Approach for Responding to Draft Requests for Additional Information Related to NRC Review of Topical Report EPRI-AR-1(NP)

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Draft RAI #1: Additional Important Irradiation Condition Parameters

- Conclusion 1 of the TR states that “testing of UCO TRISO-coated fuel particles in AGR-1 and AGR-2 constitutes a performance demonstration of these particle designs over a range of normal operating and off-normal accident conditions.” Discussions under the conclusion reference a compact-averaged burnup of 7.3-19.6% fissions per initial metal atom (FIMA) and time averaged maximum temperatures of 1069-1360 C. Are there other relevant performance parameters that bound the data set, such as those referenced in Figure 4-6 (packing fraction, fluence, power density)? Based on the discussion in the report, it appears some of these parameters could influence particle performance, but these values are not provided as bounds for the “range of normal operating and off-normal accident conditions”. Provide context for what constitutes a “range of normal operating and off-normal accident conditions” (e.g. reference a table), or provide a justification for why burnup and time averaged temperature are sufficient.

Range of Normal and Off-Normal Accident Conditions

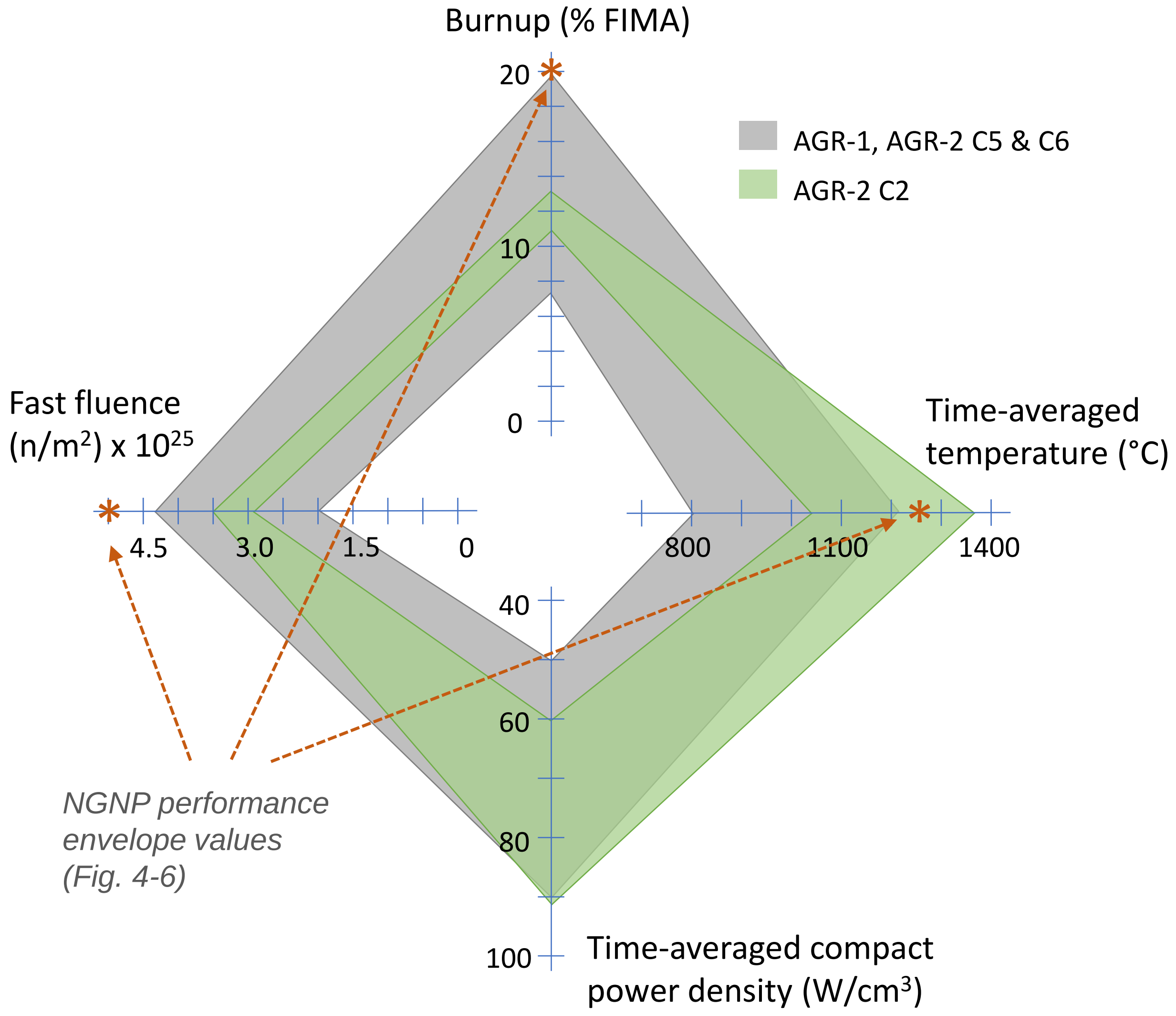
- Yes, there are other irradiation conditions that are important for fuel performance in addition to burnup and temperature
- Key irradiation condition parameters will be summarized and presented in tabular and graphical form:
  - Temperature (time-averaged)
  - Power density (time- and volume-averaged)
  - Burnup
  - Fast neutron fluence
- Time-average values used where appropriate
- Detailed irradiation conditions are included in various tables and graphs in Section 6
- Accident conditions tested in the report are elevated temperatures (1600 – 1800°C) in dry helium for times as long as 400 hours
  - Not intended to bound or imply acceptable reactor accident conditions
  - Provide sufficient data for vendors to apply to their specific accident scenarios

