157A	25%	0325 to 0432	4	24

Table 8. Position of AGR-5/6/7 compacts in test train.

Compact S/N[a]	Assigned Position[b]	Compact S/N[a]	Assigned Position[b]	Compact S/N[a]	Assigned Position[b]	Compact S/N[a]	Assigned Position[b]
0003	1-9-1	0098	1-5-6	0177	5-4-2	0289	3-7-1
0005	1-8-1	0100	1-4-6	0180	5-3-2	0291	3-6-1
0006	1-7-1	0102	1-3-6	0181	5-2-2	0293	3-5-1
0007	1-6-1	0104	1-2-6	0182	5-1-2	0294	3-4-1

Table 8. (continued).

Compact S/N[(a)]	Assigned Position[(b)]	Compact S/N[(a)]	Assigned Position[(b)]	Compact S/N[(a)]	Assigned Position[(b)]	Compact S/N[(a)]	Assigned Position[(b)]
0010	1-5-1	0105	1-1-6	0187	5-6-3	0296	3-3-1
0011	1-4-1	0108	1-9-7	0188	5-5-3	0297	3-2-1
0012	1-3-1	0112	1-8-7	0190	5-4-3	0298	3-1-1
0014	1-2-1	0114	1-7-7	0192	5-3-3	0299	3-8-2
0017	1-1-1	0115	1-6-7	0193	5-2-3	0300	3-7-2
0019	1-9-2	0117	1-5-7	0194	5-1-3	0301	3-6-2
0021	1-8-2	0119	1-4-7	0195	5-6-4	0304	3-5-2
0022	1-7-2	0121	1-3-7	0196	5-5-4	0305	3-4-2
0023	1-6-2	0122	1-2-7	0197	5-4-4	0306	3-3-2
0024	1-5-2	0123	1-1-7	0198	5-3-4	0307	3-2-2
0027	1-4-2	0124	1-9-8	0201	5-2-4	0309	3-1-2
0028	1-3-2	0125	1-8-8	0202	5-1-4	0310	3-8-3
0029	1-2-2	0126	1-7-8	0245	2-8-1	0311	3-7-3
0030	1-1-2	0127	1-6-8	0246	2-7-1	0312	3-6-3
0032	1-9-3	0128	1-5-8	0249	2-6-1	0315	3-5-3
0036	1-8-3	0129	1-4-8	0251	2-5-1	0317	3-4-3
0037	1-7-3	0130	1-3-8	0253	2-4-1	0318	3-3-3
0038	1-6-3	0132	1-2-8	0254	2-3-1	0319	3-2-3
0039	1-5-3	0133	1-1-8	0255	2-2-1	0324	3-1-3
0041	1-4-3	0135	1-9-9	0256	2-1-1	0328	4-6-1
0046	1-3-3	0136	1-8-9	0257	2-8-2	0329	4-5-1
0047	1-2-3	0138	1-7-9	0258	2-7-2	0332	4-4-1
0048	1-1-3	0141	1-6-9	0259	2-6-2	0337	4-3-1
0049	1-9-4	0142	1-5-9	0260	2-5-2	0339	4-2-1
0055	1-8-4	0145	1-4-9	0261	2-4-2	0346	4-1-1
0057	1-7-4	0146	1-3-9	0262	2-3-2	0347	4-6-2
0059	1-6-4	0147	1-2-9	0264	2-2-2	0349	4-5-2
0060	1-5-4	0148	1-1-9	0265	2-1-2	0352	4-4-2
0061	1-4-4	0150	1-9-10	0266	2-8-3	0353	4-3-2
0063	1-3-4	0151	1-8-10	0267	2-7-3	0354	4-2-2
0066	1-2-4	0152	1-7-10	0268	2-6-3	0356	4-1-2
0067	1-1-4	0153	1-6-10	0269	2-5-3	0357	4-6-3
0070	1-9-5	0156	1-5-10	0271	2-4-3	0360	4-5-3
0072	1-8-5	0157	1-4-10	0276	2-3-3	0370	4-4-3
0074	1-7-5	0159	1-3-10	0277	2-2-3	0374	4-3-3
0077	1-6-5	0161	1-2-10	0278	2-1-3	0375	4-2-3

Table 8. (continued).

Compact S/N[(a)]	Assigned Position[(b)]	Compact S/N[(a)]	Assigned Position[(b)]	Compact S/N[(a)]	Assigned Position[(b)]	Compact S/N[(a)]	Assigned Position[(b)]
0081	1-5-5	0164	1-1-10	0279	2-8-4	0378	4-1-3
0082	1-4-5	0167	5-6-1	0280	2-7-4	0379	4-6-4
0085	1-3-5	0168	5-5-1	0282	2-6-4	0382	4-5-4
0087	1-2-5	0170	5-4-1	0283	2-5-4	0383	4-4-4
0089	1-1-5	0171	5-3-1	0284	2-4-4	0385	4-3-4
0090	1-9-6	0172	5-2-1	0285	2-3-4	0392	4-2-4
0091	1-8-6	0173	5-1-1	0286	2-2-4	0394	4-1-4
0093	1-7-6	0174	5-6-2	0287	2-1-4		
0097	1-6-6	0176	5-5-2	0288	3-8-1		

(a) Compacts not listed in this table are spare compacts except compacts 0026, 0111, 0178, 0184, 0207, 0298, 0248, 0303, and 0340 that were nonconforming and rejected.

(b) Sequence is capsule number – level number – stack number where capsules are numbered sequentially from bottom (Capsule 1) to top (Capsule 5), levels are also numbered sequentially within a capsule from bottom to top, and stacks are sequentially numbered clockwise (see Sectio 3.3 for numbering of stacks in the capsules).

3.3 Test Train

As required by the test specifications, the AGR-5/6/7 test train is a multi-capsule, instrumented lead experiment designed for irradiation in the 133.4-mm diameter NEFT position of ATR. Technical and functional requirements were written to lay out the design according to the specification (INL, 2016). The AGR-5/6/7 test train consists of five separate and vertically stacked capsules containing multiple stacks of fuel compacts. In each capsule, the stacks are contained in a standard nuclear-grade graphite holder that is separate from the capsule shell by an axially varying temperature control gas gap to compensate for the axial variation in heating. Temperature of the graphite holder is monitored by thermocouples (TCs) to ensure the fuel is operated at the expected irradiation temperatures (see Section 2.2). Each capsule contains an individual gas line to separately provide the helium-neon gas mixture used in the control gas gap to adjust the temperature in the capsule according to TC readings. The capsules are welded together to form the core section of the test train. The plenum regions between capsules have been extended over previous AGR designs to accommodate the bending of larger and stiffer TCs. The core section is welded to a leadout tube that houses and protects the gas lines and TC leads. The leadout is 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 TC leads are connected to their facility counterparts in the temperature monitoring, control, and data-collection systems, similar to the other AGR experiments. An axial view of the test train is illustrated in Figure 2 (see Section 2.2).

Each capsule contains fuel compacts nominally 25.3 mm in length and 12.3 mm in diameter. The measured dimensions based on characterization data are given in Table 6. Capsules 1, 2, 4, and 5 constitute AGR-5/6, while the margin test AGR-7 is associated with Capsule 3. Figure 4 illustrates radial views of the three capsule geometries. Table 9 shows a summary of the content of each capsule.

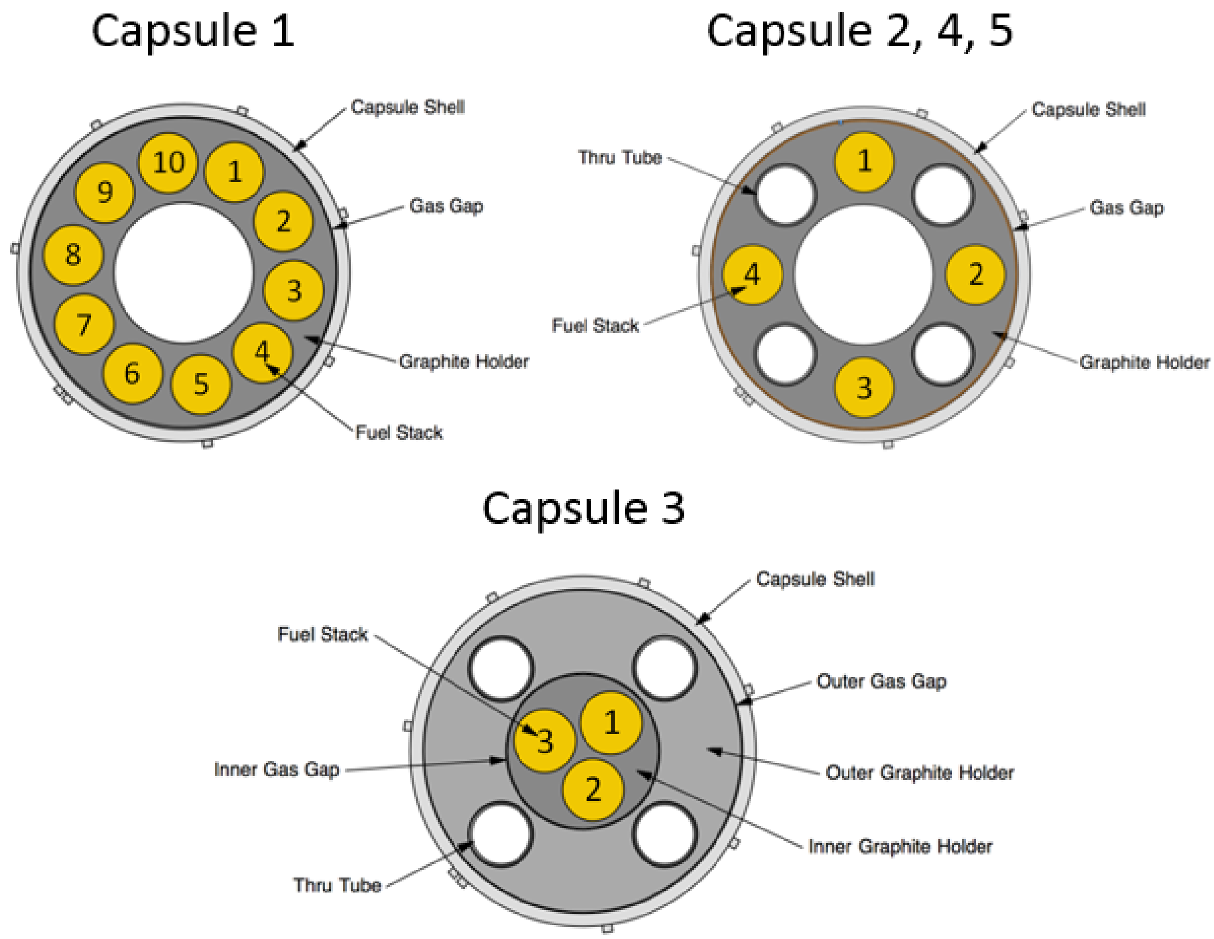


Figure 4. Cross sections of the AGR-5/6/7 capsules showing the compact stacks (Top: Capsule 1 [left] and Capsules 2, 4, and 5 [right] / Bottom: Capsule 3).

Table 9. AGR-5/6/7 capsules.

Capsule	Numbers of Levels	Numbers of Stacks	Numbers of Compacts	Packing Fraction (%)	Approximate Number of Particles [(a)]
5	6	4	24	39.3	3419
4	6	4	24	26.0	2213
3	8	3	24	26.1	2282
2	8	4	32	26.1	2281
1	9	10	90	39.3	3460
AGR-5/6 AGR-7 Total	—	—	170 24 194	—	519,560 54,768 574,328

(a) Number of particles obtained by dividing uranium mass content of a compact by uranium mass content of a particle.

Capsule 5 is located at the top of the test train and consists of a graphite annulus holder with a central hole that holds four vertical stacks of compacts and has four vertical holes for through tubes. The through tubes facilitate the passage of gas lines and TCs of the capsules below to the top and out of the test train. The hollow center of the capsule is designed to reduce graphite mass and graphite volumetric heating and to help lower compact temperatures. Each compact stack in Capsule 5 has six vertically stacked compacts for a total of 24 compacts in this capsule. Capsule 5 compacts have a packing fraction of 39.3% and each compact contains 3419 particles. Surrounding the graphite holder is a stainless-steel capsule or pressure containment wall. The ATR coolant flows outside the capsule wall in a water channel surrounded by a neutron filter (see Section 3.3.6). Capsule 4 is identical to Capsule 5, except the compacts have a packing fraction of 26.0% and each compact contains 2213 particles.

Capsule 3 has a cylindrical solid inner graphite holder surrounded by an outer graphite annulus holder. The inner graphite holder contains three compact stacks in a tightly packed triangular array at the center of the capsule. The outer graphite annulus surrounds the inner holder and has four holes drilled axially for through tubes. The separation of the holder into two pieces allows the center mass to run hot while keeping the through tubes relatively cool, thereby extending the life of the instrumentation lines contained within the through tubes. The three compact stacks in Capsule 3 have eight compacts vertically stacked for a total of 24 compacts in this capsule. The compact packing fraction is 26.1% and each compact contains 2282 particles.

Capsule 2 is identical to Capsule 4 and Capsule 5, except each compact stack has eight vertically stacked compacts for a total of 32 compacts in this capsule. Capsule 2 compacts have a packing fraction of 26.1% and each compact contains 2281 particles. Capsule 1 also has a central hole but its graphite annulus holder contains 10 stacks of compacts and has no through tube holes. Being at the bottom of the test train, Capsule 1 has no other capsule below it and it does not require any through tubes. The absence of through tubes gives more room for fuel stacks and it allows Capsule 1 to completely sealed off, therefore avoiding any risk of cross gas leakage with other capsules. The compacts in Capsule 1 are stacked nine high for a total of 90 compacts in this capsule. Capsule 1 compacts have a packing fraction of 39.3% and each compact contains 3460 particles. There is approximately 520,000 particles in AGR-5/6 and 55,000 in AGR-7, which is required to achieve the desired statistical relevance.

3.3.1 Thermocouples

Considering the importance of time at temperature for TRISO fuel performance, the AGR-5/6/7 irradiation experiment was designed to irradiate TRISO fuel for about 500 EFPDs at time-average volume-average temperatures ranging from ~800 to ~1400°C (see Section 4.2). Given these temperature specifications and feedback from previous AGR experiments, some redundancy and diversity was recommended for temperature measurements in AGR-5/6/7. Specifically, it was required that each capsule should contain at least five TCs: one TC for thermal control, two additional TCs to provide backup for the greatest extent of irradiation possible in case of failure of the control TC, and two additional TCs to provide the highest possible redundancy in the experiment.

TC varieties used in AGR-5/6/7 include:

- Type N (Ni/Cr/Si/Mg wire) with Inconel 600 (Ni/Cr/Fe/Mn alloy) sheath, MgO insulation, and sleeved with Nb (standard baseline)
- Type N with Cambridge low-drift pure Ni sheath, MgO insulation, and sleeved with Nb in AGR-5/6 capsules and with ZrO_2 in AGR-7 Capsule 3
- Type N with Inconel 600 sheath, Spinel ($MgAl_2O_4$) insulation, and sleeved with Nb
- High-temperature irradiation resistant (HTIR – Mo/Nb wire) with Nb sheath, Al_2O_3 insulation, and sleeved with Mo.

The selection of these TCs relied on the established performance of commercial TCs and on feedback from prior AGR experiments. Amongst commercial TCs, standard base metal TCs (Types K and N) de-calibrate (drift) at high temperatures due to metallurgical changes (>600°C for Type K and >1000°C for Type N). Based on AGR-1 experience, Type N TCs were deemed appropriate and selected for the low-temperature capsules (Capsules 2, 4, and 5). In addition to its Type N TCs, Capsule 5 is also instrumented with an ultrasonic temperature sensor that provides another means of measuring temperature in its graphite holder. High-temperature refractory TCs (e.g., Types C, S, B, and R) have high-neutron cross section alloying elements and are subject to rapid drift because their alloying elements transmute under irradiation into other elements with different electromotive properties. For this reason, TCs of these types were not selected for the high-temperature capsules.

