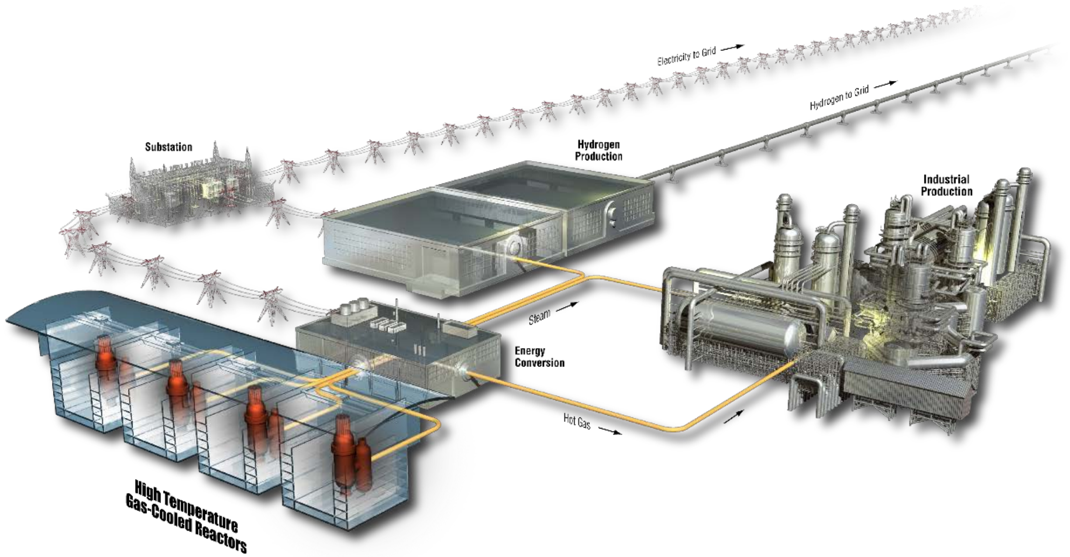
Status of AGR-5/6/7 Fuel Fabrication

Douglas W. Marshall
Fuel Fabrication Technical Lead



www.inl.gov
Idaho National Laboratory

Outline

- AGR Fuel Fabrication Overview
- TRISO Particle Fabrication
  - Challenges Overcome
  - Selection of TRISO Particle Batches
  - TRISO Particle Lot Characterization
- AGR-5/6/7 Fuel Compact Fabrication
  - Material Flowchart
  - Processes for Compact Fabrication
  - Characterization Data
    - Dimensional
    - Defect Fractions
- What We Have Learned

Advanced Gas Reactor Program Overview

Experiment	Purpose	Kernel Fabrication	TRISO Coating	Overcoating Compacting
AGR-1	Shakedown/ early fuel experiment	Engineering	Laboratory	Laboratory
AGR-2	Performance test fuel experiment	Engineering	Engineering	Laboratory
AGR-3/4	Fission product transport experiments	Engineering	Laboratory	Laboratory
AGR-5/6/7	Fuel qualification and fuel performance margin testing experiments	Engineering	Engineering	Engineering

Fuel Fabrication Overview (cont.)

AGR-5/6/7 Material	Produced	Used	Residue
Certified LEUCO kernels			
J52R-16-69317	19.0 kg	18 kg	~1 kg
J52R-16-69318	5.1 kg	---	5.1 kg
TRISO particles			
Lot 98005	11.6 kg	6.1 kg	5.5 kg
Spares (93172, 93173)	~ 6 kg	---	~ 6 kg
Overcoated particles			
25% PF	3.68 kg	3.46 kg	0.22 kg
40% PF	7.82 kg	7.08 kg	0.74 kg
Compacts		**Lab + Train**	
25% PF	684	147 + 80	457
40% PF	948	95 + 114	739

TRISO Particle Fabrication

- Restart challenges
  - Furnace maintenance
  - Operator experience
    - Infrequent operation
    - Turnover and reassignment
  - Equipment issues resulting in coating interruptions
  - Upgrading issues
    - Unexpected retention of undersized particles and fragments
    - Determined sieve shaker intensity was less than adequate
    - Re-sieved all of the product with revised parameters
    - Realized impressive reductions in the exposed kernel defect and missing-buffer fractions

TRISO Particle Lot Characterization

– Schedule Recovery Strategy:
  - Use certified kernels for 3x pre-production runs and ≤ 5 production runs
  - Use 3 – 5 TRISO particle batches for the certified TRISO particle lot

Batch/Lot Layer Thicknesses (μm)	Buffer 100 ± 15	IPyC 40 ± 4	SiC 35 ± 3	OPyC 40 ± 4
JF2O-16-93165	104.5	40.7	36.6	30.3
JF2O-16-93168	96.6	39.1	35.7	38.5
JF2O-16-93169	98.7	38.9	35.8	36.0
JF2O-16-93170	101.5	38.2	36.5	35.6
JF2O-16-93172	100.7	38.0	36.5	38.7
JF2O-16-93173	100.7	38.4	35.1	39.7
J52R-16-98005 (lot)	100.4	39.2	36.1	35.0

