Advanced Gas Reactor Fuels Program Review

AGR-1 PIE Summary

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July 15-16, 2015

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AGR-1 Compact PIE Synopsis by Capsule

Capsule	Stack 1	Stack 2	Stack 3
6	4	4	4
	3	3	3
	2	2	2
	1	1	1
5	4	4	4
	3	3	3
	2	2	2
	1	1	1
4	4	4[a]	4
	3	3	3
	2	2[b]	2
	1	1	1

Capsule	Stack 1	Stack 2	Stack 3
3	4	4	4
	3	3	3
	2	2	2
	1	1	1
2	4	4	4
	3	3	3
	2	2	2
	1	1	1
1	4	4[c]	4
	3	3	3
	2	2	2
	1[c]	1	1[c]

Ceramography

- Completed
- Planned or in progress

DLBL, IMGA, microscopy

- Completed
- Planned or in progress

Safety testing

- Completed
- Planned or in progress

[a]Loose particles heated at 1800C

[b]Multiple ramp and hold steps to explore temperature dependence of Ag release

[c]Three compacts to be tested together in a transient temperature test

AGR-1 Compact PIE Progress

	6-1-1 ORNL	6-3-2 INL	6-3-3 INL	6-4-2 ORNL	5-1-2 INL	5-2-1 ORNL	5-2-3 ORNL	5-3-1 INL	4-1-1 INL	4-1-3 INL	4-4-2 ORNL	3-2-1 INL	3-3-3 INL	2-1-3 INL	1-3-1 INL
Compact microscopy			Completed	Completed	Completed					Completed			Completed	Completed	
Deconsolidation/LBL	Completed	Completed				Completed	Completed	Completed	Completed		Completed	Completed			Completed
IMGA	Completed	Completed				Completed	Completed	Completed	Completed		Completed	Completed			Completed
Basic microanalysis[a]	Completed	Completed				Completed	Completed	Completed	Completed		Completed	Completed			Completed
Advanced microanalysis[b]		In progress				In progress	In progress	In progress	In progress						
Burnup analysis		Completed						Completed				Completed			Completed

Destructive PIE completed or in progress on 15 compacts

Completed

In progress

Planned

[a] Optical microscopy and/or SEM/EDS analysis
[b] Advanced techniques, including TEM, STEM, HRTEM, EELS, APT

AGR-1 Safety Testing Progress

Compact	6-2-1	6-4-3	6-4-1	5-1-3	5-1-1	5-3-3	4-1-2	4-2-2	4-3-2	4-3-3	4-4-1	4-4-2[c]	4-4-3	3-2-2	3-3-1	3-3-2	3-2-3	1-1-1	1-1-3	1-4-2
Temperature	1600°C	1600°C	1600°C	1800°C	1700°C	1600°C	1600°C	*Various*	1600°C	1600°C	1800°C	1800°C	1700°C	1600°C	1700°C	1600°C	1800°C	Transient	Transient	Transient
Lab	ORNL	ORNL	INL	ORNL	ORNL	ORNL	ORNL	ORNL	INL	INL	ORNL	ORNL	ORNL	ORNL	ORNL	ORNL	ORNL	INL	INL	INL
Safety testing	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	▒	▒	▒
Deconsolidation/LBL	■	■		■	■	■	■	■		■	■	■	■	■	■	■	■			
IMGA	■	■		■	■	■	■	■		■	■	■	■	■	■	■	■			
Basic microanalysis[a]	■	■		■	▨	■	■	■		■	■	■	■	■	■	■	■			
Advanced microanalysis[b]				▨						▨										