A summary of TC type and placement within the test train is provided in Table 10, whereas Figure 5, Figure 6, and Figure 7 show the positions of the TCs in the AGR-5/6/7 capsules. As seen in Capsule 3 (AGR-7), TCs placed in the hot inner section will provide temperature measurements near the compacts.

Table 10. AGR-5/6/7 TCs.

Capsule	TC	Angular Location (North is 0°)	Depth (mm)	Diameter (mm)	TC Type
5	5-1 5-2[(a)] 5-3 5-4 5-5[(b)] 5-6	22.5° 112.5° 202.5° 247.5° 292.5° 337.5°	38.1 76.2 114.3 114.3 76.2 38.1	1.57 1.57 1.57 1.57 1.57 1.57	Type N
5	Ultrasonic	67.5°	76.2	2.34	Not applicable
4	4-1 4-2[(a)] 4-3 4-4 4-5[(b)] 4-6	22.5° 112.5° 202.5° 247.5° 292.5° 337.5°	38.1 76.2 114.3 114.3 76.2 38.1	1.57 1.57 1.57 1.57 1.57 1.57	Type N

Table 10. (continued).

Capsule	TC	Angular Location (North is 0°)	Depth (mm)	Diameter (mm)	TC Type
3	3-1	0°	101.6	2.34	Spinel
	3-2	90°	101.6	2.34	Spinel
	3-3	180°	101.6	2.34	Spinel
	3-4	270°	101.6	2.34	Spinel
	3-5	0°	101.6	1.57	HTIR
	3-6	0°	38.1	1.57	Cambridge
	3-7	90°	101.6	1.57	Cambridge
	3-8	105°	152.4	1.57	HTIR
	3-9	105°	38.1	1.57	Cambridge
	3-10	120°	38.1	1.57	Cambridge
	3-11	210°	101.6	1.57	HTIR
	3-12	225°	101.6	1.57	HTIR
	3-13[(a)]	225°	50.8	1.57	Cambridge
	3-14	240°	38.1	1.57	HTIR
	3-15	330°	50.8	1.57	Cambridge
	3-16	345°	50.8	1.57	HTIR
	3-17[(b)]	345°	50.8	1.57	Cambridge
2	2-1	22.5°	50.8	1.57	Type N
	2-2	67.5°	50.8	1.57	
	2-3[(a)]	112.5°	101.6	1.57	
	2-4[(b)]	157.5°	101.6	1.57	
	2-5	202.5°	152.4	1.57	
	2-6	247.5°	152.4	1.57	
	2-7	292.5°	101.6	1.57	
	2-8	337.5°	50.8	1.57	
1	1-1	45°	50.8	2.34	Cambridge
	1-2	81°	50.8	2.34	Spinel
	1-3[(a)]	117°	50.8	2.34	Cambridge
	1-4[(b)]	153°	50.8	2.34	Cambridge
	1-5	189°	101.6	2.34	Cambridge
	1-6	261°	152.4	2.34	Cambridge
	1-7	297°	203.2	2.34	Cambridge
	1-8	333°	203.2	2.34	Cambridge
	1-9	45°	152.4	1.57	HTIR
	1-10	81°	50.8	1.57	HTIR
	1-11	117°	50.8	1.57	HTIR
	1-12	153°	101.6	1.57	HTIR
	1-13	189°	101.6	1.57	HTIR
	1-14	225°	50.8	1.57	HTIR
	1-15	261°	152.4	1.57	HTIR
	1-16	297°	50.8	1.57	HTIR
	1-17	333°	203.2	1.57	HTIR

(a) Primary control TC.

(b) First backup control TC.

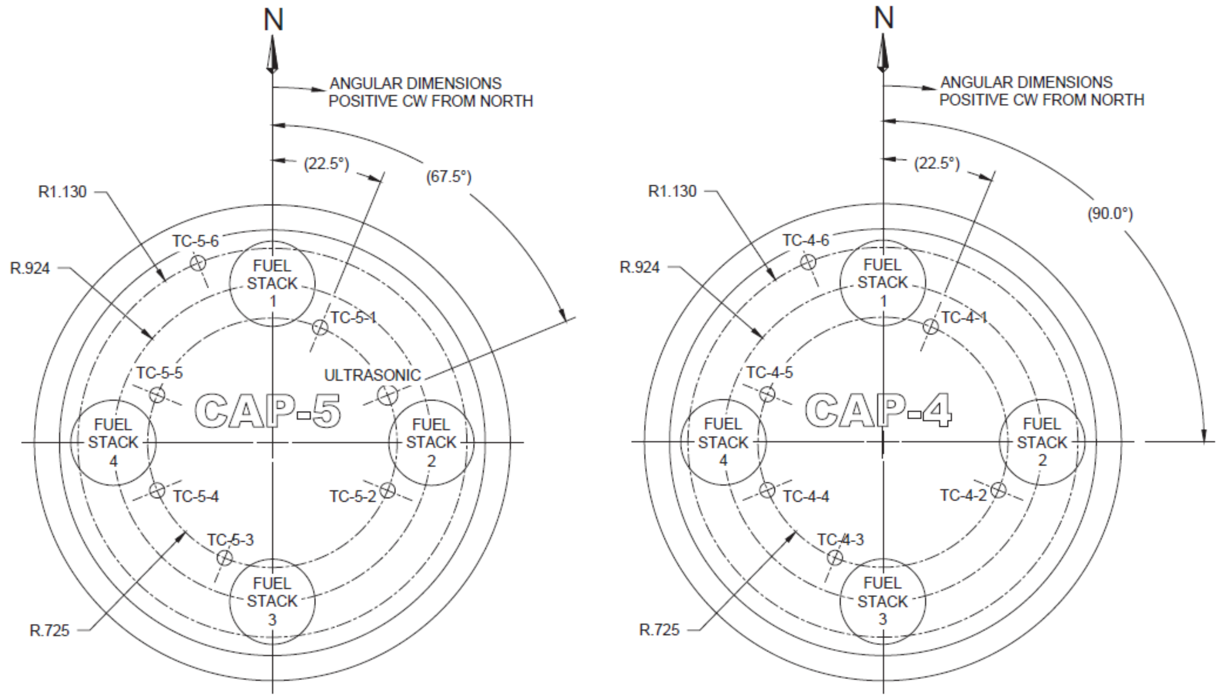


Figure 5. Cross sections of AGR-5/6/7 Capsules 5 (left) and 4 (right) showing the position of the TCs.

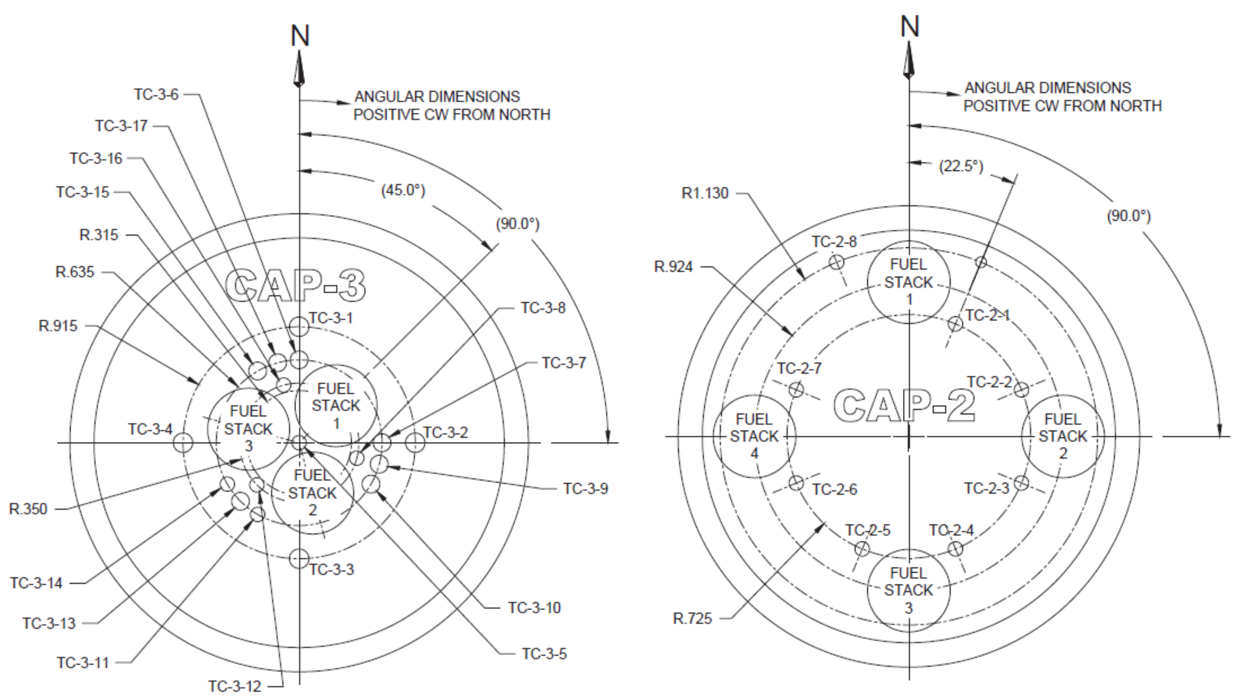


Figure 6. Cross sections of AGR-5/6/7 Capsules 3 (left) and 2 (right) showing the position of the TCs.

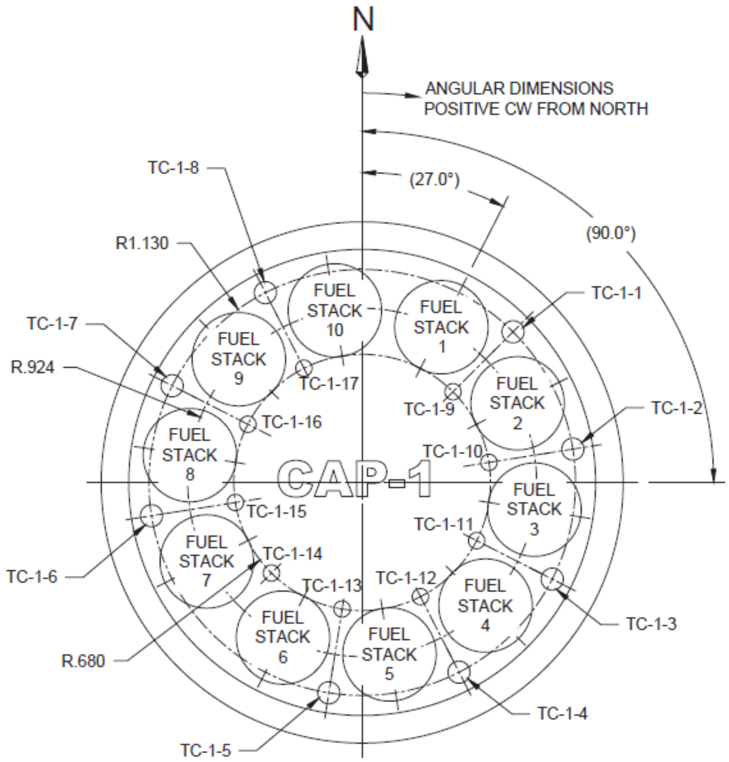


Figure 7. Cross section of AGR-5/6/7 Capsule 1 showing the position of the TCs.

Improved Type N TCs (Cambridge, Spinel), as well as refractory HTIR TCs developed at INL, will be used for capsules operating at temperatures >1000°C (Capsules 1 and 3). The sheath material developed at Cambridge University reduces the thermal drift markedly, while keeping the flexibility and robustness of a standard Type N TC. Conversely, Spinel insulation only showed a limited improvement in drift rate compared to standard Type N TCs but it was decided to include them in the test train to take advantage of the available space. The HTIR TCs, which also exhibited low drift, will primarily be used to test and confirm their performance at high irradiation temperature, as the experiment can run successfully without them. They will occupy the inner and hotter positions of Capsules 1 and 3.

Concerns have been raised that first row transition metals (Cr, Mn, Fe, Co, or Ni) of TC wires or sheaths can migrate through the graphite and compact matrix and attack the SiC layer of TRISO fuel particles when placed too close to the fuel. This is exemplified by two observed SiC failures due to chemical attack by nickel from nearby TCs in the AGR-2 experiment (Hunn et al., 2016). The Mo/Nb wires and Nb sheaths of the HTIR TCs should be better suited to prevent such SiC failures in AGR-5/6/7. They also are the only viable option for temperature measurements greater than ~1280°C. This justifies the central position of these TCs in Capsules 1 and 3. The use of Type N TCs with Inconel 600 sheaths (standard Type N or Spinel) is justified for locations where there is reasonable separation of the TCs from the fuel stacks, which limits the risk of migration of nickel, iron, or chromium (main components of the Inconel 600 alloy). The Type N TCs are sleeved with Nb to prevent migration from these transition metals, except for the hotter Cambridge TCs in Capsule 3 that are sleeved with ZrO_2. The HTIR TCs are sleeved with Mo, which shows better mechanical resistance at high temperature.

The improved Type N and HTIR TCs were tested in a furnace at INL for more than 4500 hours at temperatures ranging from 1150 to 1300°C to validate their use in AGR-5/6/7:

- 2060 hours at 1157°C
- 2006 hours at 1207°C
- 201 hours at 1258°C
- 266 hours at 1301°C (with a 77-hour excursion to 1311°C at the beginning of this period).

As noted above, Cambridge and HTIR TCs showed an improvement in thermal drift at high temperature compared to standard Type N TCs.

The TCs come in two sizes: 1.57 and 2.34 mm diameter. The 1.57-mm TC diameter is justified by the lower operating temperatures and the available space within each capsule to place instrumentation. Larger 2.34-mm TCs are only larger at their top (see Figure 8). The increased TC size resulted in only a limited improvement in drift rate but the larger diameter at the top is beneficial for mechanical strength at locations where the TCs are brazed to the capsules. Cost and availability of these larger TCs eventually dictated how many are used in the capsules.

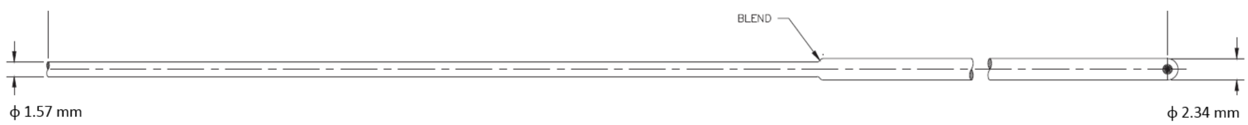


Figure 8. Schematic of a 2.34-mm TC.

3.3.2 Neutron Monitors

Contrary to the previous AGR experiments, AGR-5/6/7 does not have any in-capsule flux wires. The flux wires used in these previous AGR experiments became unavailable and the cost of procurement of other existing technologies and associated pre-irradiation testing or of new in-house laboratory developments was deemed too high compared to the benefits of having flux wires inside the capsules. In addition, PIE efforts to recover and examine the wires add to the overall expense.

Nevertheless, the test train is surrounded by four flux wire tubes located at the cardinal positions in the NEFT flux trap. The flux wires run the entire length of the test train. They are located outside of the neutron filters (see Section 3.3.6), which is dictated by the constraints of capsule and test train design.

After irradiation, the induced activity of the wires will be converted to fluences with the appropriate neutron energy range and will also be used as a benchmark for physics analyses. The materials used for the wires, consist of Al + 0.1% Co for thermal flux measurement and pure Ni for fast flux measurement. The characteristics of the flux wires are listed in Table 11.

Table 11. Characteristics of AGR-5/6/7 flux wires.

Material	Reaction	Reaction Product Half-Life	Neutron Activation Energy Range
Al + 0.1% Co	$^{59}Co(n,\gamma)\,^{60}Co$	5.3 years	Thermal
Ni	$^{58}Ni(n,p)\,^{58}Co$	70.9 days	Fast (E>1 MeV)

3.3.3 Supplementary Instrumentation

Additional instrumentation was placed in the capsules for evaluation of its performance under irradiation. It consists of measurement of both neutron flux and temperatures. Fluxes measured by the neutron instrumentation 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 and help confirm physics models. Measurements supplied by the supplementary instrumentation are not crucial to the AGR-5/6/7 experiment but used as a test bed for the corresponding technologies, taking advantage of available space in the test train. In particular, thermal control of the experiment is ensured by a large number of thermocouples and does not rely on the temperature sensors of the supplementary instrumentation. Below is a list of the supplementary instrumentation tested in AGR-5/6/7. Figure 9 shows a layout of the connector plate located above the test train to which all the supplementary instrumentation is connected.

