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Plan

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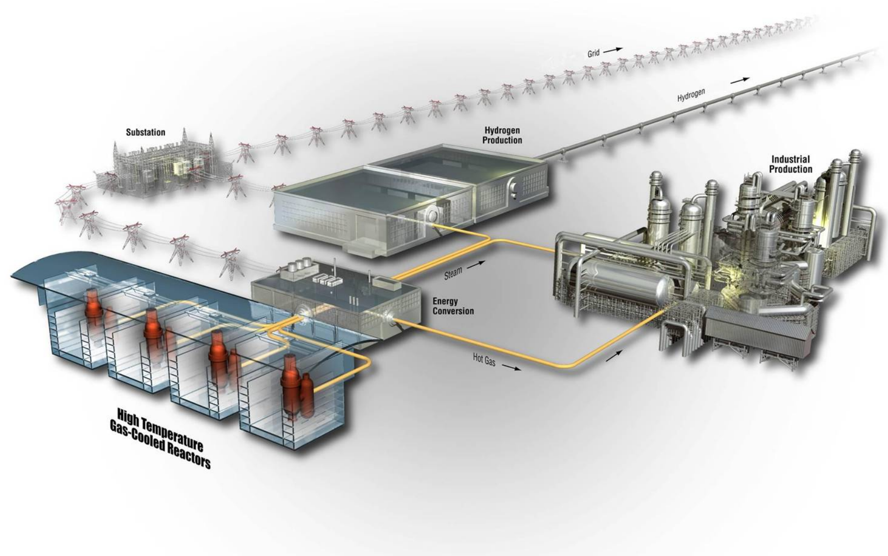
Test Plan for Reirradiation and 1400°C Heating Test of AGR-3/4 Compact 10-1



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FIGURES

TABLES

ACRONYMS

AGR	Advanced Gas Reactor
AL	Analytical Laboratory
ART	Advanced Reactor Technologies
ATR	Advanced Test Reactor
DTF	designed-to-fail
FACS	Fuel Accident Condition Simulator
FGMS	Fission Gas Monitoring System
FIMA	fissions per initial heavy metal atom
HFEF	Hot Fuels Examination Facility
HOG	HFEF Out-of-cell Gamma
ICP-MS	Inductively-coupled plasma mass-spectrometry
INL	Idaho National Laboratory
IPyC	inner pyrolytic carbon
LBL	leach-burn-leach
NRAD	Neutron Radiography Reactor
OPyC	outer pyrolytic carbon
ORNL	Oak Ridge National Laboratory
PGS	Precision Gamma Scanner
PIE	post-irradiation examination
PyC	pyrocarbon
SiC	silicon carbide
TA	time-average
TAVA	time-average volume-average
TRISO	tristructural isotropic
UCO	uranium carbide/uranium oxide mixture

1. INTRODUCTION

Post-irradiation examination (PIE) and heating tests of tristructural isotropic (TRISO)-coated fuel particles, fuel compacts, and graphite from Advanced Gas Reactor (AGR) irradiation experiment AGR-3/4 are in progress. The AGR-3/4 test train consisted of twelve separate capsules irradiated in the northeast flux trap of the Advanced Test Reactor (ATR) at Idaho National Laboratory (INL) from December 14, 2011, to April 12, 2014 (Collin 2015b). This test plan describes the reirradiation and subsequent heating test of AGR-3/4 Compact 10-1. One of the main goals of this test is to assess the retention of short-lived fission products I-131 ($t_{1/2}$ = 8.02 d) and Xe-133 ($t_{1/2}$ = 5.2 d) in fuel kernels. To generate short-lived fission products, the compact will first be reirradiated in the Neutron Radiography Reactor (NRAD). Following reirradiation, the compact will be removed from NRAD, gamma scanned on the Precision Gamma Scanner (PGS), and then loaded into the Fuel Accident Condition Simulator (FACS) furnace for heating at 1400°C. Fission gases and condensable fission products released from the compact will be collected in the Fission Gas Monitoring System (FGMS) and the FACS condensation plates, respectively.

The planned uses of AGR-3/4 compacts (including heating testing and destructive analysis) are discussed in the AGR-3/4 PIE plan (Demkowicz 2017).