Safety testing and destructive PIE completed or in progress on 17 compacts

■ Completed

▨ In progress

▒ Planned

[a] Optical microscopy, x-ray analysis, and SEM/EDS analysis

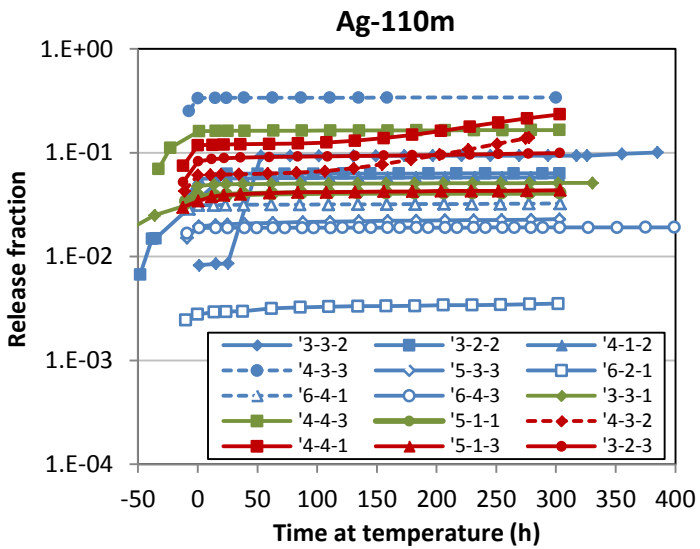
[b] Advanced techniques, including TEM, STEM, HRTEM, EELS, APT

[c] Additional safety test performed on loose particles from Compact 4-4-2

AGR-1 PIE Highlights: Fission Product Behavior

Silver

- Ag release in-pile can be high and is roughly correlated with temperature
  - Capsule-average compact release: 1 to 38%
  - Individual compact release: ~0 to 92%
  - Individual particle release: ~0 to ~100%
- Ag release from compacts at 1600 and 1700°C appears to be dominated by inventory in the matrix at end of irradiation (higher retention in matrix than models indicate)



- Have not yet identified differences in SiC microstructure that affect in-pile Ag release; however, have found different Ag release behavior at 1800°C between Baseline (larger-grain SiC) and Variant 3 (smaller-grain SiC)

AGR-1 PIE Highlights: Fission Product Behavior

Silver (cont'd)

- A single experiment indicated higher Ag release from a compact at intermediate temperatures (centered on 1150°C) than at 1600°C. (Eu behavior appeared more conventional, i.e., higher release at higher temperatures)
- Ag is found in various locations in the SiC microstructure

Cesium

- Cs release from intact particles is very low even up to 1800°C, but is quite high from failed particles (although usually <100% even at high temperatures, indicating higher retention in particles than models suggest)
- Cs release is therefore a strong function of the number of SiC failures
- Capsule-average release from compacts in-pile was $<3\times10^{-6}$

AGR-1 PIE Highlights: Fission Product Behavior

Krypton

- Kr release is low ($<5\times10^{-6}$) at 1600°C, increasing at 1800°C due to failed SiC (max release ~6×10^{-5} after 300 h) or failed TRISO (max 5×10^{-4} for 2 failed TRISO after 277 h).

Palladium

- Pd release has been observed in-pile (6×10^{-3} to 3×10^{-2} in compact matrix or OPyC) and during safety tests
- No extensive, widespread Pd corrosion of SiC in particles with intact IPyC layers
- Pd found in the SiC microstructure (sometimes with other fission products and uranium)

AGR-1 PIE Highlights: Fission Product Behavior

Strontium, europium

- Sr and Eu are released at low levels through intact SiC in-pile. In-pile capsule-average fractional release from compacts was 8×10^{-7} to 3×10^{-5} (Sr-90) and 1×10^{-4} to 5×10^{-4} (Eu-154).
- Release from compacts at 1600°C was 10^{-5} to 2×10^{-3} (Sr-90) and 3×10^{-4} to 2×10^{-3} (Eu-154). About a factor of 10 higher at 1800°C.
- Majority of Sr and Eu release during safety tests appears to be from inventory in the matrix at end of irradiation; however, some evidence of release from intact SiC at 1800°C (especially Eu)

General fission product behavior observations

- Retention of fission products in compact matrix and/or OPyC is generally higher than predicted by models