AGR-1 and AGR-2 Irradiation Conditions

- Data combined into two sets
  - AGR-1 and AGR-2 Capsules 5 and 6
  - AGR-2 Capsule 2 (higher temperature)

Property	AGR-1 + AGR2 C5&6		AGR-2 C2	
	Max	Min	Max	Min
Burnup (%FIMA)	19.7	7.3	13.2	10.8
Fast fluence ($n/m^2 \times 10^{25}$)	4.30	1.94	3.47	2.88
Time-average temperature (°C)	1210	800	1360	1034
Time-avg compact power density (W/cm^3)	90.2	50.2	92.1	59.9
Time-avg compact power density (mW/particle)	66[a]/86[b]	37[a]/48[b]	88	71

a. AGR-1 values
b. AGR-2 C5 and C6 values



Draft RAI #2: Appropriate Ranges for Additional Fuel Parameters

- Conclusion 2 of the TR states "UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by these measured particle layer properties in Table 5-5 can be relied on to provide satisfactory performance." While Table 5-5 provides a list of physical parameters for fuel specifications, it does not appear to directly cover all of the parameters that govern the specifications that constitute the parameter envelope applicable to the tested AGR fuel. Some elements in particular that the report highlights as important but that are not directly referred to in Table 5-5 include kernel-to-buffer ratio for the fuel particle (and potentially its associated size), columnar grain structure of the SiC, and carbon content of the UCO. It is not clear to the staff how these limits are applicable to the conclusions in the report. Provide a justification for how these parameters are implicitly captured in Table 5-5, supplement the report to include these parameters as limits for TR applicability, or provide justification for why these elements are not important.
- Further, the report references the importance of an uninterrupted coating process in the manufacture of the fuel. Do the parameters in Table 5-5 adequately restrict fuel particle specifications such that this process does not need to be explicitly required? If not, provide a justification, consider restricting the applicability of the TR to fuel manufactured using a similar process, or add a proxy measurable parameter to Table 5-5 that does provide assurance that an uninterrupted coating process has been followed.