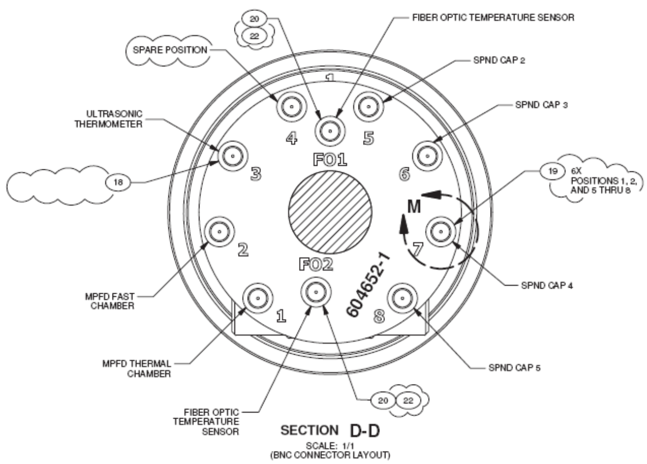


Figure 9. Supplementary instrumentation connector layout.

Self-powered neutron detectors (SPNDs)

Four SPNDs were coiled in the skirt of Capsules 2, 3, 4, and 5 to measure the thermal flux in these capsules. SPNDs provide real-time measurements of local neutron flux and local gamma flux. The subsequent data can be compared with the physics-calculated neutron and gamma fluxes to validate the physics model, code, input data, and assumptions. In turn, this provides a confidence level in the physics-calculated heat rates which can then be used in thermal analysis calculations to estimate temperatures. SPND measurements also indicate differential changes in the flux which correlate to the changes in core power levels and changes in the experimental apparatus. On the other hand, SPNDs may not survive the entire irradiation and they only provide a relative (not absolute) magnitude of gamma or neutron flux. Furthermore, signal processing for SPNDs is delicate because of the low signal (of the order of nanoamperes).

Micropocket fission detector (MPFD)

One MPFD with two chambers was slid down in a through tube of Capsule 5 to measure its thermal and fast fluxes.

Ultrasonic temperature sensor

One ultrasonic temperature sensor was added in Capsule 5 to measure temperature in its graphite holder.

Fiber-optic temperature sensor

Two fiber-optic temperature sensors were added to Capsule 5 to measure temperature in its graphite holder.

3.3.4 Sweep Gas

In each AGR-5/6 capsule, the fuel stacks are contained in a graphite holder that is separated from the capsule shell by a gas gap (see Figure 4 in Section 3.3) that is used to control the temperature. Independent gas lines will route a mixture of helium and neon gases through the capsule gas gaps to provide temperature control, and to sweep and carry any released fission product gases to the FPMS (see Section 3.4). Temperature in the graphite holders will be monitored using TCs (see Section 3.3.1) and temperature in each capsule will be controlled by varying the sweep gas composition (between 100% helium for high conductivity and 100% neon for low conductivity).

A particular range of irradiation temperature has been selected for each capsule, in order to achieve the desired fuel compact temperature distribution in the test train (see Section 4.2). The gas gap widths and gas mixtures were chosen in order to meet the desired specimen temperature requirements, based on initial thermal analyses (see Section 4.2). The helium-neon blend will be adjusted throughout irradiation to maintain the fuel within its desired temperature range and to compensate for irradiation-induced effects on the graphite holders, such as shrinkage or decreased thermal conductivity. As detailed in Section 3.3, in the case of AGR-7 (Capsule 3), fuel stacks are contained in an inner graphite holder separated from an outer graphite holder by an inner gas gap. An outer gas gap separates the outer graphite holder from the capsule shell. A single gas blend will be fed into the capsule and permeate both gas gaps.

The initial design of the AGR-5/6/7 experiment considered injecting impurities into one capsule to study the effects on fuel performance of sweep gas impurities, such as CO, H_2O, and H_2 typically found in the primary coolant circuit of HTGRs, but results from the AGR-3/4 experiment showed essentially no impact of such impurities on its fuel performance (Collin, 2016). In addition, it was decided that the large amount of oxidant-gettering materials in the hot capsules (including graphite, stainless steel, and refractory metals) would significantly react with the impurity gases inside the capsules such that the overall oxidant partial pressures and their distribution inside the capsules could not be precisely known. As a result, interpretation of the data with regard to the effect of impurities on fuel performance or fission product transport would be very problematic. Therefore, it was decided to not proceed with the injection of impurities in the AGR-5/6/7 experiment.

Sweep gas flow, originating from gas supply bottles, is routed to the mass flow controller cabinet where the helium and neon gases are blended for each capsule. Low neutron activation inert gases were specified for the sweep gas to minimize background activity in the FPMS. 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 <5 ppm H_2O within the sweep gas reduces possible reactions with the graphite contained in the test capsule. Consequently, moisture content of the inlet sweep gas will be measured at least once after each gas cylinder change on the inlet side of the capsule and will have to be <5 ppm H_2O at a dew point of −100 ± 2.5°C. When a new bottle is connected to the system, a solenoid valve is actuated and a sample of the gas from the new bottle is temporarily routed to the gas verification panel where thermal conductivity and moisture measurements are performed for both the helium and neon gas lines. After verification, the solenoid is again actuated and the gas flow bypasses the gas verification cabinet and is routed directly from the gas regulator panel to the mass flow control cabinet. The blending of sweep gases is accomplished by a computerized mass flow controller before the gas enters the test train. Gas flow will be ≤50 sccm at a pressure of about 7–21 kPa-gauge (or 1–3 psig). The sweep gas is then routed on to the capsule inlet isolation panel, which can be used to isolate inlet gas flow to each capsule independently during reactor outages or in the event of a failure. Upon exiting the capsule and test train, the gas flows through the outlet isolation panel to another panel containing a particulate filter, moisture detector, and three-way valve. The valve routes the gas either to the designated fission product monitor or to the standby-backup fission product monitor. Another three-way valve allows the gas to be routed to a manual grab sample line for additional analysis if needed. After passing through the FPMS, the gas lines combine into a common exhaust header that routes the gas through a silver-zeolite filter. The exhaust gas is finally routed to the ATR stack. A schematic of this gas flow is presented in Figure 10.

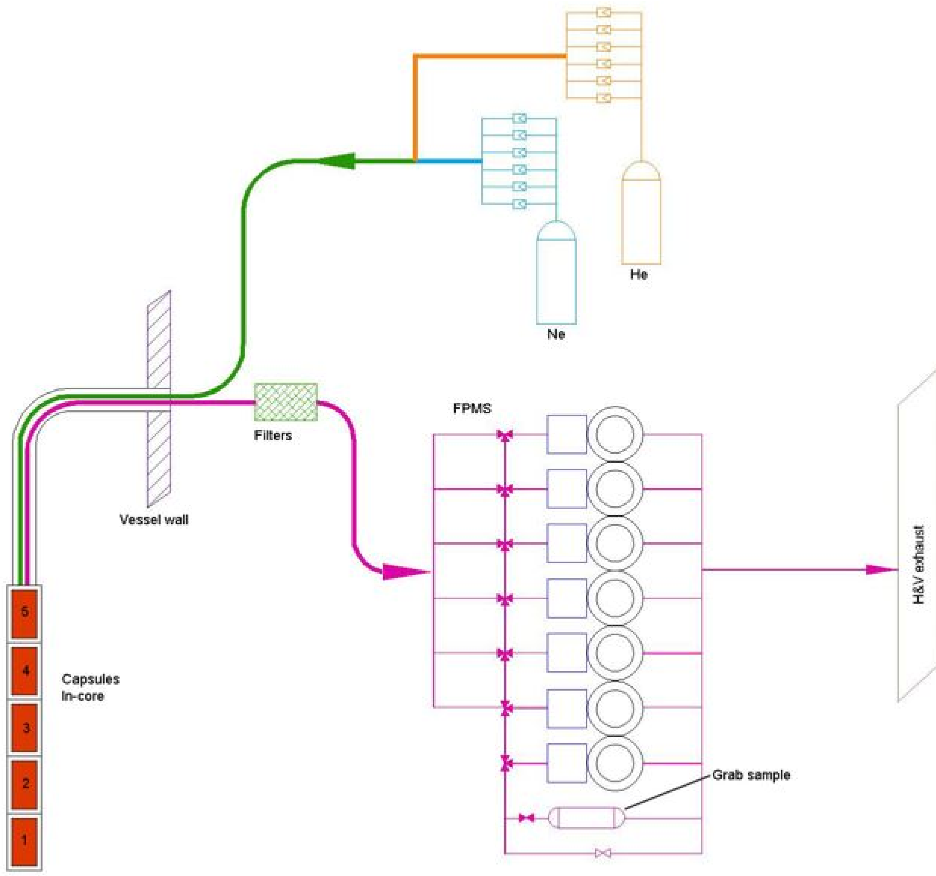


Figure 10. Simplified flow path for AGR-5/6/7 sweep gas.

3.3.5 Through Tubes

Through tubes provide passages for TCs and gas lines to be routed to each of the five capsules. The through tubes penetrate both the top and bottom heads of the capsules. Capsule 1, at the bottom of the test train, does not have any through tubes as no instrumentation is connected underneath it. It maximizes its available space by having ten fuel stacks instead of four in the other AGR-5/6 capsules and three in the AGR-7 capsule.

For Capsules 2, 4, and 5, the through tubes are made of stainless steel and wrapped in a 0.25-mm thin Mo sleeve to prevent migration from transition metals in the TCs through the graphite holders (see Section 3.3.1 for the issue with transition metals associated to SiC failure). For Capsule 3, space constraints favored the use of molybdenum instead of stainless steel. Unfortunately, the Mo through tubes developed cracks during assembly. As a repair measure, thinner stainless-steel through tubes were inserted inside the Mo through tubes to correct the issue but still allow the instrumentation to go through.

The through tubes are brazed to the top heads, but there is only a close slip-fit at the bottom heads. This arrangement is employed because of the differential thermal expansion between the hot through tubes and the relatively cool capsule shells. Neolube is applied around the tubes where they pass through the bottom heads to aid in assembly and act as a gasket. To further prevent capsule to capsule cross gas leakage, a nominal helium or neon flow of 1–5 sccm per capsule at about 6.9 kPa-gauge (or 1 psig) above the capsule pressure will be provided via a mass flow controller into the leadout cavity, for a total flow of 5-20 sccm (Capsule 1 has no through tubes) which then flows into the common plenums between capsules. This small gas flow will provide an inward flow into each capsule through the space between the capsule bottom heads and around the through tubes. Experimental validations will be conducted prior to start of irradiation to confirm that ingress gas flow and tube clearances are sufficient to prevent gas leakage from capsule to capsule. This technique was used successfully in the AGR-1, AGR-2, and AGR-3/4 experiments. Additional cross flow tests will be conducted between ATR cycles as needed.

3.3.6 Power Shaping

Two techniques will be used to adjust the neutron flux incident on the AGR-5/6/7 test train to shape the temporal and spatial fuel power distribution. These techniques include placing a neutron filter around the capsules and raising the power throughout irradiation.

The AGR-5/6/7 experiment will be irradiated in the NEFT of ATR. Since the ratio of fast-to-thermal neutron flux in the NEFT is too high compared to that of an HTGR, the neutron flux needs to be tailored to prevent excessive fast neutron damage while achieving the desired fuel burnup. An irradiation housing provides neutron moderation and absorption to meet this need. It allows the experiment to simultaneously achieve the desired fuel burnup and fast neutron fluence, while adapting to the ATR constraint of maintaining a minimum level of reactor power. The housing also helps lower the overall thermal neutron flux rate to keep the irradiation acceleration factor to less than three and prevent possible premature fuel particle failures. The irradiation housing surrounds the test train between the capsule wall and the ATR aluminum baffle and, therefore, interfaces with the ATR core structure that supports the ATR fuel elements surrounding the NEFT.

The irradiation housing for AGR-5/6/7 consists of inner and outer stainless-steel shells with a hafnium filter sandwiched between them. Three different filters (shrouds) will be used during the irradiation: a heavy filter, an intermediate filter, and a light filter (see Figure 11). The neutron filters are designed to reduce and adjust thermal neutron flux impacting the AGR-5/6/7 compacts, such that the compact heat rates can remain relatively constant and uniform for the anticipated northeast lobe power variations during irradiation (Table 12). All three AGR-5/6/7 filters are stainless-steel tubes with a total thickness of 6.79 mm for the light and intermediate filters and 3.86 mm for the heavy filter. The heavy filter (Filter 1) will be reused from AGR-3/4. The two other filters were made larger to minimize the chances of them hanging up on the test. Both Filters 1 (heavy) and 2 (intermediate) have natural hafnium metal foil sandwiched between an inner and outer stainless-steel tube; the hafnium efficiently absorbs thermal neutrons, which in turn significantly decrease compact fission and heat rates to control temperature and burnup. The hafnium foil is centered axially about the ATR core mid-plane and extends 50.8 cm above and below the core mid-plane for a total axial length of 101.6 cm. The axial extent of the hafnium does not fully cover the top of Capsule 5 or the bottom of Capsule 1 to increase the compact heat rates and burnup in these regions.

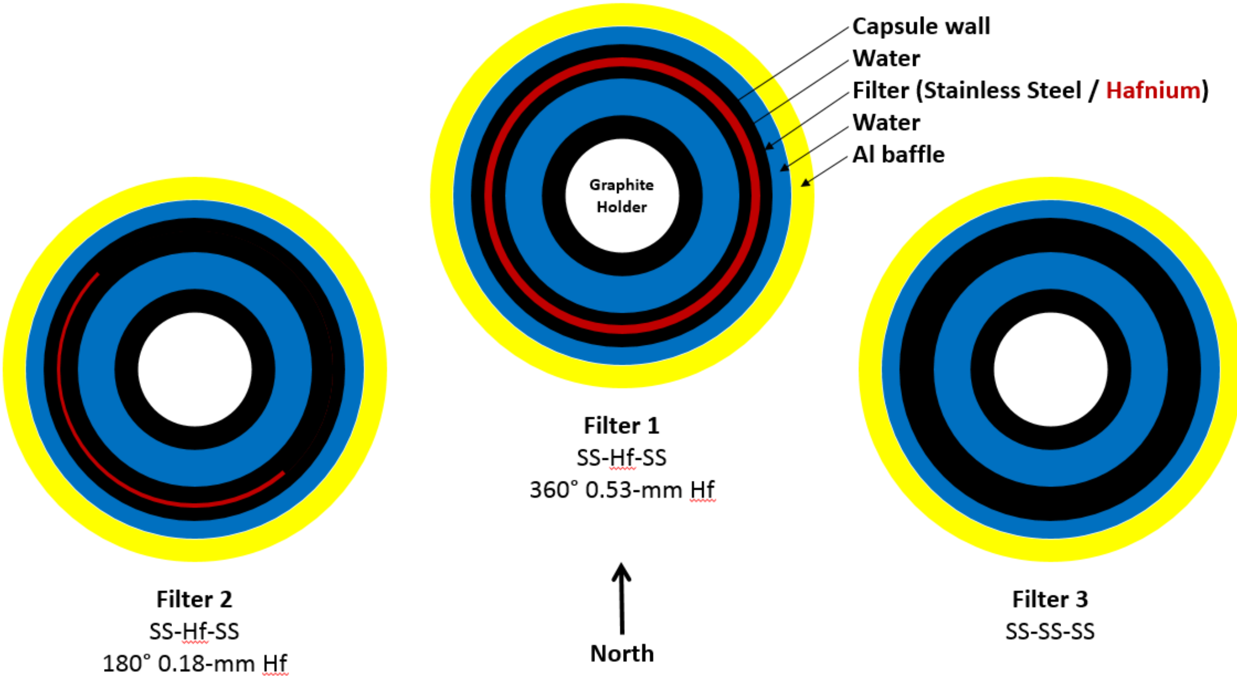


Figure 11. The three AGR-5/6/7 neutron filters.