AGR-1 PIE Highlights: Particle Microstructure

- Buffer fractures are fairly common. These do not cause problems with PyC or SiC layers when buffer detaches from IPyC. IPyC fractures are usually associated with buffer adhesion. **Buffer-IPyC detachment is desirable.**
- UCO fuel is effective at controlling P_{O2} and limiting kernel migration
- Kernel and coating morphology appears to have little dependence on burnup over the range ~11-19% FIMA. Other factors besides local irradiation conditions appear to dominate the behavior.
- Our understanding of the dominant SiC failure mechanism has greatly increased: appears to be a two-part mechanism involving (1) fracture of the IPyC layer due to densification of adherent buffer layer and (2) localized Pd accumulation at the IPyC-SiC interface and subsequent corrosion of the SiC layer; corrosion is accelerated at elevated temperatures. This is somewhat different from current fuel performance models.

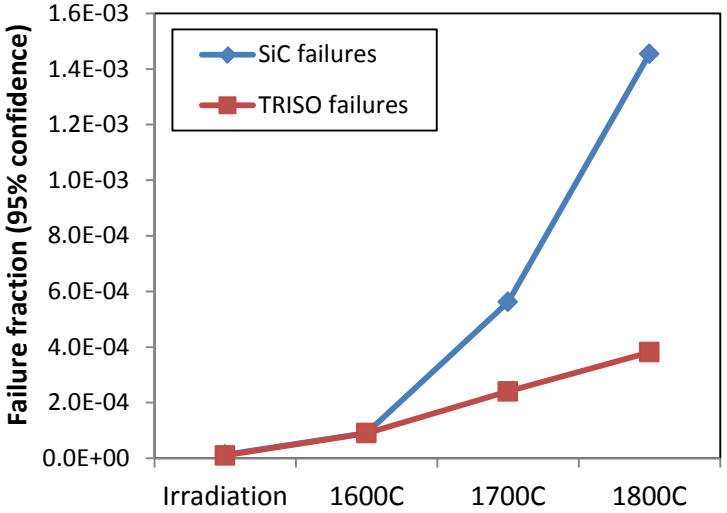
AGR-1 PIE Highlights: Particle failure statistics

- Particle failure statistics based on PIE and safety testing:

Test conditions	# particles	SiC failures			TRISO failures		
		# failures	Failure fraction	Failure fraction (95% Conf)	# failures	Failure fraction	Failure fraction (95% Conf)
Irradiation	298000	4	1.3E-05	3.1E-05	0	0	1.0E-05
1600°C	33100	3	9.1E-05	2.3E-04	0	0	9.0E-05
1700°C	12450	7[a]	5.6E-04	1.1E-03	0	0	2.4E-04
1800°C	16500	24	1.5E-03	2.0E-03	2	1.2E-04	3.8E-04

[a] Includes data from Compact 5-1-1 not included in HTR2014 proceedings

- These fractions are better than existing reactor design specifications, often under more severe accident conditions (temperatures, durations)



AGR-1 PIE Highlights: General Observations

- Burnup measurements match physics calculations well
- Many of the new PIE methods developed have been very effective
  - **Gamma-scanning capsule components** (*locating compacts containing SiC failure*)
  - **Advanced-IMGA** (*finding particles with SiC failure*)
  - **Nondestructive x-ray analysis of particles** (*imaging interior particle morphology, locating point of SiC failure*)
  - **Focused ion beam sample preparation and advanced microscopy methods such as STEM** (*advancing our understanding of fission product transport behavior*)

Progress Over the Past year

- Completed 5-1-1 safety test at 1700°C and post-test analysis
- 5-3-1 particle cracking and kernel/coating analysis
- Advanced microscopy on selected particles

<u>Upcoming work</u>

- Non-isothermal accident simulation test (three Capsule 1 compacts)
- Loose kernel heating tests
- Completion of advanced microscopy work (including safety-tested particles)
- AGR-1 Final PIE Report (August 2015)

Selected AGR-1 PIE References (1)