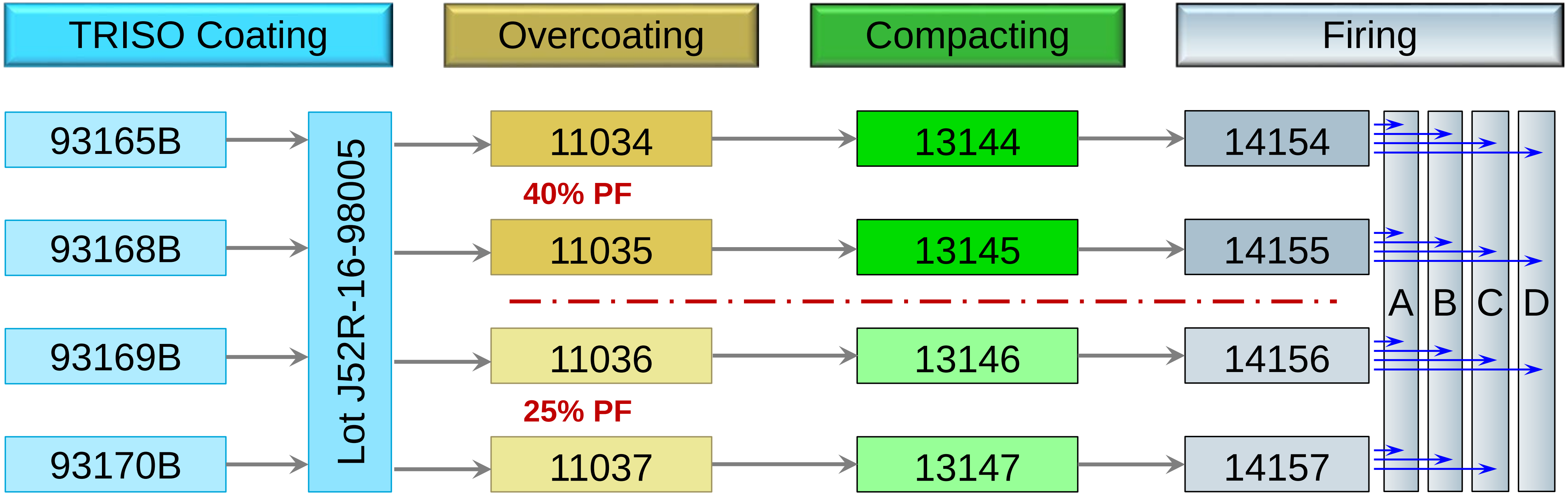
Note: J52R-16-93166, 93167, and 93171 were excluded due to process interruptions.

TRISO Particle Lot Characterization (cont.)

Batch/Lot Layer Density and BAF_o	Buffer	IPyC		SiC	OPyC	
	ρ_B	ρ_I	BAF_o	ρ_S	ρ_O	BAF_o
	1.05 ± 0.10	1.90 ± 0.05	≤ 1.045	≥ 3.19	1.90 ± 0.05	≤ 1.035
JF2O-16-93165	1.04	1.895	1.042	3.195	1.894	1.030
JF2O-16-93168	1.05	1.899	1.041	3.194	1.901	1.030
JF2O-16-93169	1.00	1.898	1.039	3.196	1.900	1.028
JF2O-16-93170	1.03	1.897	1.042	3.194	1.895	1.032
JF2O-16-93172	1.02	1.900	1.040	3.190	1.888	1.030
JF2O-16-93173	1.04	1.896	---	3.190	1.893	---
J52R-16-98005	1.03	1.897	1.041	3.195	1.897	1.030

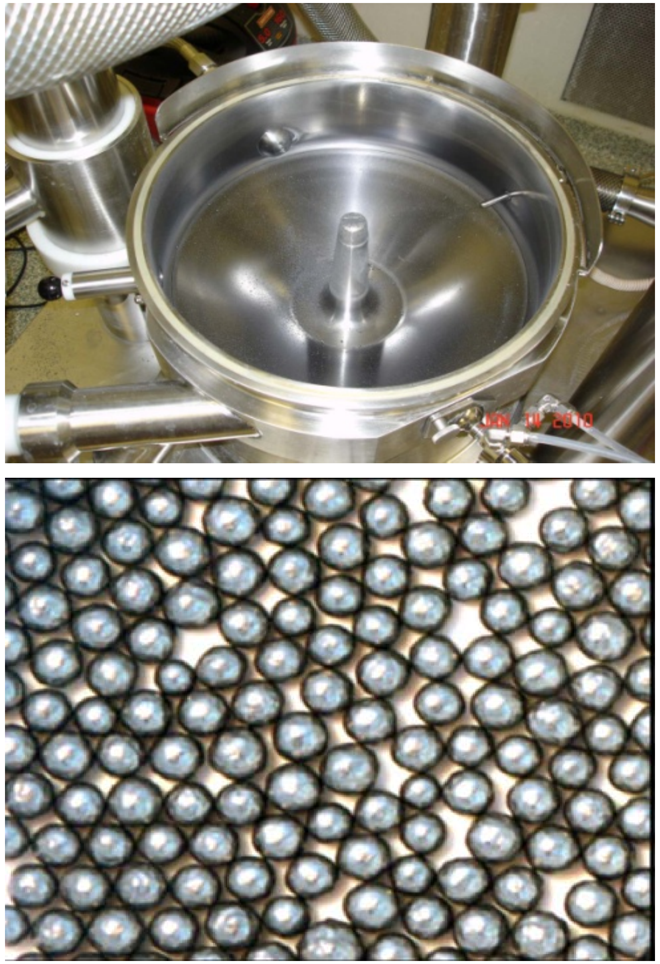
- SiC aspect ratio passes the fuel specification
- Missing OPyC defect passes
- 11.6 kg of TRISO particles in the lot