Table 12. AGR-5/6/7 irradiation schedule.

Cycle	Cycle Type	Cycle Length (EFPD)	Northeast Lobe Power (MW)	Filter
1	Regular	38	14 ± 1	2
2	PALM	7 (a)	11 ± 3 and 20 ± 2	1
3	Regular	54	14 ± 1	2
4	Regular	59	14 ± 1	2
5	PALM	14	20 ± 2	2
6	Regular	59	14 ± 1	3
7	Regular	56	14 ± 1	3
8	PALM	7 (a)	11 ± 3 and 20 ± 2	3
9	Regular	56	16 ± 1	3
10	Regular	56	18 ± 1	3
11	PALM	14	20 ± 2	3
12	Regular	56	18 ± 1	3
13	Regular	45	18 ± 1	3

(a) The 7-day PALM cycles will be run 5 days at 11 MW and 2 days at 20 MW.

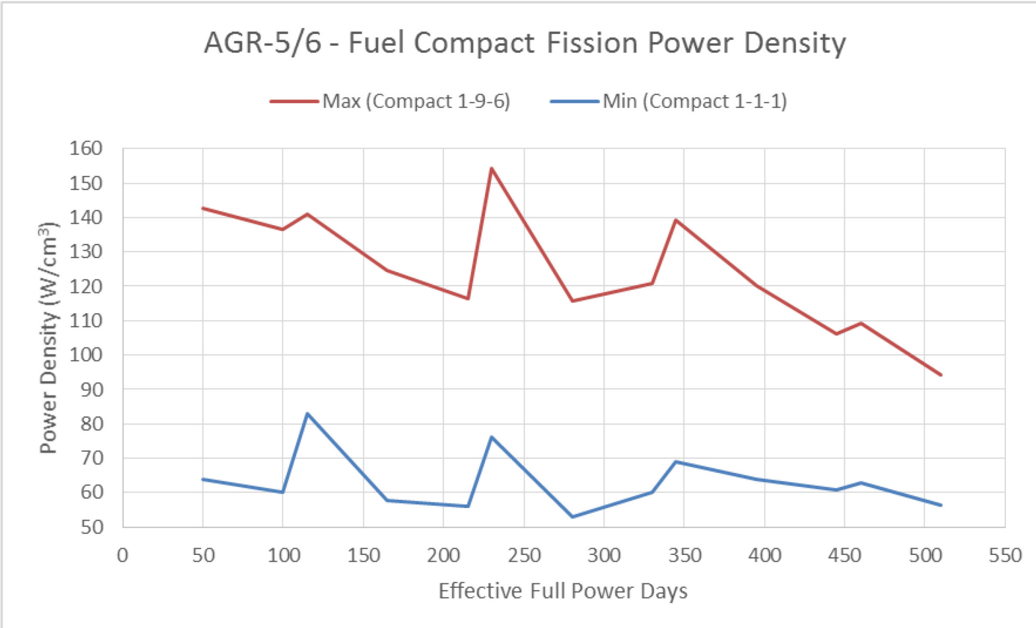
Pre-test physics predictions were performed to determine the adequate filter for each cycle of the initially-proposed irradiation schedule (see Section 2.3). It is anticipated that the same filter selection will be used in the revised irradiation schedule. Table 12 shows this filter selection. At beginning of irradiation, the 180° 0.18-mm hafnium filter (Filter 2) will be used for the first four regular cycles to help limit compact heat rates. Later in the irradiation, this filter will be removed and replaced with an all stainless-steel filter (Filter 3) to help boost heat rates as the fuel depletes. In anticipation of the early-irradiation PALM cycle, the 360° 0.53-mm hafnium filter (Filter 1) will be used to limit AGR-5/6/7 compact heat rates. The use of the heavy filter will allow the AGR-5/6/7 test train to remain in the core during this early PALM cycle, thus preventing potential damage to the AGR-5/6/7 test train from removal and re-insertion into the core. The three filters shown in Figure 11 (relative dimensions not to scale) represent the hafnium metal foil (red), stainless steel (black), ATR coolant (blue), ATR lobe baffle (yellow), and a central region (white) where the graphite holders containing the compacts reside.

Another power shaping technique used in AGR-5/6/7 will consist of raising the power in the NEFT throughout the 500 EFPDs of irradiation. At a given power level, heat generation rate is highest at the beginning of life (BOL) and drops exponentially as the fissile fuel content is consumed. For AGR-5/6 and AGR-7 test fuels, these ranges of heat generation rates span up to about 50 and 70 MW/m^3, respectively, from BOL to essentially full burnup (end of life [EOL]). Unfortunately, temperature control of the test fuel can only be maintained within a limited range of heat generation rates (about half of the maximum heat rate, i.e., 70 MW/m^3 at most) for given control gas gap widths and with a varying mixture of helium and neon sweep gas. To reduce the range of test fuel heat generation rates, power will be increased in the NEFT throughout irradiation from 14 MW (BOL) to 18 MW (EOL). The increase of power will balance the loss of heat generation caused by fuel depletion. This temporal effect is shown in Figure 12 for both AGR-5/6 and AGR-7 using the initially-proposed irradiation schedule (see Table 1 in Section 2.3). Note that the 20 MW lobe powers indicated in Table 12 are characteristic of PALM cycles and cannot be altered.

3.4 Fission Product Monitoring System

Each AGR-5/6/7 capsule will be continuously monitored for fission product gas release by the FPMS. The FPMS consists of seven sets of gross radiation monitor and spectrometer detector pairs. One detector set is designated for each of the five capsules, while the two remaining detector sets serve as spares. A detector set is illustrated in Figure 13.

Sweep gas carries released fission product gases from the capsules to the detector system under normal conditions with a transit time expected to be about 150 seconds. An accurate measurement of this transit time will be performed after installation of the test train in the reactor. The sweep gas passes in front of the gross radiation monitor, which uses a thallium-doped sodium iodide (NaI(Tl)) detector to detect each fuel particle failure up to the first 250 failures. Flow continues on to the spectrometer system, which uses a high-purity germanium (HPGe) detector. The spectrometer system measures radionuclide concentrations, which are used to determine release to birth ratios. Under normal operation, computerized data acquisition, analysis, and storage occur continuously without operator intervention.



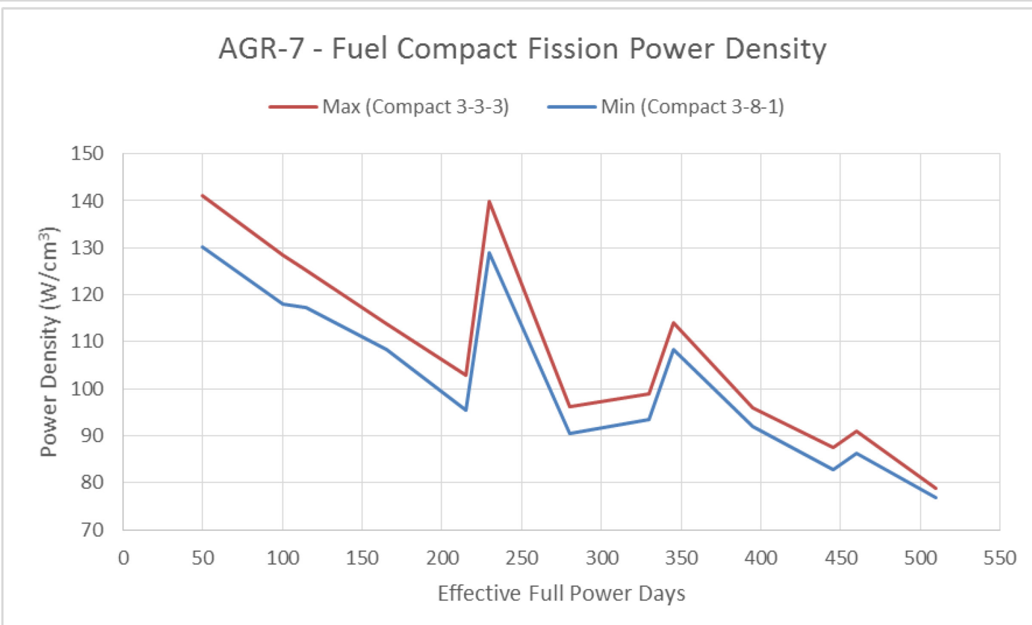


Figure 12. AGR-5/6 (top) and AGR-7 (bottom) minimum and maximum fuel compact fission power densities. The power density increases at 100, 215, 330, and 445 EFPDs correspond to PALM cycles.

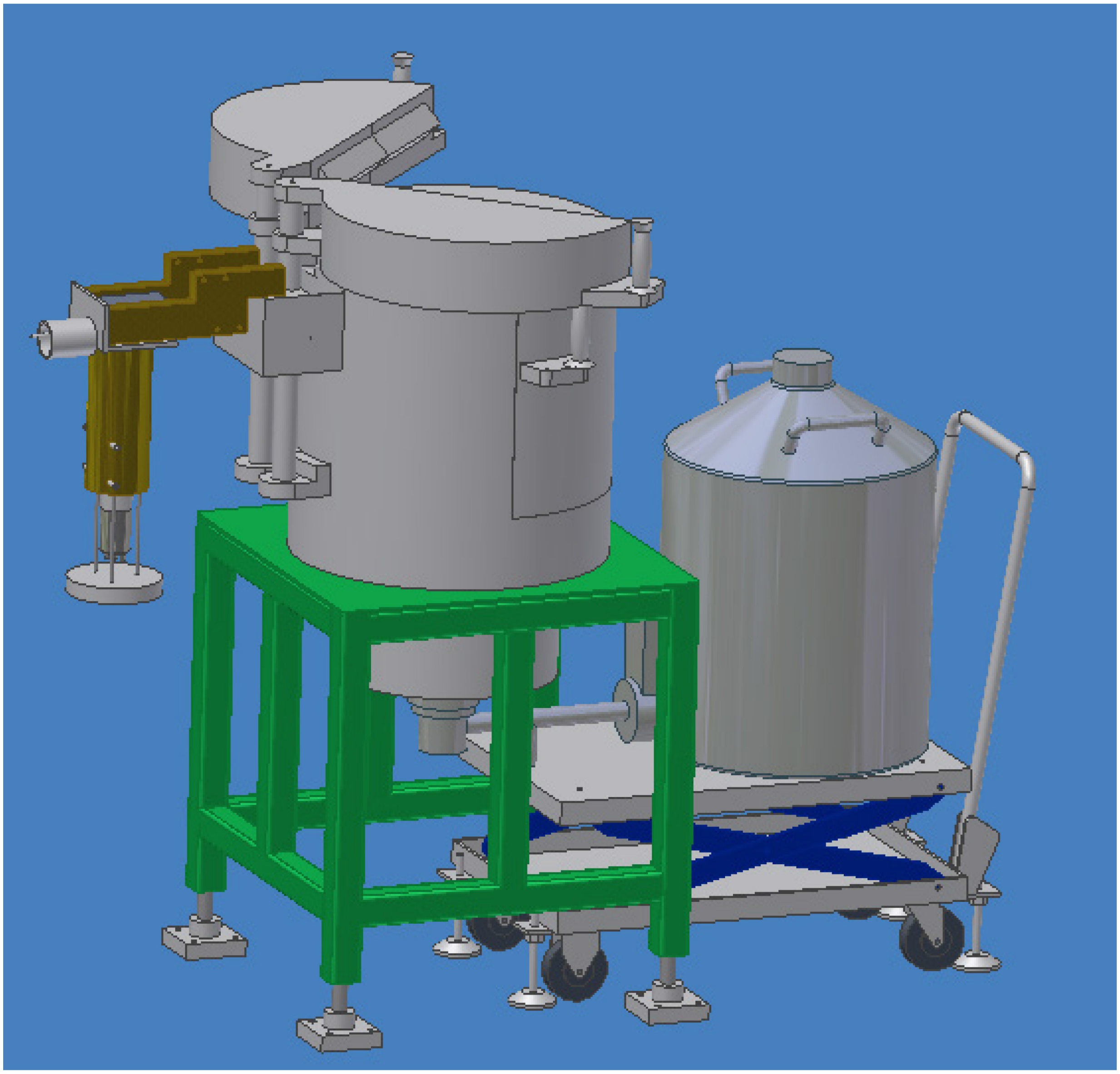


Figure 13. Gross radiation monitor and spectrometer detector for one AGR-5/6/7 sweep gas line.

4. TEST CONDITION REQUIREMENTS

This section presents the irradiation conditions expected for the AGR-5/6/7 experiment. These calculated conditions were derived from the latest available physics (Sterbentz, 2017) and thermal (Murray, 2017) analyses. Initial calculations, presented below, were performed using AGR-5/6/7 fuel specifications and assuming a maximum irradiation of 510 EFPDs, according to the initially-proposed irradiation schedule (see Table 1 in Section 2.3).

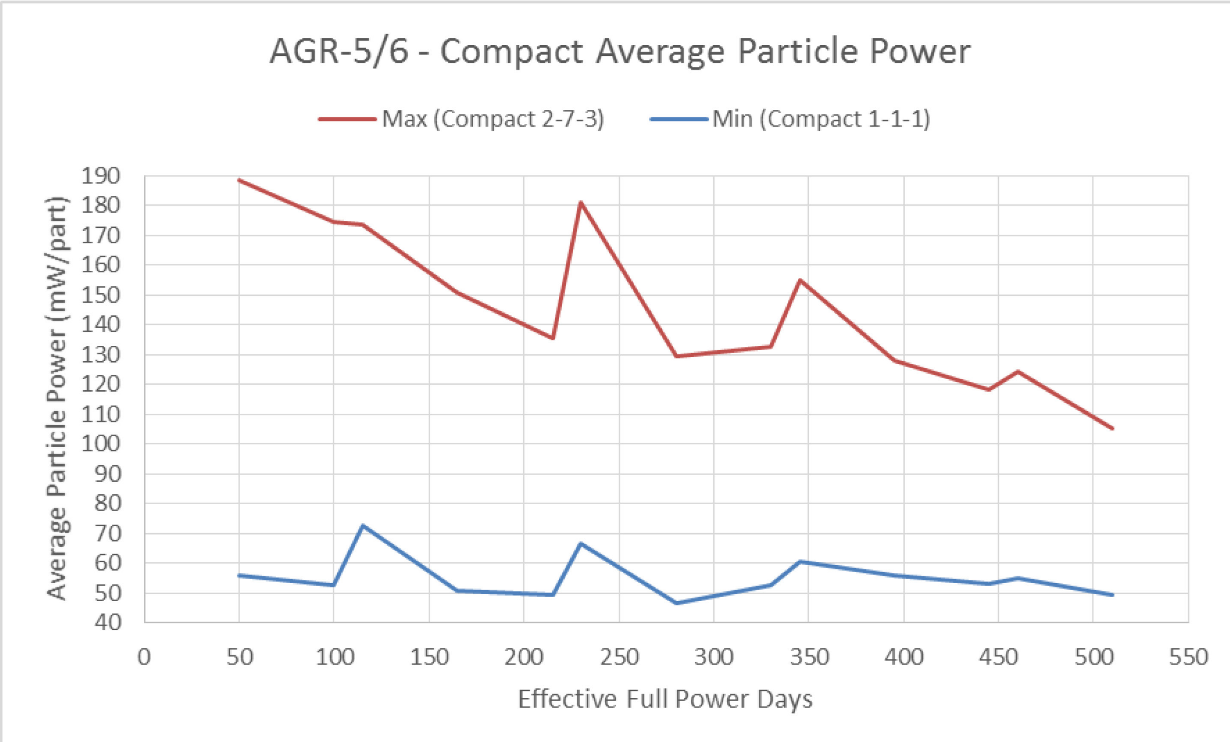
4.1 Particle Power

Fuel power is restricted by specification (Maki, 2015) and by an operational need to control test temperature (which is defined as the ability to adjust and maintain fuel temperatures within a prescribed range). The instantaneous peak power per particle specification of ≤400 mW per particle is intended to limit peak kernel temperatures and temperature gradients across the particle, which reduces fission product diffusion and potential interactions between fission products and the SiC layer. A typical TRISO particle in an HTGR experiences a power level of 50–100 mW per particle.