Topical area	Publication ID	Additional description
Test train inspection, disassembly, and metrology	INL/EXT-10-20722	
Flux and melt wire analysis	Greenwood 2012 (PNNL report)	
Capsule component analysis	INL/EXT-13-28483	AGR-1 Capsule FP Analysis
	Harp et al., HTR2012-3-006 (2012)	
	ECAR-1709	AGR-1 graphite holder gamma spectrometry
Compact non-destructive analysis	ECAR-1682 Rev 3	AGR-1 fuel compact gamma spectrometry
Compact cross-section analysis	INL/EXT-12-25301 Rev 1	AGR-1 compact ceramography
	Ploger et al., Nuc. Eng. Des. (2014)	
	Ploger et al., HTR2012-3-020 (2012)	
Compact deconsolidation-leach-burn-leach, particle gamma counting, and microanalysis	INL/EXT-12-27123	Compact 6-3-2 report
	ORNL/TM-2012/233	Compact 6-1-1 report
	ORNL/TM-2012/236	Compact 4-4-2 report
	ORNL/TM-2014/171	Compact 5-2-1 and 5-2-3 report
	INL/EXT-15-DRAFT	Compact 4-1-1 report
	INL/EXT-15-DRAFT	Compact 3-2-1 report
	INL/EXT-15-DRAFT	Compact 5-3-1 report
	INL/EXT-15-DRAFT	Compact 1-3-1 report
Burnup analysis	Harp et al., Nuc. Eng. Des. (2014)	
	Sterbentz et al., ICAPP 2015 (2015)	
Advanced microscopy on particles	Van Rooyen et al., Nuc. Eng. Des. (2014)	
	Van Rooyen et al., J. Nuc. Mat. (2014)	
	Lillo et al. JNM (2015)	
	Wen et al. M&M2015 (2015)	
	Wen et al. ASME P&E (2015)	
	Lillo et al., ANS (2015)	
	Van Rooyen et al. HTR2014-31255 (2014)	

Selected AGR-1 PIE References (2)

Topical area	Publication ID	Additional description
High temperature safety testing	ORNL/LTR-2012/396	Compact 3-3-2, 3-2-2, and 6-2-1 safety test report
	ORNL/LTR-2012/00926	Compact 3-3-1 safety test report
	ORNL/LTR-2013/290	Compact 4-4-1, 4-1-2, and 4-4-3 safety test report
	ORNL/LTR-2013/603	Compact 5-5-3 and 5-1-3 safety test report
	ORNL/LTR-2014/486	Compact 4-4-2 loose particle safety test report
	ORNL/LTR-2014/485	Compact 4-2-2 safety test report
	Morris et al., Nuc. Eng. Des. (2015)	AGR-1 safety test summary
	Morris et al., HTR2014-31135 (2014)	AGR-1 safety test summary
	Demkowicz et al., J. Nuc. Mat. (2015)	Compact 4-3-2, 4-3-3, 6-4-1 safety test paper
	Baldwin et al., HTR2012-3-027 (2012)	Compact 6-2-1 safety test and post-test analysis paper
	Baldwin et al., Nuc. Eng. Des. (2014)	Compact 6-2-1 safety test and post-test analysis paper
Post-safety-test destructive compact analysis	ORNL/LTR-2012/397	Compact 6-4-3 and 3-3-2 PIE report
	ORNL/LTR-2012/00928	Compact 3-2-2 PIE report
	ORNL/LTR-2013/291	Compact 6-2-1, 3-3-1, 4-4-1 PIE report
	ORNL/LTR-2014/101	Compact 4-1-2, 4-4-3 PIE report
	ORNL/LTR-2014/484	Compact 5-3-3, 5-1-3, and 3-2-3 PIE report
	ORNL/TM-2015/161	Compact 4-4-2 loose particle safety test PIE report
	ORNL/TM-2015/033	Compact 4-2-2 PIE report
	INL/EXT-15-DRAFT	Compact 4-3-3 report
Causes of SiC failure	Hunn et al., Nuc. Eng. Des. (2015)	
	Hunn et al., HTR2012-31254 (2012)	

Questions?

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