Material Flow Chart



AGR-5/6/7 Fuel Compacts

- Overcoat of resinated graphite applied in a mechanically fluidized bed
- Use of alcohol as a resin solvent eliminated
- Mass of resinated graphite overcoat calculated and applied
- Bulk density varies with packing fraction and from run-to-run
- Volumetric feeder insert chosen to give desired compact length
- BWXT delivered fuel compacts 3-weeks ahead of the milestone date



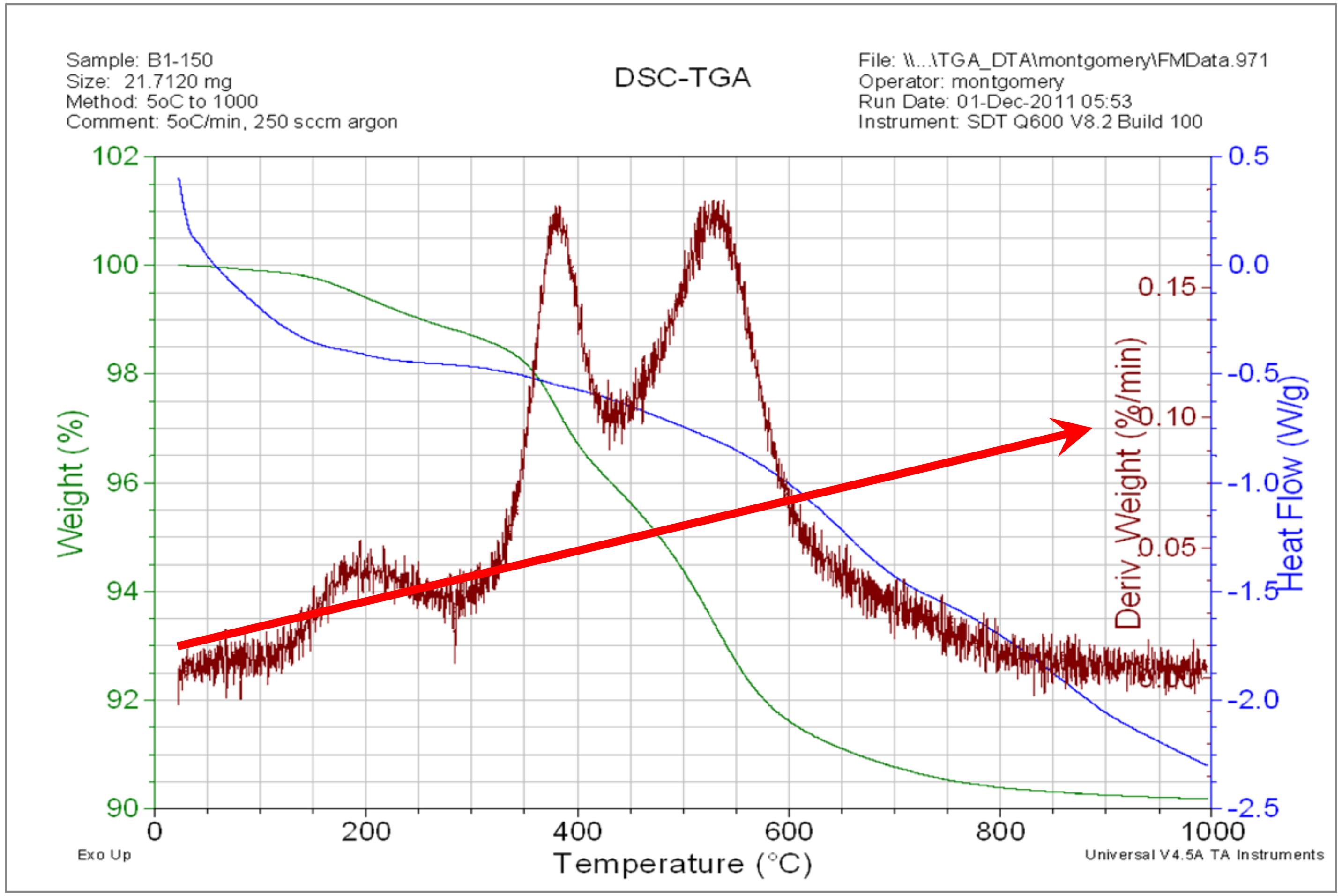
Overcoater and overcoated surrogate with non-uniform core diameters

AGR-5/6/7 Fuel Compacts (cont.)