2. DESCRIPTION OF THE REIRRADIATION/HEATING TEST

2.1 Fuel Description

One of several features of AGR-3/4 that set it apart from AGR-1 and AGR-2 is the incorporation of 20 designed-to-fail (DTF) particles in each compact. The fuel kernels in the DTF particles were coated only with a thin (20 µm thick) pyrocarbon layer having high anisotropy such that the coating would most-likely fail during the irradiation, resulting in up to 20 exposed kernels per compact (Collin 2015a). All AGR-3/4 TRISO-coated particles (both driver particles and DTF particles) contain low-enriched UCO (a uranium carbide, uranium oxide mixture) fuel kernels approximately 350 µm in diameter manufactured at BWX Technologies Nuclear Operations Group (Lynchburg, VA). The U-235 enrichment was 19.7%. Each AGR-3/4 compact contains approximately 1872 driver fuel particles and precisely 20 DTF particles. As shown in Figure 1, the DTF particles (highlighted in red) were aligned in each compact roughly along the compact axial centerline. The white circles in Figure 1 are the driver particles. The DTF particles were fabricated at Oak Ridge National Laboratory (ORNL). The driver fuel particles were also fabricated at ORNL by applying TRISO coatings to the kernels, with the following average thickness for each layer:

- Buffer: 109.7 µm
- Inner pyrolytic carbon (IPyC): 40.4 µm
- silicon carbide (SiC): 33.5 µm
- Outer pyrolytic carbon (OPyC): 41.3 µm.

AGR-3/4 fuel compacts were fabricated at ORNL. The compacts are nominally 12.3 mm in diameter and 12.5 mm long (in contrast to the AGR-1 and AGR-2 compacts, which were approximately 25 mm long). A summary of AGR-3/4 fuel properties are provided in the AGR-3/4 Experiment Irradiation Test Plan (Collin 2015a). Detailed characterization data of the fuel particles and compacts have been provided by ORNL (Hunn and Lowden 2007; Hunn, Trammel, and Montgomery, 2011; Kercher et al. 2011).

AGR-3/4 Compact 10-1 was chosen for this 1400°C heating test. In the X-Y compact naming convention, X denotes the capsule number, and Y denotes the level of the compact within the capsule. In AGR-3/4 there were four compacts per capsule, and thus, Compact 10-1 is the bottom-most compact in

Capsule 10. Fabrication parameters and elements of the irradiation history for AGR-3/4 Compact 10-1 are listed in Table 1. The estimated number of DTF particle failures per AGR-3/4 irradiation capsule is listed in Table 2. Based on experience from AGR-1, it is very unlikely that any driver particles failed during the irradiation; therefore, all supposed in-pile particle failures are assumed to be DTF failures. Since there are only 80 DTF particles per capsule, a combination of measurement uncertainty and calculational biases in the physics analyses may explain why greater than 80 DTF particle failures are listed in the best-estimate and max columns for Capsules 2, 3, and 9. Using the maximum and minimum values for Capsule 10, it is estimated that between 9 and 19 failed DTF particles may be present in Compact 10-1 at the start of this test. It should be noted that given the uncertainty of the in-pile measurements from which the estimates in Table 2 were derived, it is still possible that Compact 10-1 has between 0 and 20 failed DTF particles.