Temperature control is achieved by varying the composition of the sweep gas (between 100% helium for high conductivity and 100% neon for low conductivity) within the control gas gap surrounding the fuel. For a given gas gap width, this control can be maintained within a range, or window, of fuel heat generation rates. Typically, temperature control requires peak heat rate to EOL heat rate ratio to be ≤2.

In order to extend the time that thermal control can be maintained, the power level in the NEFT will be adjusted throughout the AGR-5/6/7 irradiation. It will be raised from 14 MW at BOL to 18 MW at EOL. This power shaping measure will enhance the fuel heat generation rate as the fuel depletes throughout irradiation. From 14 MW during the first five regular ATR power cycles (Cycles 1, 2, 4, 5, and 7), the power will be increased to 16 MW during Cycle 8 and finally to 18 MW for the last three regular power cycles (Cycles 10, 11, and 13). Cycles 3, 6, 9, and 12 are projected to be high-power PALM cycles during which the power will be raised to 20 MW. Neutron filters will be used to reduce and adjust thermal neutron flux and help maintain the compact heat rates relatively constant and uniform (see Section 3.3.6).

Based on projected ATR power cycles, the minimum and maximum compact average heat generation rates for AGR-5/6 and AGR-7 are presented in Figure 14. In both tests, a peak compact average power of 190 mW per particle is reached at BOL. Considering that a conservative upper bound for compact peak-to-average power ratio is 1.1, the peak particle power is well within the specification limit of ≤400 mW per particle. The particle power increases at 100, 215, 330, and 445 EFPDs correspond to PALM cycles.



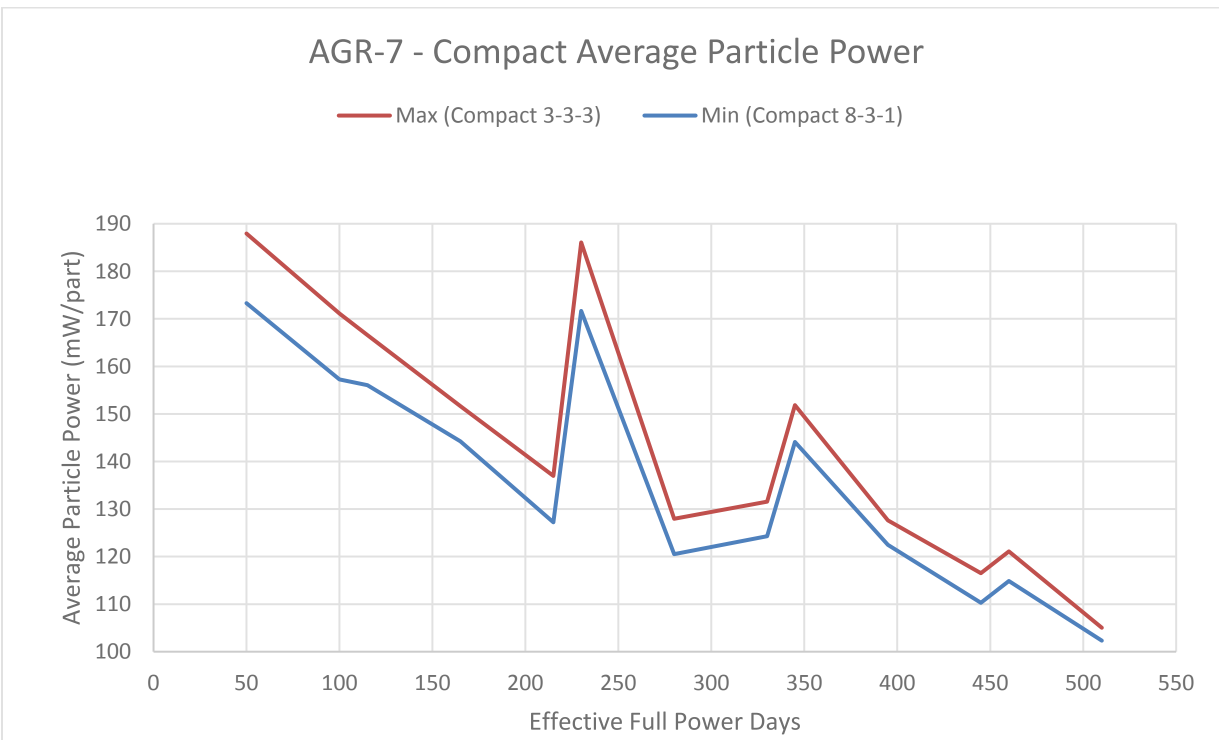


Figure 14. AGR-5/6 (top) and AGR-7 (bottom) minimum and maximum compact average heat generation rates.

4.2 Temperature

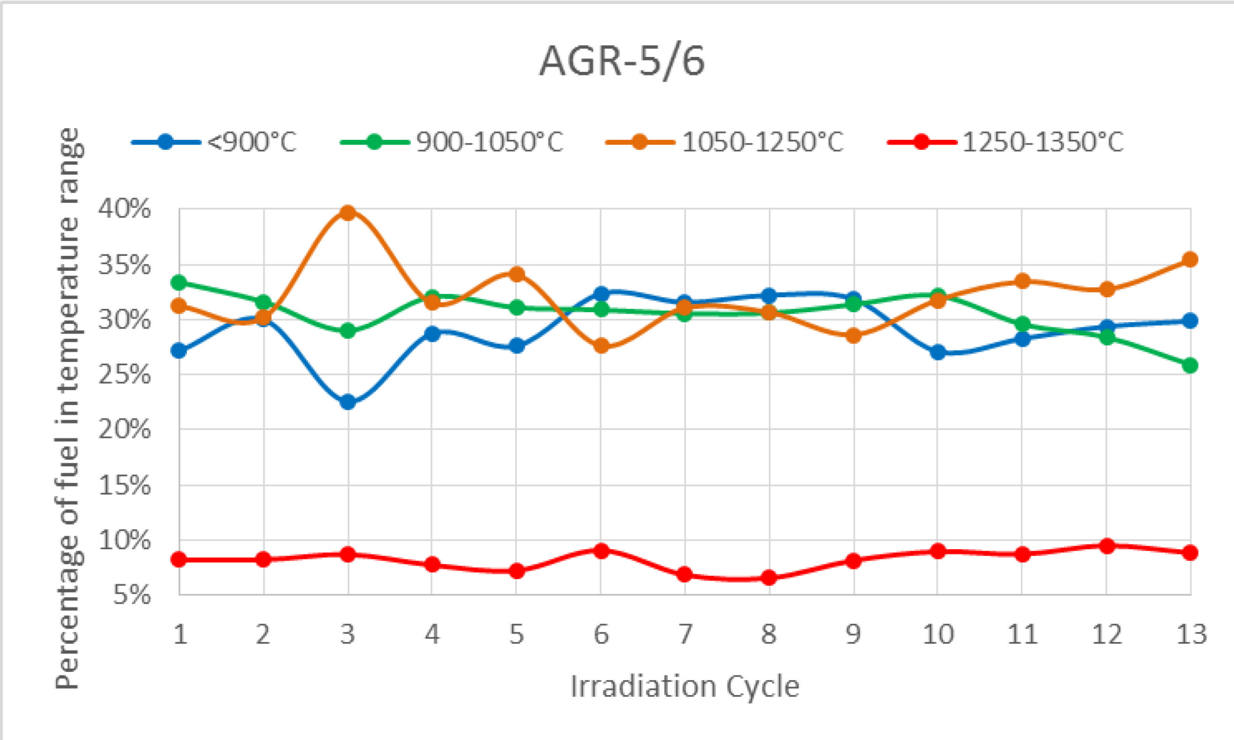
Three-dimensional finite element thermal calculations were performed at each projected irradiation cycle of the AGR-5/6/7 experiment. These preliminary calculations were performed with the heat generation rates described in Section 4.1 and with optimized control gas gap widths and varying sweep gas compositions.

As required by the test specifications, the optimization of the control gas gap widths and adjustment of the sweep gas mixtures must ensure that ~30% of the ~500,000 particles of the AGR-5/6 fuel will operate at <900°C, ~30% will operate between 900 and 1050°C, ~30% will operate between 1050 and 1250°C, and the remaining ~10% will operate between 1250 and 1350°C. Temperatures from <900°C to >1250°C conservatively span a range expected in HTGRs. Since AGR-7 is designed as a margin test of the UCO fuel, a dominant fuel performance parameter for this test is time at temperature. Considering AGR-2 tested UCO fuel at a time-average peak temperature of 1360°C with online data indicating no deleterious effects (Collin, 2014), AGR-7 will be tested at a higher peak temperature of 1500°C and the majority of the ~50,000 particles will operate above 1350°C. Figure 15 shows that the fuel is expected to operate in its required temperature ranges.

For each capsule, the fuel temperature will be controlled to provide the required number of particles in each specified temperature range. This will be achieved by adjusting the helium fraction in the helium-neon sweep gas mixture. Figure 16 displays the helium fractions required in each capsule and at each cycle to maintain the fuel temperatures at their required levels throughout irradiation.

In both AGR-5/6 and AGR-7, an instantaneous peak temperature specification of ≤1800°C will provide an operational limit to minimize overheating of the fuel. Figure 17 shows that the instantaneous peak temperatures for both AGR-5/6 and AGR-7 will be less than the 1800°C limit.

The time-average peak temperature of AGR-5/6 is required to be 1350 ± 50°C, while the time-average peak temperature of AGR-7 should be 1500 ± 50°C. As seen in Figure 18, both these requirements are met in the preliminary thermal calculations. Furthermore, the AGR-5/6 test specifications require the time-average minimum temperature to be less than 700°C, which is expected to be the case in Capsule 5, as seen in Figure 19. Finally, Figure 20 shows the time-average volume-average temperatures for the AGR-5/6 and AGR-7 capsules.



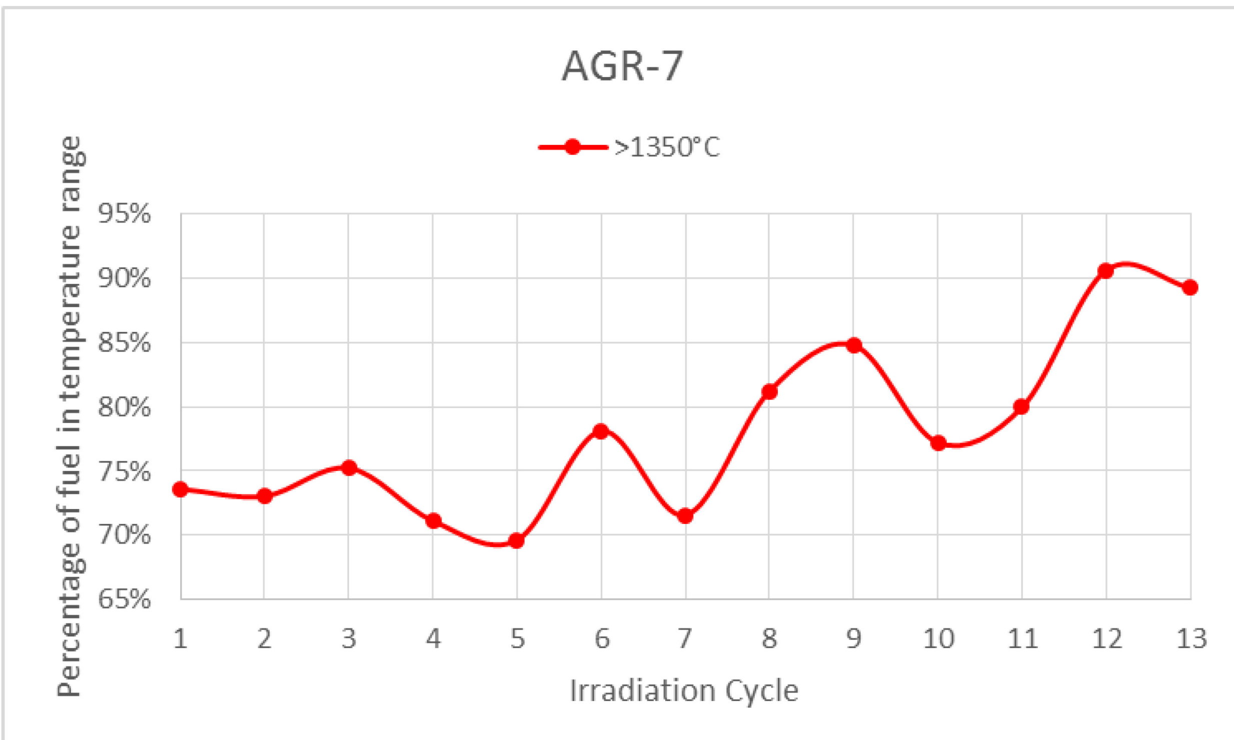


Figure 15. Percentage of the fuel in the AGR-5/6 (top) and AGR-7 (bottom) temperature ranges.

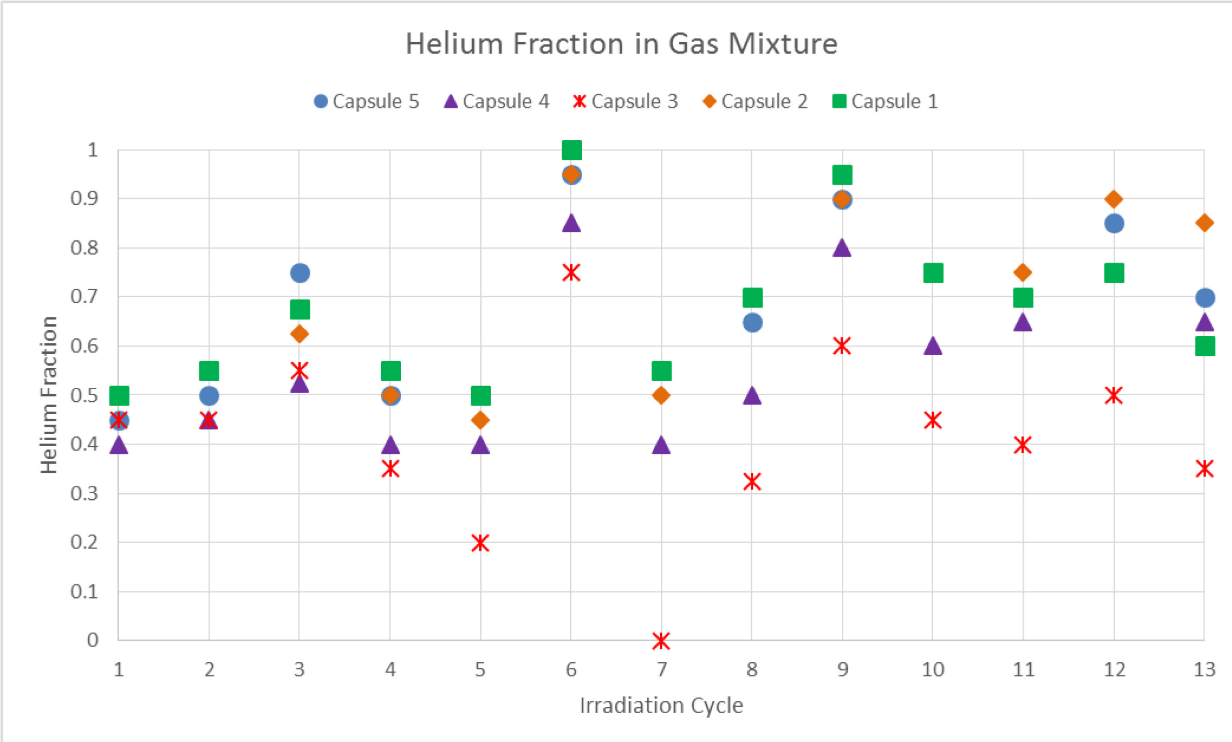


Figure 16. Helium fraction in the temperature control sweep gas mixture.