- Warm pressing used to reduce stresses on TRISO particles
  - A3-27 based matrix (novolac resin with HMTA, no alcohol)
  - Die body temperature ~ 165ºC
  - Punch hold with partial compression for better heating to soften the resin
  - Hold at force; 4.5 kN (9.3 MPa) to 5.0 kN (10.4 MPa) for partial cure
- Thermal treatment (firing) of compacts
  - Cure, carbonization, and final heat soak without unloading the furnace
  - Cure and carbonization at ~ 680 torr in an argon atmosphere
  - Final heat treatment under sub-millitorr vacuum
  - Temperature ramp rate
    - Varied temperature ramp rates from resin cure through carbonization
    - DSC/TGA data used for setting temperature schedule
- Dimensional measurements on “green” and “fired” compacts to monitor changes

Resinated Graphite DSC-TGA Scan

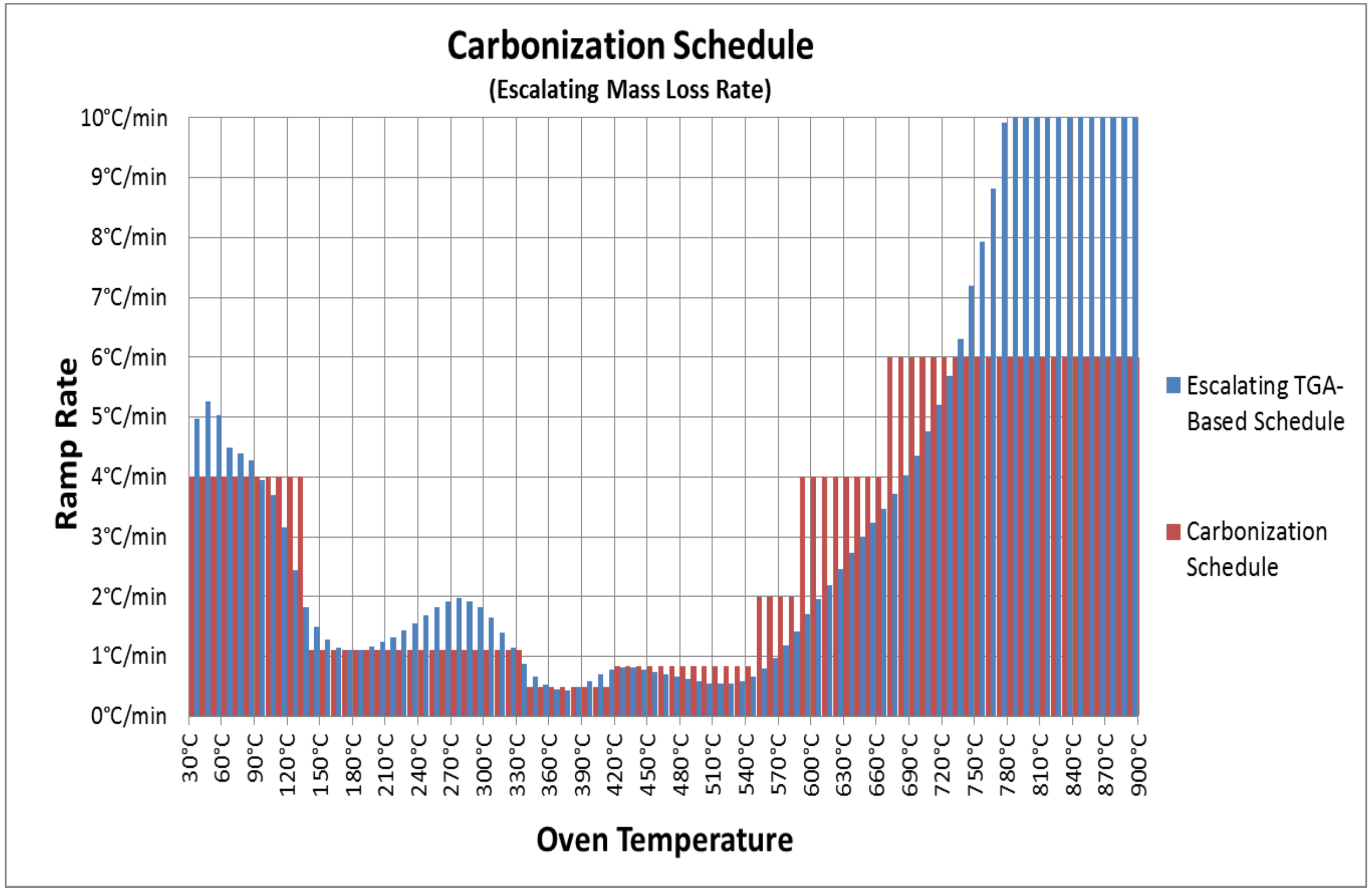
- At low temperatures:
  - lower MW gases/high specific volume
  - low matrix porosity
  - low matrix stiffness
  - highest susceptibility for deformation
- At high temperatures:
  - higher MW gases/low specific volume
  - high matrix porosity
  - rigid matrix
- A more linear mass loss rate thought preferable