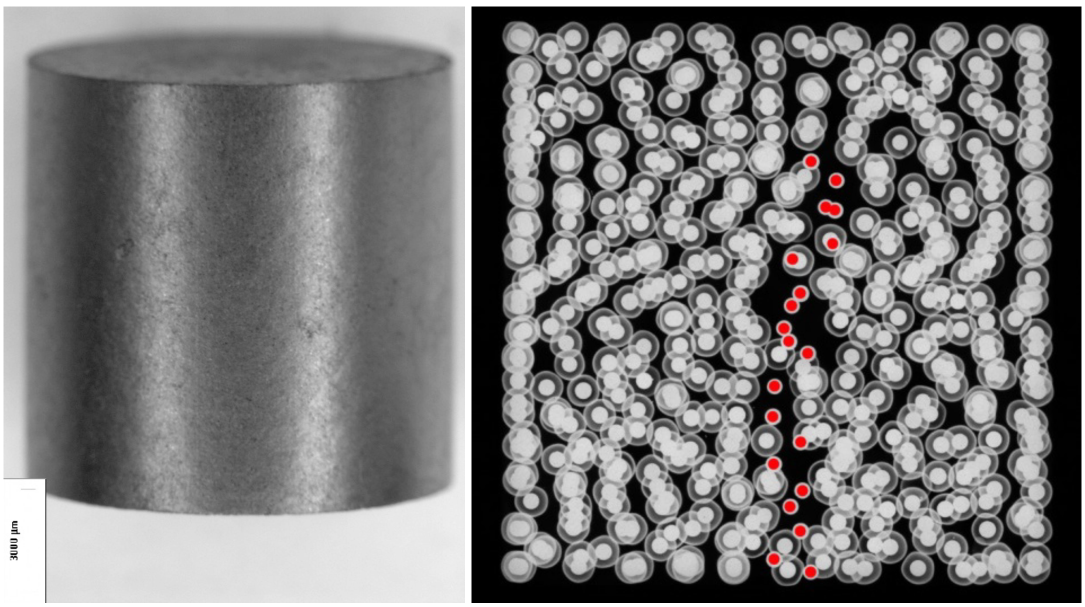

Figure 1. Image of an AGR-3/4 fuel compact (left) and x-ray side view image (right) (Hunn, Trammell, and Montgomery 2011). DTF particles are highlighted with red dots in the x-ray image.

Table 1. Selected fuel fabrication and irradiation properties.

Compact[a]	10-1
Fuel Compact Fabrication ID[b]	(LEU03-10T-OP2/LEU03-07DTF-OP1)-Z133
UCO Fuel Kernel Lot[b]	Lot G37V-20-69303
TRISO-coated Particle Lot (driver particles)[b]	LEU03-09T (renamed as LEU03-10T)
Designed-to-fail Particle Lot[b]	LEU03-07DTF
Compact Average Burnup (%FIMA)[c]	12.08
Compact average Fast Fluence (n/m^2, E > 0.18 MeV)[c]	4.12×10^{25}
TAVA Irradiation Temperature (°C)[d]	1172
TA Peak Irradiation Temperature (°C)[e]	1238
TA Minimum Irradiation Temperature (°C)[e]	1080

a. X-Y naming convention denotes location in irradiation test train: Capsule-Level (Demkowicz 2017).
b. From (Collin 2015a) and (Hunn, Trammel, and Montgomery, 2011).
c. Based on physics calculations (Sterbentz 2015).
d. TAVA = Time-average volume average temperature determined from thermal calculations (Hawkes 2016).
e. TA = Time-average temperature, determined from thermal calculations (Hawkes 2016).

Table 2. AGR-3/4 estimated DTF particle failure count in each irradiation capsule. There were four compacts in each capsule. Table from (Collin 2015b) and (Scates 2015).

Capsule	Best-estimate	Max	Min
1	41	81	21
2	91	168	51
3	96	146	53
4	76	100	57
5	54	92	36
6	47	53	42
7	52	75	38
8	78	129	54
9	90	99	98
10	47	75	36
11	69	92	48
12	39	49	38

2.2 Reirradiation and Heating Testing

2.2.1 Process Overview

Figure 2 shows a flow chart depicting the major steps of the compact reirradiation/heating test. Utilizing the NRAD cask, the compact will be loaded into NRAD for reirradiation for up to 7 consecutive, 24-hour days. A shorter reirradiation may be conducted after consulting with the PIE Technical Lead. Following completion of the reirradiation, the compact will be unloaded from NRAD and loaded into the PGS to quantify the compact inventory of gamma-emitting fission products. Special emphasis shall be placed on detecting I-131 and Xe-133. Once gamma scanning has completed, the compact will be loaded into the FACS furnace for heating. Condensation plates exchanged during the heating test shall be gamma counted on the Hot Fuels Examination Facility (HFEF) Out-of cell Gamma (HOG) station as they become available. The heating test will continue while plates exchanged early in the test are counted. After gamma counting, the condensation plates shall be transferred to the Analytical Lab (AL) for Sr-90 analysis. After the FACS test has completed, the compact will be removed and counted on PGS. After PGS, the compact will be stored at HFEF for possible future transfer to AL. Some decay time between steps may be appropriate to reduce gamma detector dead times. The sequence and duration of the decay time shall be discussed with the Fuels PIE Technical Lead in advance of the pause to allow some radioisotope decay. Certain major steps are discussed in additional detail in the following subsections.