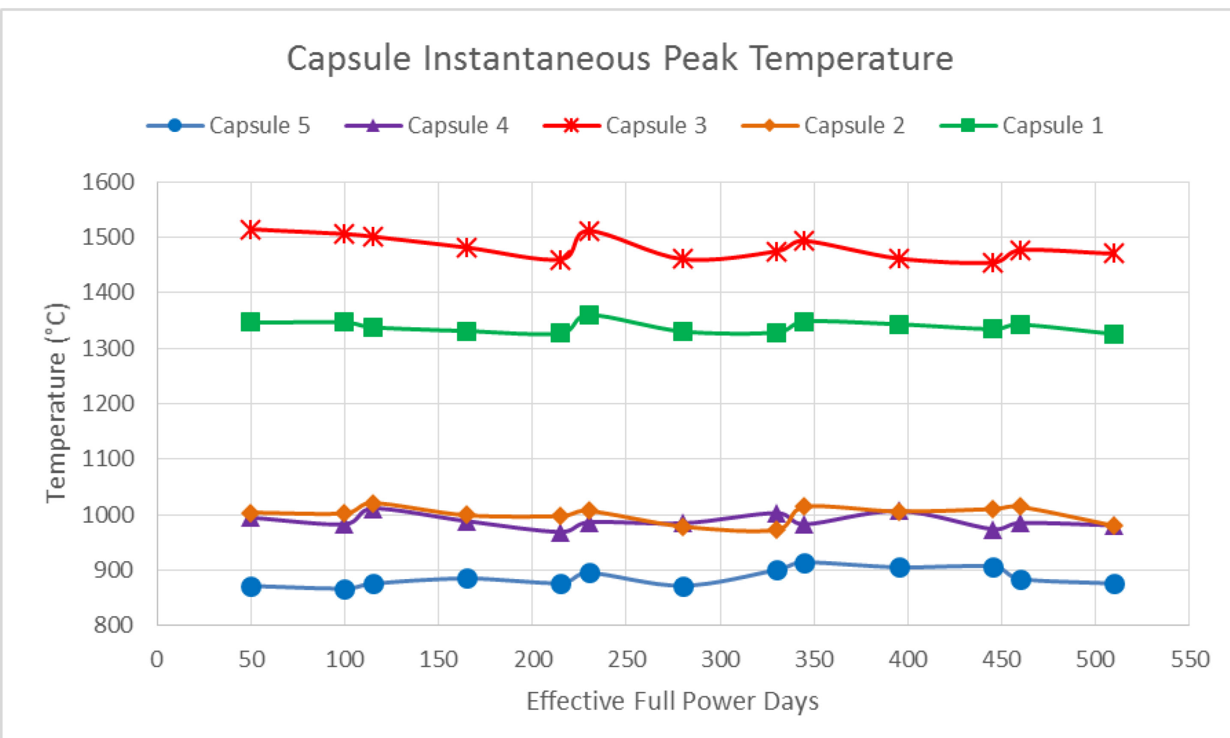


Figure 17. Instantaneous peak temperature for AGR-5/6 (Capsules 1, 2, 4, and 5) and AGR-7 (Capsule 3).

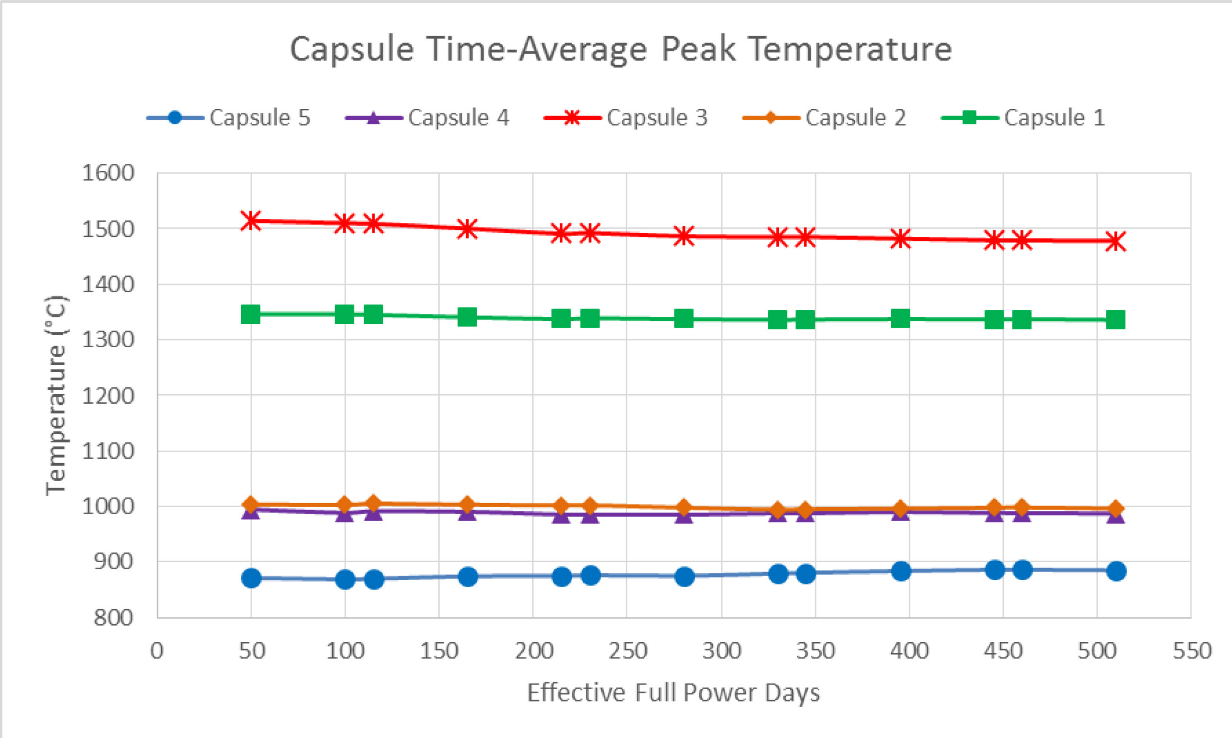


Figure 18. Time-average peak temperature for AGR-5/6 (Capsules 1, 2, 4, and 5) and AGR-7 (Capsule 3).

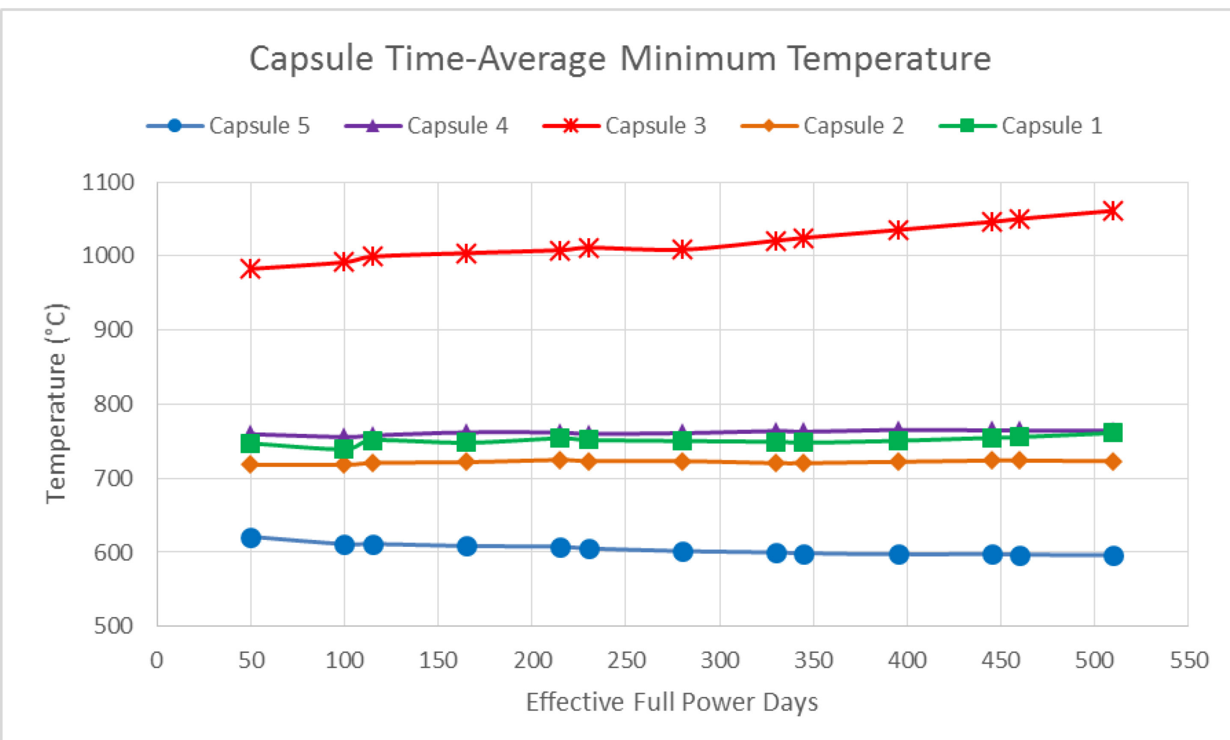


Figure 19. Time-average minimum temperature for AGR-5/6 (Capsules 1, 2, 4, and 5) and AGR-7 (Capsule 3).

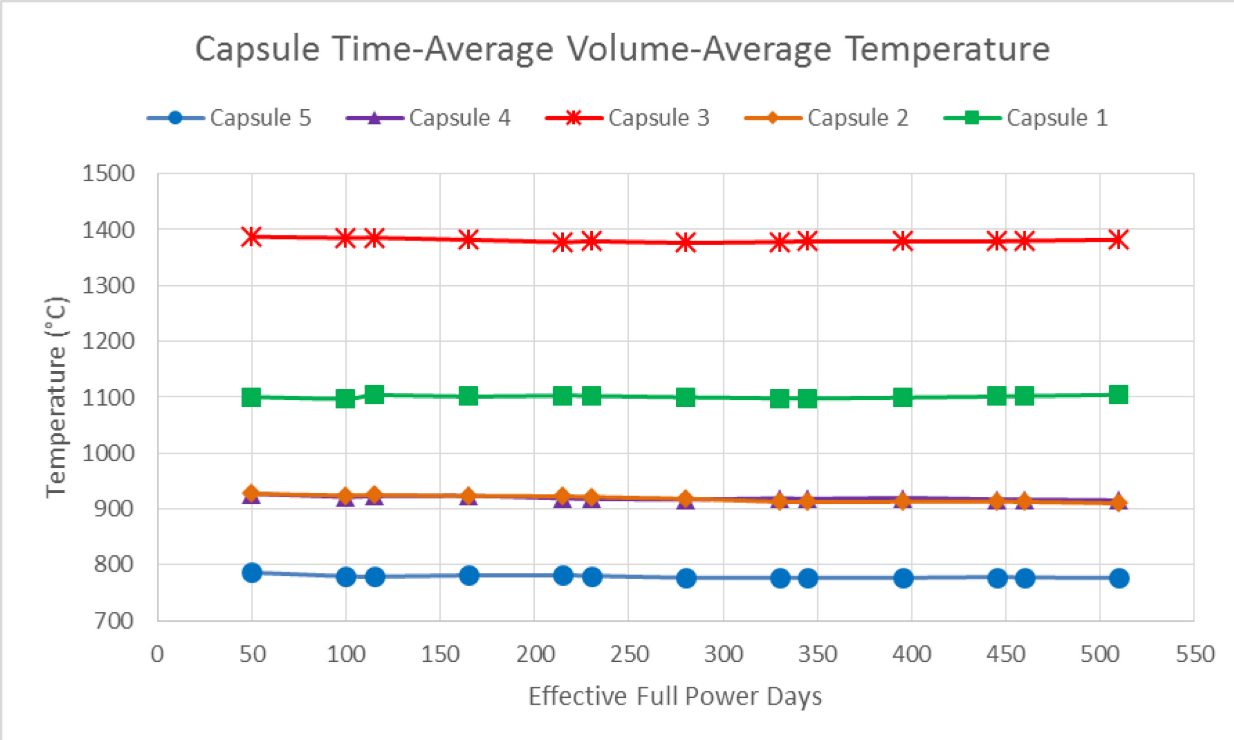


Figure 20. Time-average volume-average temperature for AGR-5/6 (Capsules 1, 2, 4, and 5) and AGR-7 (Capsule 3).

4.3 Fuel Burnup

The intent of the AGR-5/6 and AGR-7 test objectives and test specifications is for the fuel to obtain a substantial fraction of burnup within a reasonable amount of time (on the order of 2.5 calendar years). The burnup specifications are identical for the AGR-5/6 and AGR-7 tests (Maki, 2015). In each test, the specification requires a minimum compact average fuel burnup of 6% FIMA for all compacts and greater than 18% FIMA for at least one compact. A burnup of 18% FIMA exceeds the expected maximum burnup reached in HTGRs loaded with 15.5wt% enriched fuel. On the other hand, the lower burnup specification of 6% FIMA ensures that a level of significant irradiation is achieved.

Figure 21 presents the predicted capsule average burnups for AGR-5/6 and AGR-7 and Figure 22 displays the minimum and maximum compact average burnups for each portion of the AGR-5/6/7 experiment. These results indicate that after 510 EFPDs of irradiation, all the AGR-5/6/7 compacts will have reached the minimum specified burnup of 6% FIMA. Furthermore, at least one compact in each test is expected to reach a burnup greater than 18% FIMA at 510 EFPDs.

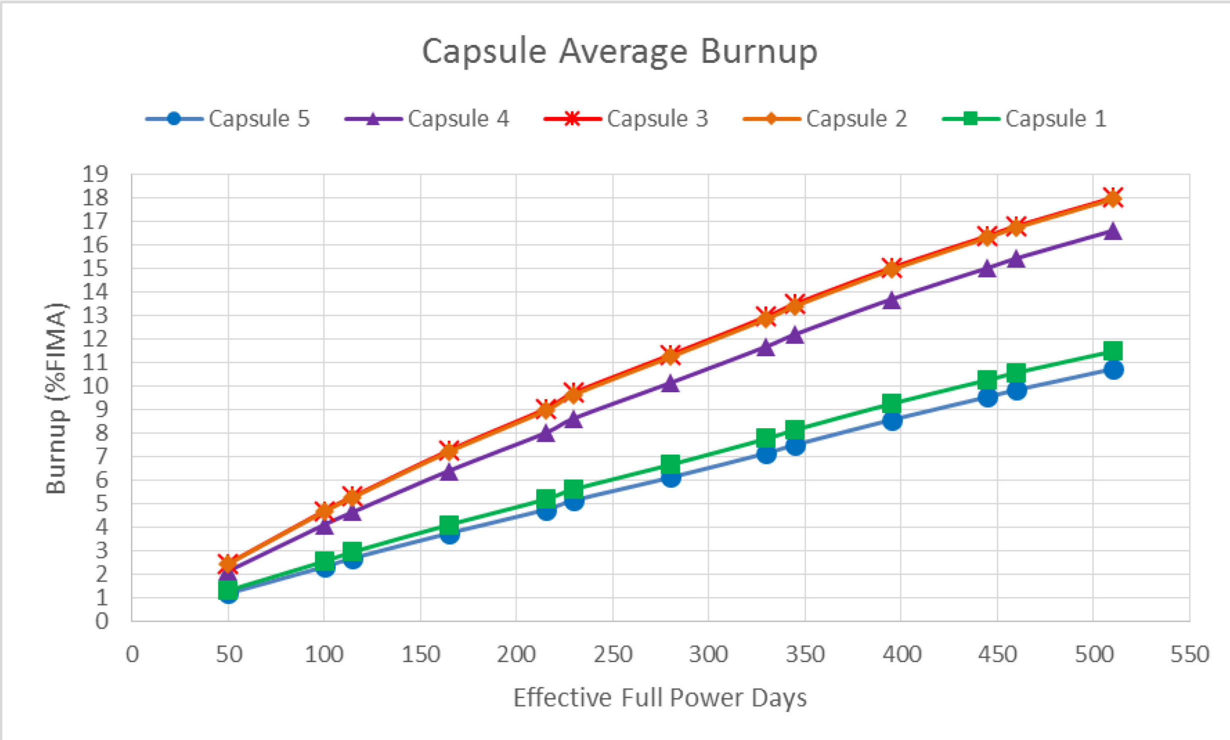


Figure 21. Capsule average burnups for AGR-5/6 (Capsules 1, 2, 4, and 5) and AGR-7 (Capsule 3).