Temperature Ramp Rates for Carbonization

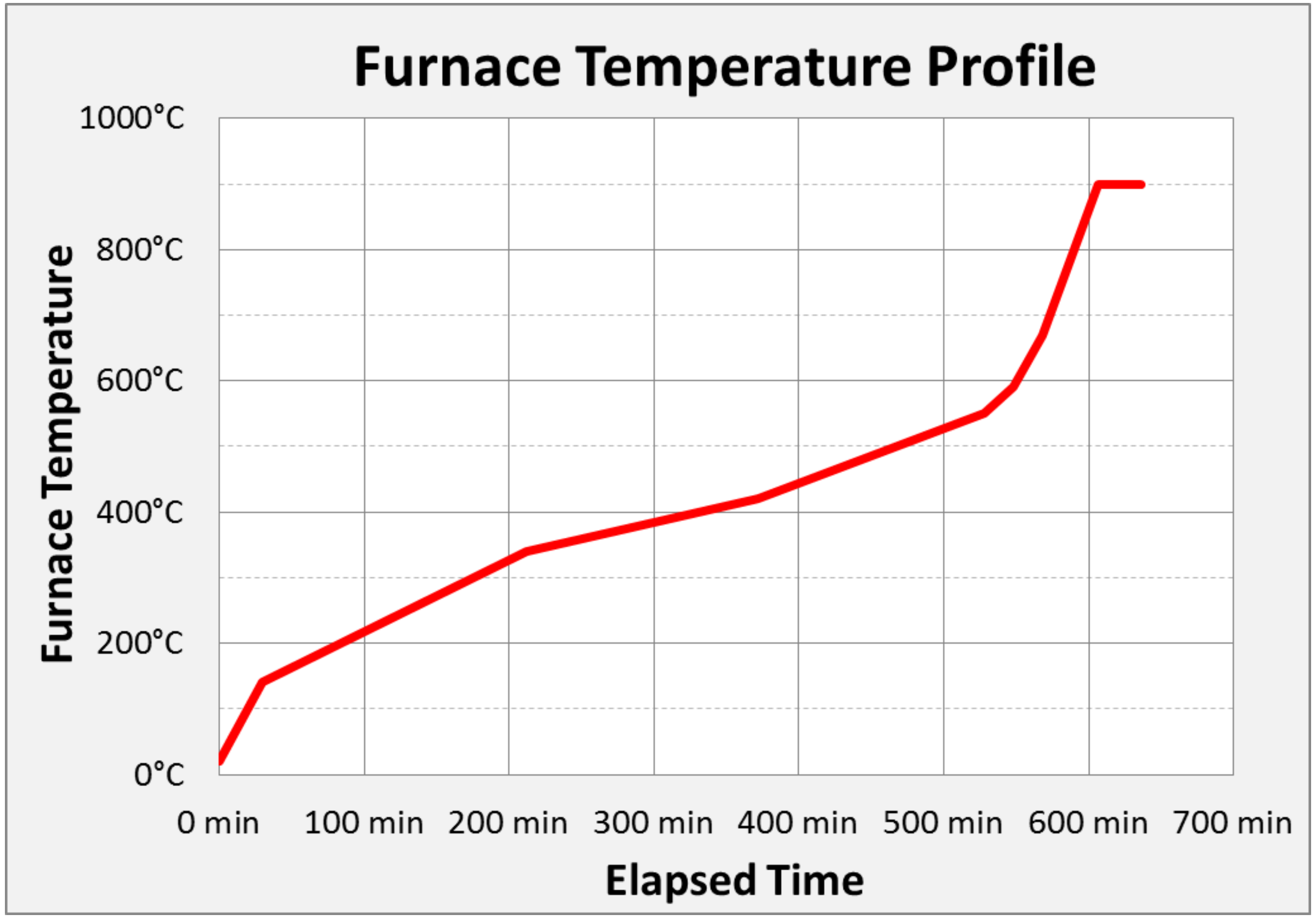
- Blue bars show temperature ramp rate for a linearly increasing mass loss rate