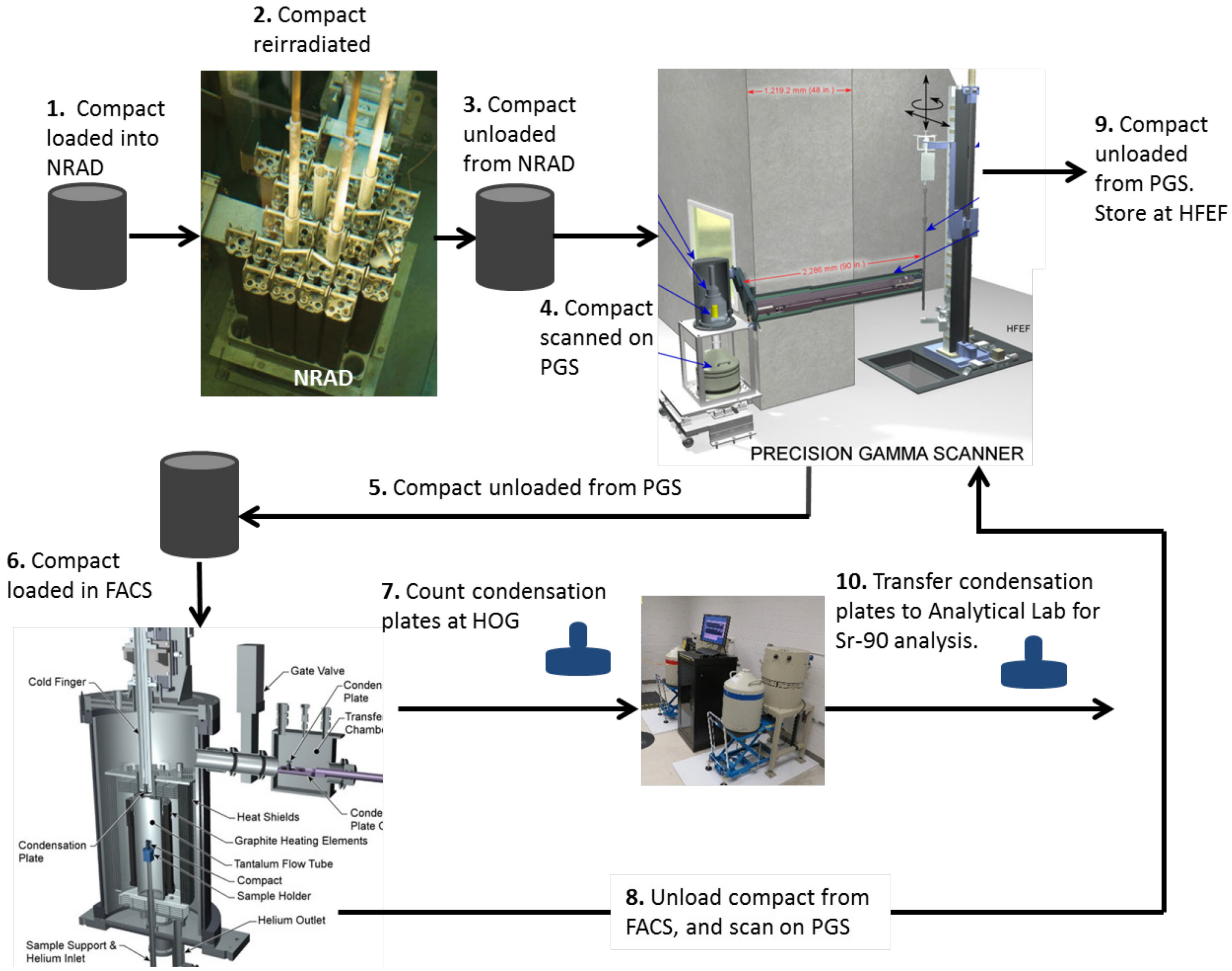

Figure 2. Flow chart of compact reirradiation, heating testing, and gamma scanning/counting activities.

2.2.2 Heating Test Conditions

The compact will be loaded into a tantalum sample holder in the FACS furnace. Helium flow in the flow tube will be at a rate of 900 mL/min, and the flow in the vessel will be 100 mL/min. The cold finger position will be 17.0 cm. The sample holder should be positioned to center the specimen vertically in the furnace. Prior to starting the furnace heating profile, helium will flow through the furnace for approximately 24 hours in order to purge it. During this pre-test purge, the helium will bypass the FGMS.