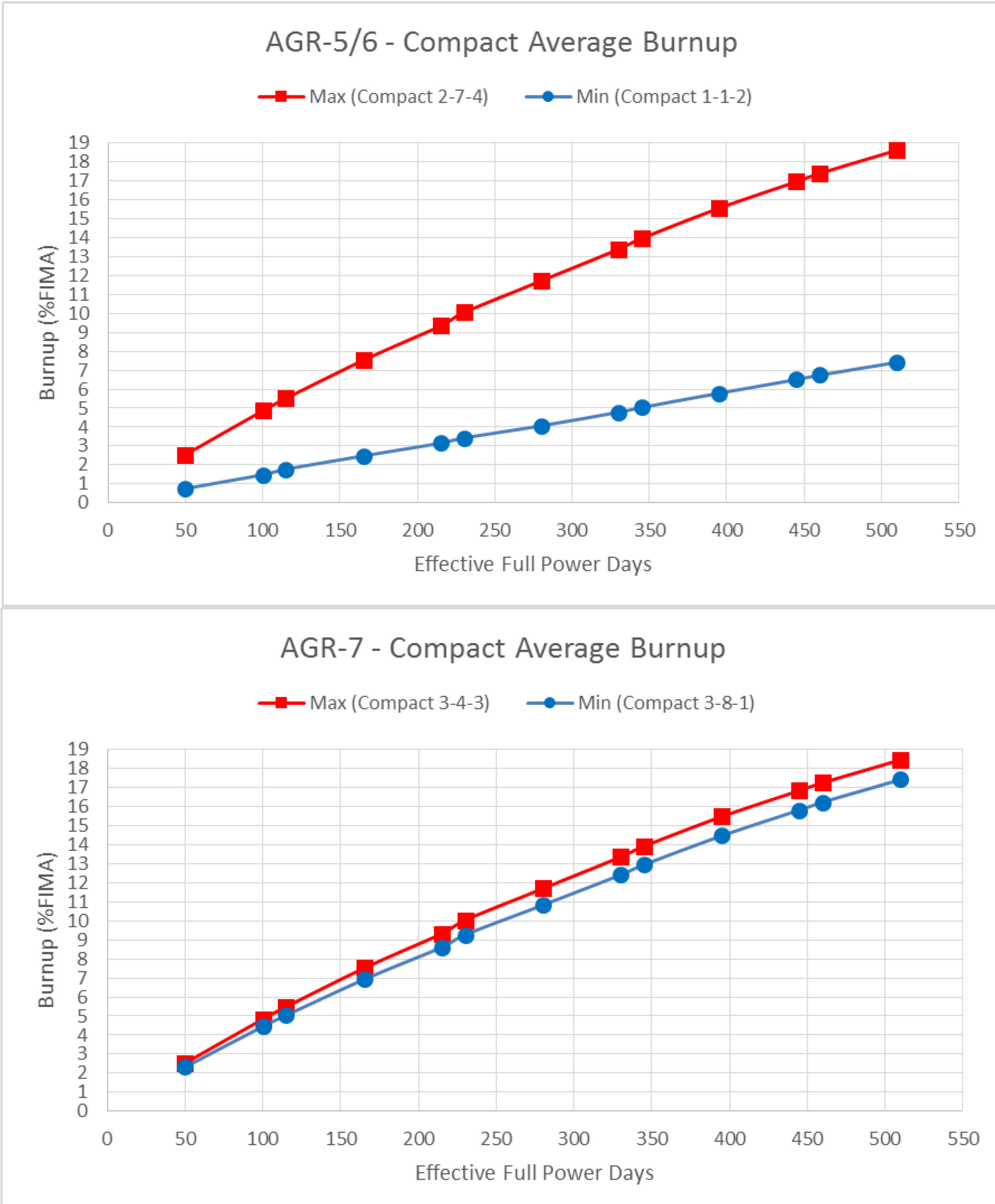


Figure 22. AGR-5/6 (top) and AGR-7 (bottom) minimum and maximum compact average burnups.

4.4 Fast Neutron Fluence

The fast neutron fluence for each fuel compact is restricted by specification to be > 1.5 and < 7.5×10^{25} n/m^2 (E>0.18 MeV) in both the AGR-5/6 and AGR-7 tests (Maki, 2015). In addition, at least one compact in each test is required to achieve a fast neutron fluence > 5.0×10^{25} n/m^2 (E>0.18 MeV), which is a level of fast neutron fluence that bounds expected HTGR service conditions.

Figure 23 presents the predicted capsule average fast neutron fluences for AGR-5/6 and AGR-7 and Figure 24 displays the minimum and maximum compact average fast neutron fluences for each test. These results indicate that after 510 EFPDs of irradiation, all the AGR-5/6/7 compacts will have reached the minimum specified fast neutron fluence of 1.5×10^{25} n/m^2 (E>0.18 MeV) and that none of the compacts will exceed a fast neutron fluence of 7.5×10^{25} n/m^2 (E>0.18 MeV). Furthermore, at least one compact in each portion of the AGR-5/6/7 experiment is expected to reach a fast neutron fluence > 5.0×10^{25} n/m^2 (E>0.18 MeV) at 510 EFPDs.

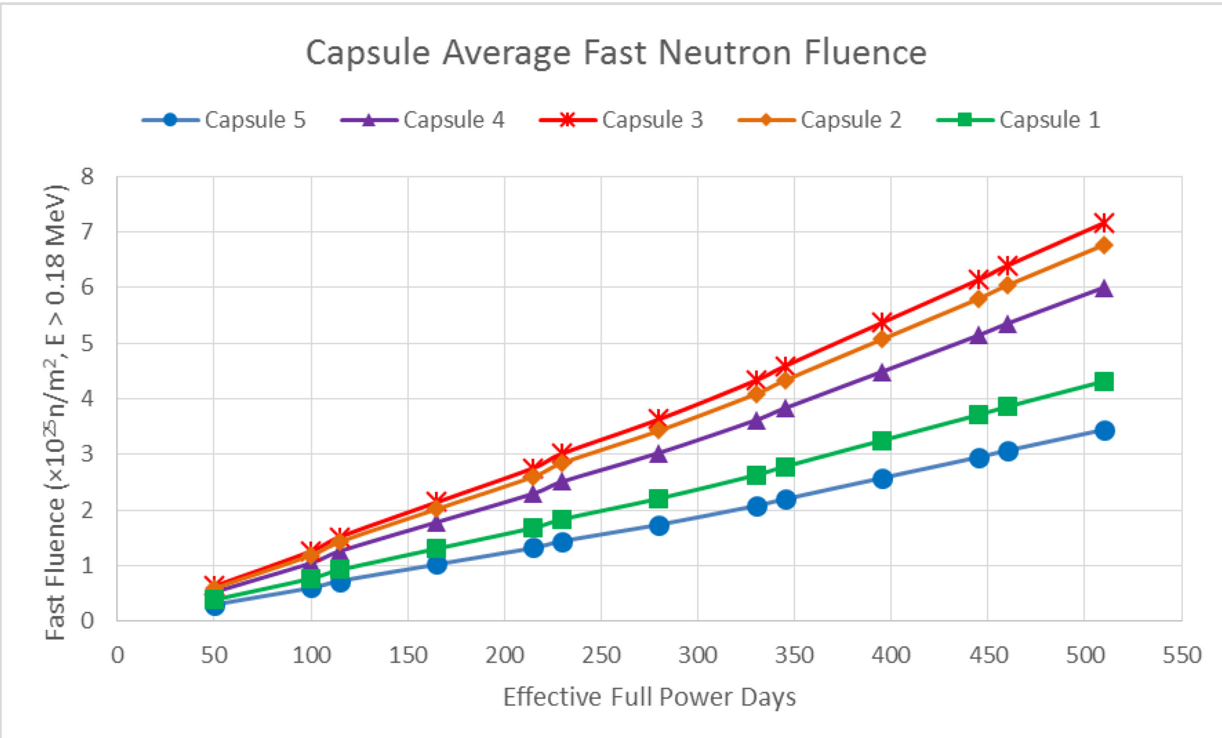
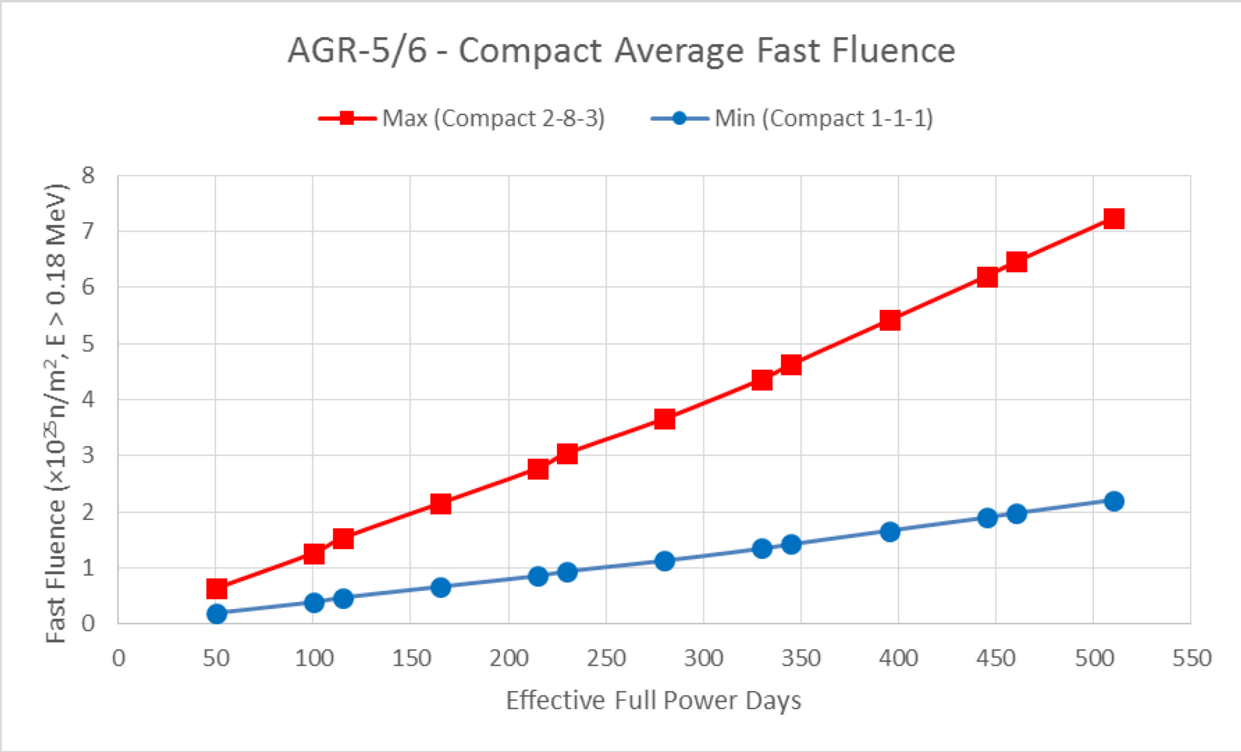


Figure 23. Capsule average fast neutron fluences for AGR-5/6 (Capsules 1, 2, 4, and 5) and AGR-7 (Capsule 3).



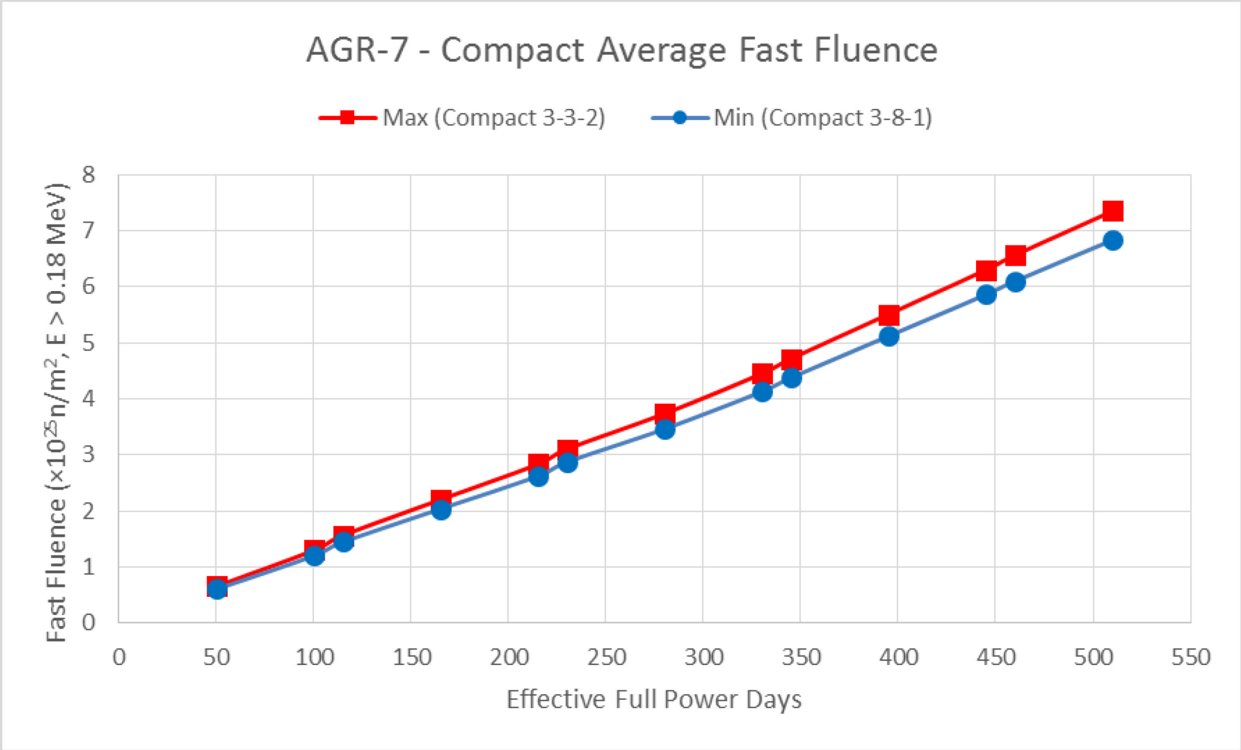


Figure 24. AGR-5/6 (top) and AGR-7 (bottom) minimum and maximum compact average fast neutron fluences.

4.5 Irradiation Duration

The AGR-5/6/7 irradiation duration is scheduled to be around 500 EFPDs. It is constrained by the AGR Technical Program Plan (INL, 2017a) assumption to limit the irradiation test acceleration to under three times that expected in a real-time HTGR irradiation, and by the test specifications for ancillary irradiation conditions. Since irradiating in a flux trap in ATR assures test acceleration is under a factor of three, test duration is determined by evaluating the attributes of temperature, fast neutron fluence, and burnup. This approach must balance increasing duration with decreasing temperatures and increasing burnup and fast fluence.

A summary of the scheduled AGR-5/6 an AGR-7 irradiation conditions and associated test specifications are presented in Table 13 and Table 14. Irradiation duration was initially scheduled to be 510 EFPDs but the irradiation schedule has since been altered and the current schedule projects an irradiation duration of 476 or 521 EFPDs depending on whether the irradiation is stopped before CIC or resumed for one cycle after the 9-month outage. Furthermore, additional ATR constraints could result in shorter or longer cycles. The objective is to stop the irradiation around 500 EFPDs as a shorter or longer irradiation could result in a violation of the test specifications.

Table 13. Summary of AGR-5/6 irradiation conditions.