- Red bars show programmed temperature ramp rates



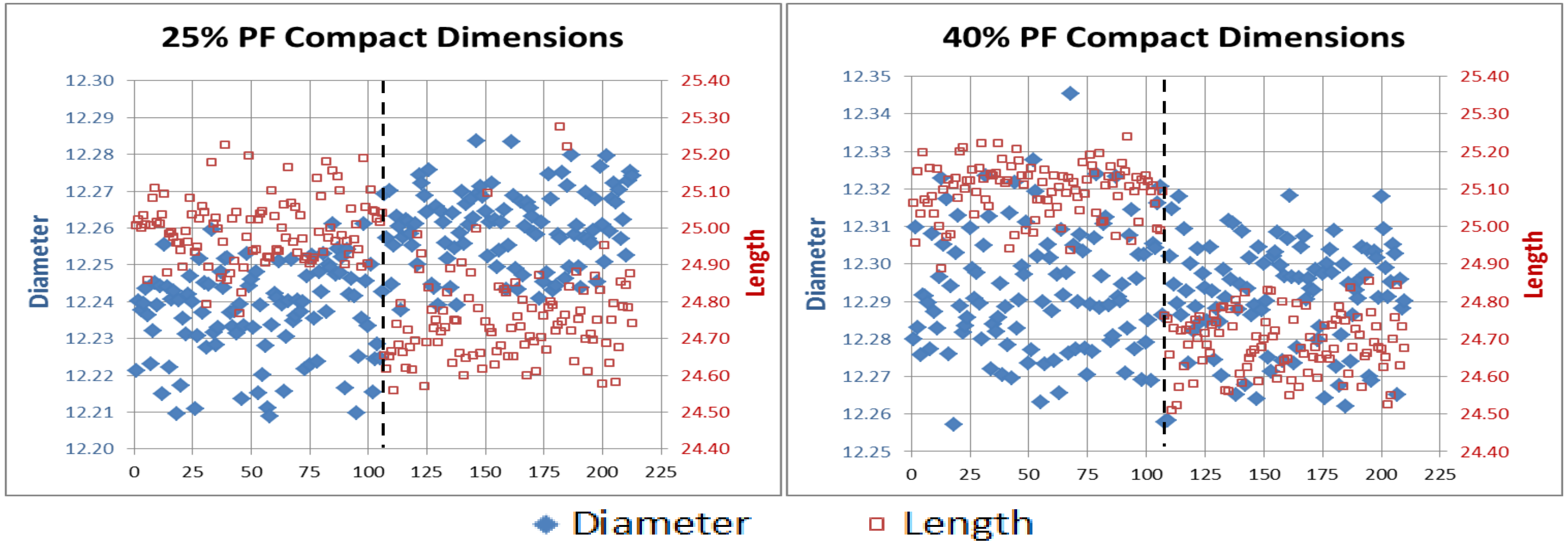
Furnace Temperature Profile

- Temperature soak holds were eliminated, except at the final carbonization temperature



AGR-5/6/7 Compact Characterization

Compact Batch	Diameter (mm)	Length (mm)	Mass (g)	ρ Matrix (g/cm³)	U loading (g)
J52R-16-14154A	12.293	25.094	6.729	1.74	1.428
J52R-16-14155A	12.291	24.692	6.607	1.73	1.388
J52R-16-14156A	12.237	24.996	6.182	1.76	0.923
J52R-16-14157A	12.260	24.752	6.093	1.74	0.914