After the purge has been completed, the furnace heating profile can be started and the helium gas flow will be directed to the FGMS traps. FGMS will continually monitor its cold traps for Kr-85 and Xe-133. To drive out any moisture from the compact, the furnace should first be heated under a helium environment from room temperature to 300°C in 2-hours. This temperature shall be held for 2-hours. After this 2-hour hold, the temperature will be raised from 300°C to 1400°C in 2-hours. The temperature shall be held for 300 hours at 1400°C. The total time from the beginning of the initial ramp up from room temperature to the end of the final ramp back down to room temperature is 309 hours. The temperatures shall be maintained within the accuracy of the FACS thermocouples, typically ±1%.

The ramp and soak cycles for this temperature profile are given in Table 3, and the condensation plate change schedule is given in Table 4. The temperature program and condensation plate exchanges are visualized in Figure 3. Condensation plates should be exchanged as close to the schedule indicated in Table 4 and Figure 3 as possible. Some deviations from exact times may be required to accommodate work shifts. Alterations to the plate exchange schedule may also be made after discussing with the Fuels PIE Technical Lead. Plate exchanges occurring immediately before, during, or after temperature ramps should be performed on-schedule. After removal from the furnace, all condensation plates will be placed in individual, labeled containers.

The FACS furnace and supporting systems will be operated according to relevant laboratory instructions and procedures. The FACS process engineer shall provide the Fuels PIE Technical Lead with periodic updates to the FACS run data for review during the test. Analysis of furnace process data (temperatures, voltage and current, flow rates, etc.) will be performed to verify correct operation of the system.

AGR-3/4 compacts with DTF particles will start with exposed fuel kernels similar to what would be expected if all three TRISO layers failed on a TRISO-coated particle. In addition, even intact DTF particles are expected to be less retentive than TRISO particles with failed SiC. Depending on the levels of Kr-85 or Xe-133 measured in the FGMS traps and/or other considerations, the heating test may be terminated early only after consulting with the Fuels PIE Technical Lead. After consulting with the Fuels PIE Technical Lead, the temperature program and/or condensation plate exchange schedule may also be modified.

Table 3. Ramp and soak cycles for the heating test.

Start Temperature (°C)	Ramp Time from Start Temperature to End Temperature (hrs)	End Temperature (°C)	Soak Time at End Temperature (hrs)
30*	2	300	2
300	2	1400	300
1400	3	30*	0

* The start temperature should roughly correspond to ambient temperature of the hot cell.

Table 4. Schedule for FACS condensation plate exchanges if test starts at 8:00 AM on a Monday. Note that final plate change interval is 30 minutes prior to ramp down from test temperature.

Elapsed Time (hr)	**Temp (°C)**	**Time**	**Notes on Plate Change**
3.5	300	Monday 11:30:00 AM	Exchange 30 minutes prior to ramp from 300°C to 1400°C
5	950	Monday 1:00:00 PM	Exchange half-way through ramp from 300°C to 1400°C
6.5	1400	Monday 2:30:00 PM	Exchange 30 minutes after reaching 1400°C
8	1400	Monday 4:00:00 PM	Exchange 1.5 hours after previous exchange
11.5	1400	Monday 7:30:00 PM	Exchange 3.5 hours after previous exchange
15.5	1400	Monday 11:30:00 PM	Exchange 4 hours after previous exchange

Table 4. (continued).

Elapsed Time (hr)	Temp (°C)	Time	Notes on Plate Change
19.5	1400	Tuesday 3:30:00 AM	Exchange 4 hours after previous exchange
23.5	1400	Tuesday 7:30:00 AM	Exchange 4 hours after previous exchange
29.5	1400	Tuesday 1:30:00 PM	Exchange 6 hours after previous exchange
35.5	1400	Tuesday 7:30:00 PM	Exchange 6 hours after previous exchange
41.5	1400	Wednesday 1:30:00 AM	Exchange 6 hours after previous exchange
47.5	1400	Wednesday 7:30:00 AM	Exchange 6 hours after previous exchange
59.5	1400	Wednesday 7:30:00 PM	Exchange 12 hours after previous exchange
71.5	1400	Thursday 7:30:00 AM	Exchange 12 hours after previous exchange
83.5	1400	Thursday 7:30:00 PM	Exchange 12 hours after previous exchange
95.5	1400	Friday 7:30:00 AM	Exchange 12 hours after previous exchange
119.5	1400	Saturday 7:30:00 AM	Exchange 24 hours after previous exchange
143.5	1400	Sunday 7:30:00 AM	Exchange 24 hours after previous exchange
167.5	1400	Monday 7:30:00 AM	Exchange 24 hours after previous exchange
191.5	1400	Tuesday 7:30:00 AM	Exchange 24 hours after previous exchange
215.5	1400	Wednesday 7:30:00 AM	Exchange 24 hours after previous exchange
239.5	1400	Thursday 7:30:00 AM	Exchange 24 hours after previous exchange
263.5	1400	Friday 7:30:00 AM	Exchange 24 hours after previous exchange
287.5	1400	Saturday 7:30:00 AM	Exchange 24 hours after previous exchange
305.5	1400	Sunday 1:30:00 AM	Exchange 18 hours after previous exchange, 30 min prior to shutdown