Parameter	Test Specification	AGR-5/6
Irradiation length (EFPD – with / without CIC and 13th cycle)	Not specified (estimated at 510)	476 / 521
Calendar years[(a)] (with / without CIC and 13th cycle)	Not specified	2.3 / 3.3
Instantaneous peak temperature for each capsule (°C)	≤1800	<1347 (Compact 1-8-3)
Time-average temperature distribution goals (°C)	≥600 and <900 for about 30% of the fuel ≥900 and <1050 for about 30% of the fuel ≥1050 and <1250 for about 30% of the fuel ≥1050 and <1250 for about 10% of the fuel	29% 31% 32% 8%
Time-average peak temperature goal (°C)	1350 ± 50	1335 (Compact 1-8-6)
Time-average minimum temperature goal (°C)	≤700	<598 (Compact 5-6-1)
Minimum fuel compact average burnup (% FIMA)	>6 for all compacts >18 for at least one compact	>7.4 for all compacts >18 for 18 compacts
Minimum fuel compact fast neutron fluence ($\times 10^{25}$n/m^2, E>0.18 MeV)	>1.5 for all compacts ≥5.0 for at least one compact	>2.2 for all compacts ≥5.0 for 89 compacts
Maximum fuel compact fast neutron fluence ($\times 10^{25}$n/m^2, E>0.18 MeV)	≤7.5	≤7.3 for all compacts
Instantaneous peak power per particle (mW per particle)	≤400	≤190 for all compacts

(a) Assumes 210 EFPDs per calendar year to account for ATR outages; CIC is a planned 9-month outage.

Table 14. Summary of AGR-7 irradiation conditions.

Parameter	Test Specification	AGR-7
Irradiation length (EFPD – with / without CIC and 13th cycle)	Not specified (estimated at 510)	476 / 521
Calendar years[a] (with / without CIC and 13th cycle)	Not specified	2.3 / 3.3
Instantaneous peak temperature for each capsule (°C)	≤1800	<1515 (Compact 3-6-2)
Time-average peak temperature goal (°C)	1500±50	1478 (Compact 3-6-2)
Time-average minimum temperature goal (°C)	Not specified	<1062 (Compact 3-1-3)
Minimum fuel compact average burnup (% FIMA)	>6 for all compacts >18 for at least one compact	>17.4 for all compacts >18 for 14 compacts
Minimum fuel compact fast neutron fluence ($\times 10^{25} n/m^2$, E>0.18 MeV)	>1.5 for all compacts ≥5.0 for at least one compact	>6.8 for all compacts ≥5.0 for 24 compacts
Maximum fuel compact fast neutron fluence ($\times 10^{25} n/m^2$, E>0.18 MeV)	≤7.5	≤7.4 for all compacts
Instantaneous peak power per particle (mW per particle)	≤400	≤190 for all compacts
(a) Assumes 210 EFPDs per calendar year to account for ATR outages; CIC is a planned 9-month outage.		

5. MEASUREMENT REQUIREMENTS

Several measurements are needed to demonstrate that AGR-5/6/7 has reached the irradiation condition goals and test specifications. These conditions include time-average peak temperature, time-average volume-average temperature, fuel burnup, fast neutron fluence, and fission gas release. Because the fuel compacts cannot be directly instrumented (which may induce particle failures), burnup, neutron fluence, and fuel temperature will be determined by calculations that require supporting measurement data. Each of these measurement categories are discussed below.

5.1 Neutron Dosimetry

Both thermal and fast neutron fluence measurements will be made for the AGR-5/6/7 experiment. The purpose of these measurements is to provide neutron exposure data that will support the calculations of the average burnup, fast neutron fluence, and fission product inventory of each compact.

Following irradiation, the flux wires (see Section 3.3.2) will be counted for their neutron-induced radionuclide activities in both neutron fluence ranges. Data collected from the flux wires will be corrected for decay according to standard procedures. Derived fast neutron fluence data will be compared to physics-calculated fluence >1 MeV to validate the physics model. Upon agreement, the physics model will calculate the fluence for energies >0.18 MeV, which is the standard energy range over which the AGR fast neutron fluence is reported.

5.2 ATR Parameters

ATR data that describes the core neutronics and thermal-hydraulic environment will be required. These data will be used to assist physics analysis (to calculate fuel burnup, heat generation rates, and fast neutron fluences), assist thermal analysis (to calculate compact temperatures), and support temperature control.

ATR is a light-water-moderated 93% enriched uranium fueled test reactor. As shown in Figure 1, the fueled core is arranged in a four-lobe clover leaf configuration. Each of the four corner lobes can be controlled at different powers to match the requirements of various in-pile experiments. ATR is rated at a total thermal power of 250 MW, however the reactor is normally operated in the range of 105 to 115 MW to meet most experiment needs.

ATR data that will be provided include individual lobe powers, shim cylinder (hafnium absorber) positions, and core inlet temperatures. These data are recorded, and backed up on a separate storage device, once every minute.

5.3 Temperature Measurements

Temperature measurements will be performed by TCs terminating within the graphite holder of each capsule. These measurements will support thermal analyses of the test train, which ultimately will determine fuel temperatures, and will also support temperature control of the experiment. For this function, one TC per capsule is designated as the control TC. Measurements from the control TCs provide feedback to the automated sweep gas control system, which adjusts gas blend to maintain reference temperatures.

AGR-5/6/7 TCs have an as-installed accuracy of at least ±2% of reading as required by the test specifications. During normal operation, TC data will be recorded and backed up on a separate storage device, at least every 5 minutes. During abnormal events, the frequency will increase to recording at least every minute.

5.4 Sweep Gas Parameters

In addition to the TC measurements, several sweep gas parameters are required for thermal analyses and temperature control. These include pressure, mass flow rates of each constituent gas, and moisture content. Sweep gas pressures and constituent mass flow rates (which determine gas mixture ratios) will be used in physics and thermal analyses of the test train. Moisture content measurements (measured on the outlet side of the capsule and compared to the gas supply verification measurement) provide indicators of capsule integrity.

Capsule inlet pressure is measured to within ±0.007 MPa (±1 psi) with constituent mass flow rates measured within 1% root mean square. Moisture data are converted to parts per million by volume relative to atmospheric pressure. These data are recorded, and backed up on a separate storage device, once every minute during irradiation and for at least 2 days after each reactor shutdown.

5.5 Fission Gas Release Monitoring

Fission gas release measurements provide indicators of fuel irradiation performance. Gross radiation monitors (NaI(Tl)) continuously measure the sweep gas from each capsule to indicate fuel particle failures. Spectrometer detectors (HPGe) measure radionuclide concentrations to determine release rate to birth rate (R/B) ratios of selected nuclides. R/B values provide indicators of initial fuel quality and also provide indications of fuel failure.

The gross radiation monitors have sufficient sensitivity to detect every fuel particle failure up to and including the first 250 failures from each capsule. 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. These fuel particle failures are indicated by a rapid rise and drop, or spike, in the measured count rate. Such spikes are a result of a sudden release of stored fission product inventory. Measured spectra are automatically stored and backed up. 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 FPMS is kept under 25 minutes.

The spectrometer detector systems measure the concentrations of various krypton and xenon isotopes in the sweep gas from each capsule. During normal operation, 8-hour counting intervals are used to measure the concentrations of Kr-85m, Kr-87, Kr-88, Kr-89, Kr-90, Xe-131m, Xe-133, Xe-135, Xe-135m, Xe-137, Xe-138, and Xe-139. These concentrations are converted to fuel release rates, which with calculated birth rates will be used to determine R/B ratios. Measured spectra are automatically stored and backed up. During reactor outages, the capsules are swept with pure helium. This sweep gas is analyzed for Xe-133, Xe-135, and Xe-135m, whose concentrations are measured and recorded for at least 2 days following each reactor shutdown. These xenon concentrations are used to calculate concentrations of their parent iodine isotopes. Presence of the fission product iodine is also an indicator of fuel performance.

5.6 Data Validation and Qualification

Measured data are evaluated for validation and then qualified for use. The Nuclear Data Management and Analysis System (NDMAS) processes the data for this purpose. The following parameters are captured and processed by NDMAS: fuel irradiation data (TC readings, sweep gas compositions, flow rates and pressures, and moisture monitor readings), FPMS data (isotopic release data and gross gamma counts), and ATR operating conditions data (lobe powers, control cylinder positions, neck shim positions, and control rod positions). All test data will be backed up and stored in separate facilities at least daily.

6. OPERATIONAL REQUIREMENTS

All operational activities associated with the AGR-5/6/7 experiment comply with all applicable INL and ATR standard procedures. These activities also comply with all safety and quality assurance requirements outlined in Section 7. Activities requiring special or unique consideration are identified below.

6.1 Pre-irradiation

After assembly, test train and fission product monitor components and subsystems will undergo inspection, testing, and calibration, as needed. This includes, but is not limited to, leak testing of all pressure boundaries and gas lines and continuity checks of all TCs. Following these activities, a review will be conducted whereby any findings will be corrected.

Following successful completion of the review and obtaining all appropriate ATR approvals, the AGR-5/6/7 test train will be inserted into the NEFT of ATR, air within the lead and gas lines will be purged, and final component inspections will be performed.

6.2 Irradiation

During irradiation, temperature control is automatically maintained by the gas control system. This system requires temperature feedback from a control TC within each capsule. Should a control TC fail, a previously selected backup TC within the same capsule will be used as the control TC and the reference control temperature reset based on thermal analysis calculations. Should all TCs fail within a capsule, results from physics and thermal analyses supported by the operating history of an adjacent capsule will be used to manually set the gas blends of the affected capsule. Ultimately, should all TCs fail within the test, temperature control may be based on predictive thermal analyses, augmented by analyses of fission product gas release, which is sensitive to temperature.

TC drift will be monitored by analyses. With actual gas mixes and predicted heat generation rates from physics analyses, the thermal model will be adjusted and calibrated to TC readings during the start of the first irradiation cycle (about 2 days after reactor startup so that xenon equilibrium is reached). Thereafter, thermal model results will be compared to the TC readings. Should the difference between model predictions and actual readings of a control TC differ by more than 50°C (about 4 to 5% of reading), control set points for the gas mix system will be adjusted to compensate for the TC drift.

The current ATR planning includes four PALM cycles during the span of AGR-5/6/7 irradiation. These PALM cycles are scheduled to last about 7, 14, 7, and 14 EFPDs, respectively, and are planned after about 38, 158, 287, and 406 EFPDs of irradiation. The use of neutron filters will allow the AGR-5/6/7 test train to remain in the NEFT during these PALM cycles. However, during the long CIC outage (274 days), the test train will be removed from the core and placed in the ATR canal.

During any switch in control gas (to pure helium, to a neon-helium mix, etc.), flows of the common plenum gas and each control gas will be appropriately adjusted to ensure that continuity is maintained in the pressure differential between the common plenum and each capsule. This ensures that cross flow between capsules is avoided. After each ATR shutdown and during the entire outage, the control gas will be switched to pure helium for each capsule, and the helium will continuously flow through each capsule at the nominal operating flow rate. The plenum flow will also be maintained at its nominal operating flow rate.

Should a capsule experience excessive fuel particle failures, sweep gas to the capsule will be set to consist of 100% helium. The helium sweep gas will be maintained at the nominal operating flow rate until the end of the irradiation.

Indicators of moisture ingress (sweep gas outlet moisture content higher than inlet content) will be closely monitored. Past experience has shown that once the presence of moisture is detected, the content rapidly increases. Should a rapid increase in moisture be observed in a capsule, the test train may be removed from the reactor at the next scheduled reactor outage to avoid significant water-graphite interactions possibly compromising other capsules via gaps that may form around the through tubes.

Program participants will be able to view time-series data online via a secured site. Summary plots and downloadable data will be able for TC temperatures, sweep gas parameters, and gross radiation monitor count rates. Additionally, ATR operational data will be updated daily.

As a result of cycle-to-cycle variations in ATR lobe powers, accumulated burnup and fast neutron fluence for the AGR-5/6/7 compacts must be periodically updated based on as-run data. These as-run physics data reports will be issued as interoffice memoranda after the end of each reactor cycle to the test completion. They will be used to generate birth rates of short-lived Kr and Xe isotopes for R/B calculations and to perform as-run thermal analyses. Both resulting R/B ratios and calculated fuel temperatures can be used to monitor the experiment and fine tune it from one cycle to the next as needed.

6.3 Post-irradiation

The AGR-5/6/7 test train will be removed from the reactor after completion of the irradiation. For removal, the TCs and gas lines will be disconnected at the reactor vessel penetration flange (where the leadout passes through the reactor wall). The gas lines will then be capped and a cover installed on the test train leadout flange. The entire test train will then be lifted from the NEFT test position and placed in the ATR canal.

The test train will cool in the canal for about three months before being transferred to the INL Materials and Fuels Complex Hot Fuel Examination Facility for disassembly. Preliminary PIE will be conducted during and immediately after disassembly. A description of the basic approach for PIE is presented in the technical program plan (INL, 2017a). A detailed AGR-5/6/7 PIE Plan will be developed prior to the end of the irradiation.

Within a year of test completion, an irradiation test final as-run report will be issued. Results from PIE and safety testing will be documented separately after the completion of those activities.

7. SAFETY AND QUALITY ASSURANCE

7.1 Safety

The design, fabrication, installation, operation, and disassembly activities of the AGR-5/6/7 experiment comply with all applicable health, safety, and environmental requirements. These activities and their corresponding requirement directives are listed in Table 15.

Table 15. AGR-5/6/7 safety requirements.

Activity/Component	Requirements
Design, installation and operation of test lead	ATR Technical Safety Requirements Upgraded Final Safety Analysis Report
Capsule containment tube	American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code
Mechanical design	Applicable sections of ASME and American Welding Society (ASW) Codes
Nuclear materials accountability	Applicable Department of Energy orders
Radioactive material shipments	Applicable Department of Energy orders

7.2 Quality Assurance

Quality assurance activities associated with the AGR-5/6/7 experiment comply with all applicable requirements set forth in:

- INL Quality Assurance Program Description (INL, 2017c) based on ASME NQA-1-2008 (ASME, 2008) and Addenda NQA-1a-2009 (ASME, 2009)
- INL Advanced Reactor Technologies Technology Department Office Quality Assurance Program Plan (INL, 2017b)
- ATR Complex site-specific quality assurance implementation procedures and forms

8. PROGRAM CONSTRAINTS AND SCHEDULE

Several possible programmatic constraints may affect the scheduling and accomplishment of significant activities presented in this test plan. Some of these constraints are discussed below.

The AGR-5/6/7 irradiation is scheduled to start on December 6, 2017 and to run until January 16, 2021. It will be followed by a 3-month cooling period of the test train in the ATR canal.

The irradiation duration is planned for approximately 3 calendar years. This duration may be shortened because of significant test train or fuel failures or lengthened to gain more fuel performance data with increased burnup. Duration to achieve targeted burnups also depends on ATR operation, where lobe powers are adjusted each cycle for the needs of various experiments including PALM cycles, possible increased maintenance outage durations, or unforeseen additional outages.

Four of these PALM cycles are planned during the scheduled 521 EFPDs irradiation of AGR-5/6/7, respectively after about 38, 158, 287, and 406 EFPDs of irradiation, and they are expected to last 7, 14, 7, and 14 EFPDs respectively.

A 9-month outage is currently scheduled from February 29, 2020 to November 29, 2020 to proceed to the replacement of the core internals of ATR. During this outage, the AGR-5/6/7 test train will be removed from the NEFT and placed in the ATR canal. It is expected that the AGR-5/6/7 experiment will not have reached its burnup and fast neutron fluence targets prior to CIC. In this case, the test train would be re-inserted in the NEFT after the outage for an additional power cycle. A schedule indicating major irradiation-related activities for the AGR-5/6/7 experiment is shown in Table 16.

Table 16. Schedule for AGR-5/6/7 irradiation-related activities (calendar years).

	Start	**Finish**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
Fuel Fabrication	4/1/2011	3/31/2017						
Design and Assembly	5/1/2014	9/25/2017						

	Start	**Finish**	**2017**	**2018**	**2019**	**2020**	**2021**
Fuel Fabrication	4/1/2011	3/31/2017					
Design and Assembly	5/1/2014	9/25/2017					
Irradiation	12/6/2017	1/16/2021				CIC	
Data Analysis and Reporting	10/1/2017	10/12/2021					

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