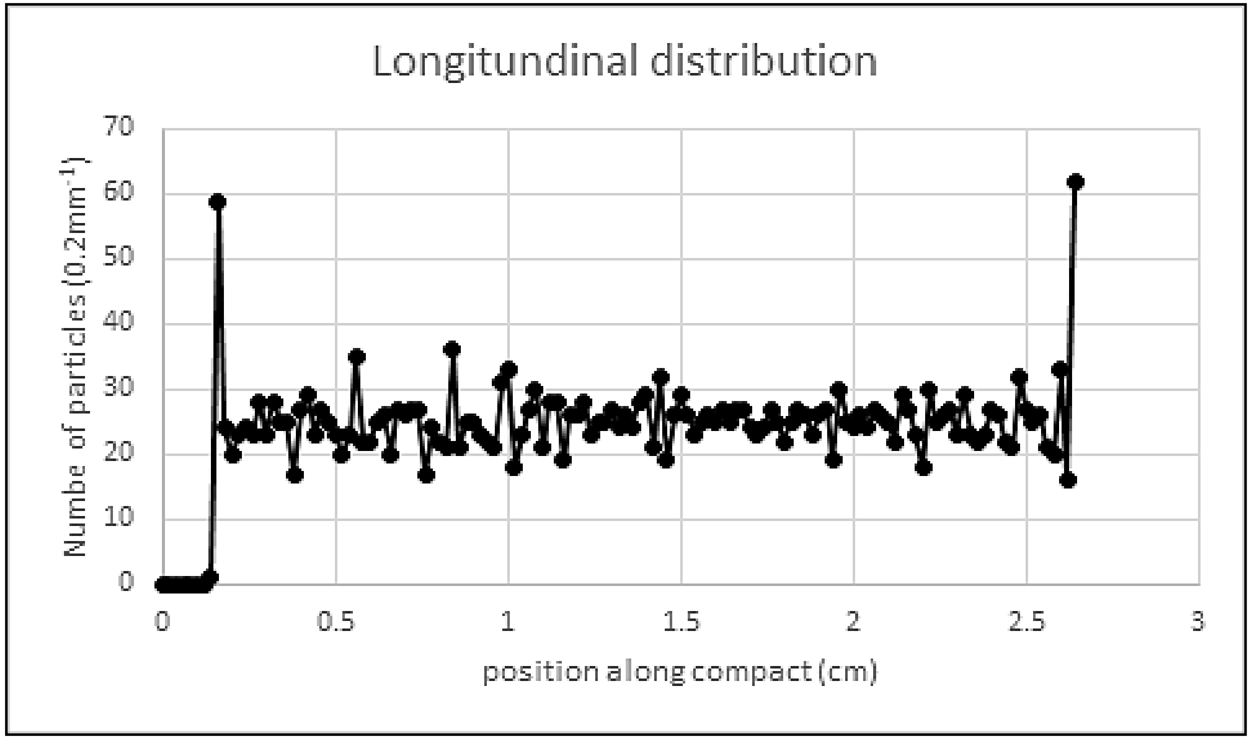


Compact Photos

25% PF Compacts

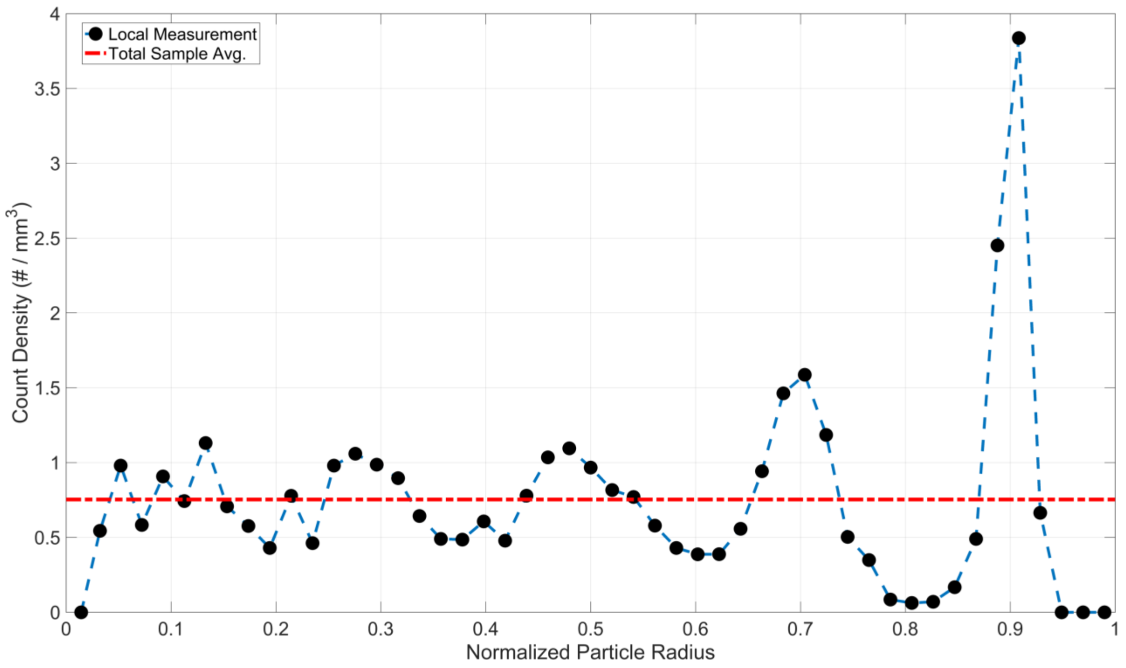
40% PF Compacts

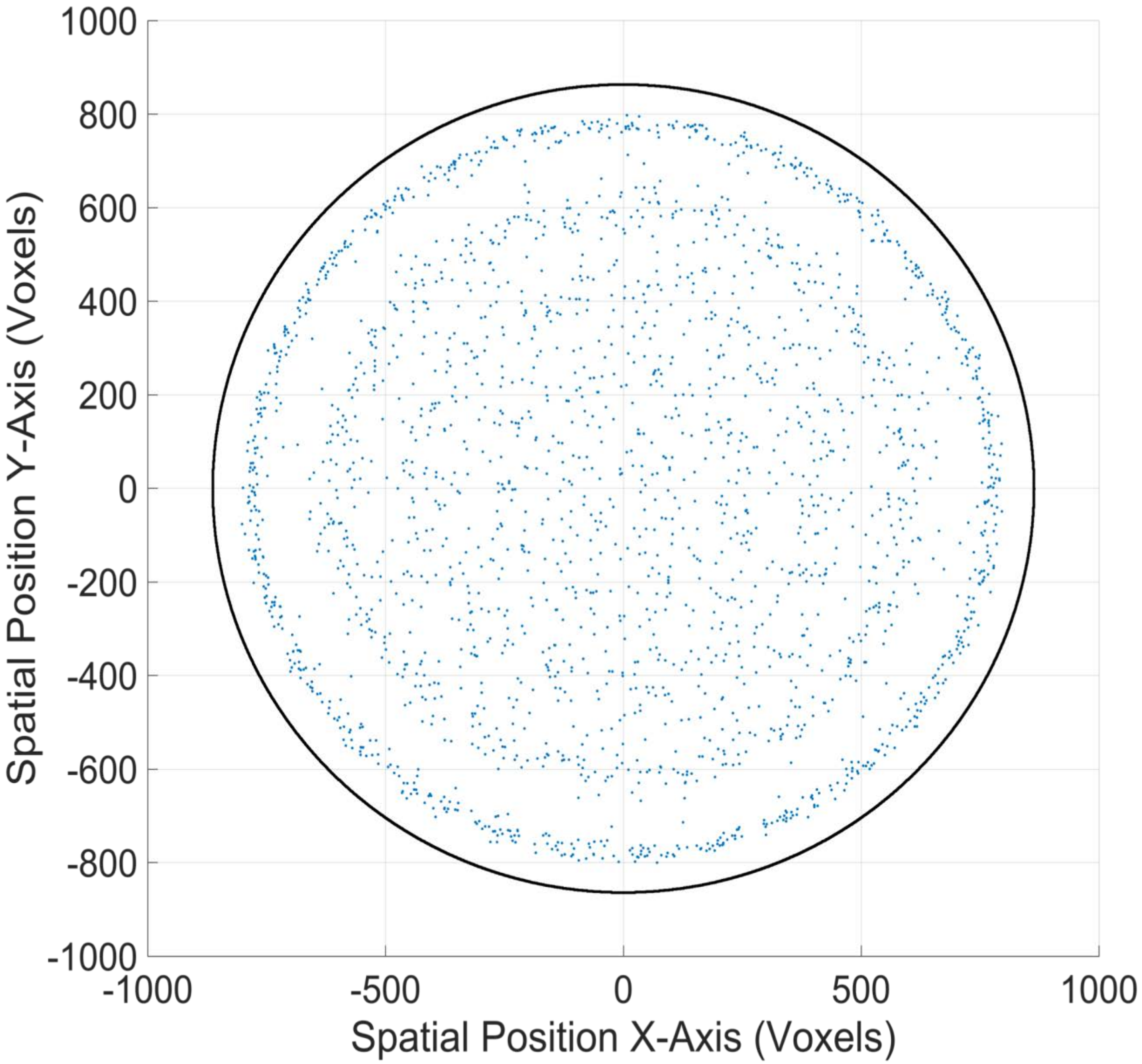
AGR-5/6/7 Compact Tomography



LANL Proton CT showing localized axial particle density, which is higher on the compact end faces of a development compact, but homogenous in the interior

AGR-5/6/7 Compact Tomography (cont.)

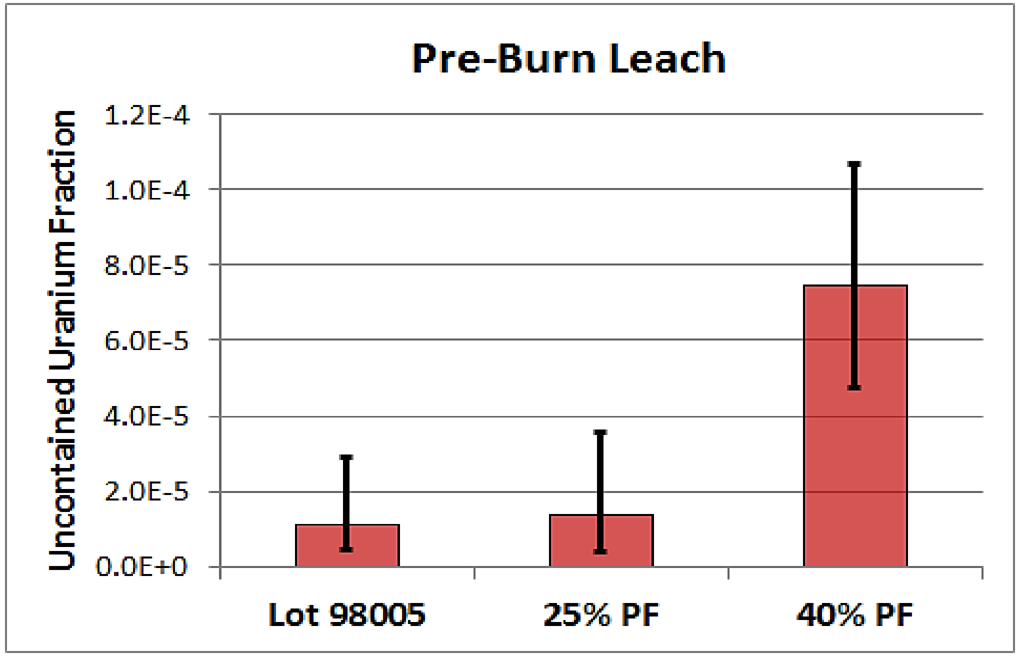




INL X-ray CT showing radial particle distribution in a 25% PF AGR-5/6 compact.

AGR-5/6/7 Fuel Compacts (cont.)

- Significant damage can be done to TRISO particles
  - 25% PF compacts show no net increase in U contamination
  - 40% PF compacts show high U contamination; failing the fuel specification
- Source of damage is being investigated



What We Have Learned

- TRISO Particle Coating
  - “Like kind” or “like-for-like” parts replacement
  - “Operational Rhythm” impacts quality and production schedule
- Overcoating
  - Highly uniform product – no upgrading is required
  - Alcohol as solvent and wetting agent is not necessary
  - Batch-to-batch overcoat density variability (product bulk density) was noted
- Compacting and Firing
  - Mold release lubricant – flush capability needed
  - Holding at partial compression to warm the particles is beneficial
  - Firing schedule based on DSC/TGA data is beneficial
  - TRISO particles are concentrated near the compact surfaces
- Yet to be learned
  - Source of damage to TRISO particles during overcoating and/or compacting

INL

Idaho National Laboratory