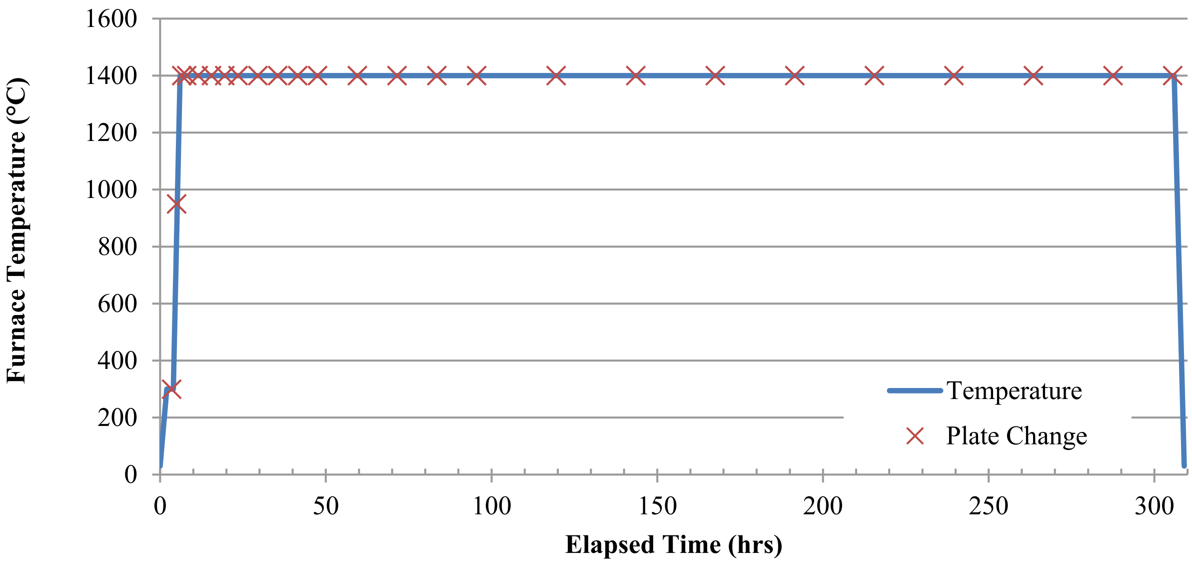

Figure 3. Temperature profile for the test, including time and temperatures of plate changes. See Table 4 for complete list of plate exchanges and timings of exchanges.

2.3 Post-test Activities

2.3.1 Compact Analyses

Following the FACS test, the compact will be removed from the FACS sample holder and scanned on PGS. After PGS scanning has finished the compact will be placed in a storage container. At a later date, the compact may be sent either to AL or ORNL for radial deconsolidation. A general description of the radial deconsolidation process is available in (Stempien 2017). Briefly, the compact will be electrolytically deconsolidated in three or four radial steps. For each radial step, particles, matrix debris, and a deconsolidation solution will be generated. The particles and matrix debris from each radial segment will undergo leach-burn-leach (LBL) analysis, and 30 particles from each radial segment will be selected for gamma counting following LBL. The deconsolidation solutions and solutions from particle/matrix LBL will undergo gamma counting and Sr-90 analysis; and inductively-coupled plasma-mass-spectrometry (ICP-MS) may also be performed for actinides. After radial deconsolidation, a compact core (containing the DTF particles) remains. This core will be axially deconsolidated in a single step, generating free particles, matrix debris, and a deconsolidation solution. The particles and matrix debris will undergo LBL, and 30 particles will then be selected for gamma counting. The deconsolidation solution will have gamma counting and Sr-90 analyses; and ICP-MS may also be performed.

2.3.2 Post-test Purge, Condensation Plate Analyses, and Furnace Cleanup

When the test has concluded, a 24 hour post-test purge with helium shall be performed at a total helium flow rate of 1000 mL/min. The details of the post-test purge (e.g., duration and flow rate) may be altered after discussing with the Fuels PIE Technical Lead.

All condensation plates changed during the test and subsequent cleanup run (described below) shall be gamma counted at the HOG. After gamma counting, plates will undergo acid leaching and analysis for Sr-90 at AL. Following removal of the compact, a clean-up run will be performed with the FACS furnace. The objective of this run is to ensure that any remaining fission products released during the test and deposited on the furnace tantalum internals have been removed or to ensure that they are relatively stable at the temperatures likely to be encountered during future testing and will not influence the results of subsequent tests. The furnace will be heated to a temperature of approximately 1725°C at a rate of ~600°C/h with no specimen on the sample holder and helium flowing at a total rate of 1000 mL/min. The FGMS will run for the duration of the cleanup run to monitor the Kr-85 inventory collected from the furnace. The duration of the hold at ~1725°C will be approximately 48-hours with two condensation plate changes during the clean-up run (a total of three condensation plates will be exposed in the furnace during the clean-up run). The cleanup run temperature, hold time, ramp rates and number of plate exchanges etc. may be altered after consulting the Fuels PIE Technical Lead. The furnace power will then be shut off so that the furnace executes an uncontrolled return to ambient temperature. Cleanup run condensation plates will be placed in individual, labeled containers. These plates will be gamma counted on the HOG station. Following gamma counting, plate leaching and Sr-90 analysis will be performed at AL. The effectiveness of the cleanup run will be assessed based on the measured activity on the three condensation plates used during the run.

2.4 Data Processing and Transmittal

At the completion of the test, the FACS process engineer will provide a formal data transmittal consisting of the daily FACS furnace system run data. The FGMS lead engineer will process the FGMS data to determine time-dependent Kr-85 and Xe-133 activity in the FGMS cold traps and provide these data to the Fuels PIE Technical Lead.

3. REFERENCES

Collin, Blaise P., 2015a, “AGR-3/4 Irradiation Experiment Test Plan,” PLN-3867, Idaho National Laboratory, Rev. 1, May 2015.

Collin, Blaise P., 2015b, “AGR-3/4 Irradiation Test Final As-Run Report”, INL/EXT-15-35550, Rev. 0, Idaho National Laboratory, June 2015.

Demkowicz, Paul A., 2017, “AGR-3/4 Phase 2 Post-Irradiation Examination Plan,” PLN-5382, Idaho National Laboratory, May 5, 2017.

Hawkes, Grant L., 2016, “AGR-3/4 Daily As-Run Thermal Analyses,” ECAR-2807, Rev. 1, Idaho National Laboratory, April 21, 2016.

Hunn, J.D., R.A. Lowden, 2007, “Data Compilation for AGR-3/4 Driver Fuel Coated Particle Composite LEU03-09T”, ORNL/TM-2007/019, Oak Ridge National Laboratory

Hunn, J., M.P. Trammell, F.C. Montgomery, 2011, “Data Compilation for AGR-3/4 Designed-to-Fail (DTF) Fuel Compact Lot (LEU03-10TOP2/LEU03-07DTF-OP1)-Z”, ORNL/TM-2011/124, Oak Ridge National Laboratory.

Kercher, A.K., B.C. Jolly, F.C. Montgomery, G.W.C. Silva, and J.D. Hunn, 2011, “Data Compilation for AGR-3/4 Designed-To-Fail (DTF) Fuel Particle Batch LEU03-07DTF”, ORNL/TM-2011/109, Oak Ridge National Laboratory

Scates, D. M., 2015, “Release-to-Birth Ratios for AGR-3/4 Operating Cycles 151A through 155B”, ECAR-2457, Rev. 1, June 5, 2015.

Stempien, J.D., 2017, “Radial Deconsolidation and Leach-Burn-Leach of AGR-3/4 Compacts 3-3, 12-1, and 12-3”, INL/EXT-17-43182, Idaho National Laboratory, September, 2017.

Sterbentz, James W., 2015, "JMOCUP As-Run Daily Physics Depletion Calculation for the AGR-3/4 TRISO Particle Experiment in the ATR Northeast Flux Trap," ECAR-2753, Rev. 1, Idaho National Laboratory, September 2015.