Draft RAI #2: Response Summary

- **Kernel-to-buffer ratio**: ranges of actual values of the important parameter (dimensionless SiC stress proportionality) will be provided for AGR-1 and AGR-2 fuel
- **SiC microstructure**: reference to the SiC visual standard used for AGR-1 and AGR-2 fuel fabrication will be discussed
- **UCO kernel stoichiometry**: Nature of AGR-1 and AGR-2 kernel chemistry analysis will be discussed in light of published studies; supplementary data on AGR-1 kernel-to-kernel chemistry variability will be discussed
- **Uninterrupted coating**: This is considered a process requirement when evaluating the conclusions of this report

Draft RAI #2: Relationship Between Kernel and Buffer Volumes

- Relationship is actually more complex than just kernel and buffer volumes, and involves several other terms, including ***peak burnup***
- SiC stress proportionality given in Eq. 4-1:

$$\sigma \propto \frac{B \cdot V_k}{V_b} \cdot \frac{r_{SiC}}{t_{SiC}} \qquad \text{Eq. 4-1}$$

B = Peak burnup (% FIMA)

V_k = Kernel volume (mm^3)

V_b = Buffer volume (mm^3)

r_{SiC} = SiC radius (mm)

t_{SiC} = SiC thickness (mm)

- Calculate range of values for σ for AGR-1 and AGR-2 particle geometries and burnup targets
- Use published data on particle dimension means and standard deviations (1 SD)
- Ignore interdependence of some particle geometry parameters
- More rigorous statistical analysis to define the range of possible values can be performed

$$\sigma_{max} \propto \frac{B \cdot V_{k(max)}}{V_{b(min)}} \cdot \frac{r_{SiC(max)}}{t_{SiC(min)}}$$

$$\sigma_{min} \propto \frac{B \cdot V_{k(min)}}{V_{b(max)}} \cdot \frac{r_{SiC(min)}}{t_{SiC(max)}}$$

Draft RAI #2: Relationship Between Kernel and Buffer Volumes (cont'd)

Estimated range of AGR-1 and AGR-2 SiC tensile stress metric (preliminary)

	AGR-1[a]	AGR-2
σ_{min}	0.409	0.441
σ_{avg}	0.584	0.617
σ_{max}	0.857	0.889

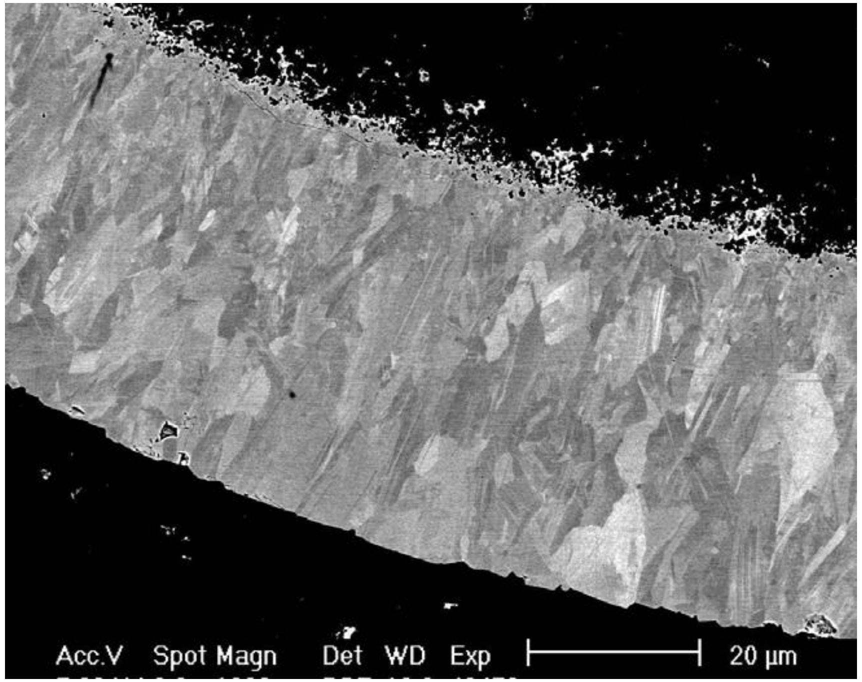
a. Example is for AGR-1 Baseline fuel

Table 4-2. Particle design attributes contributing to tensile stress in SiC

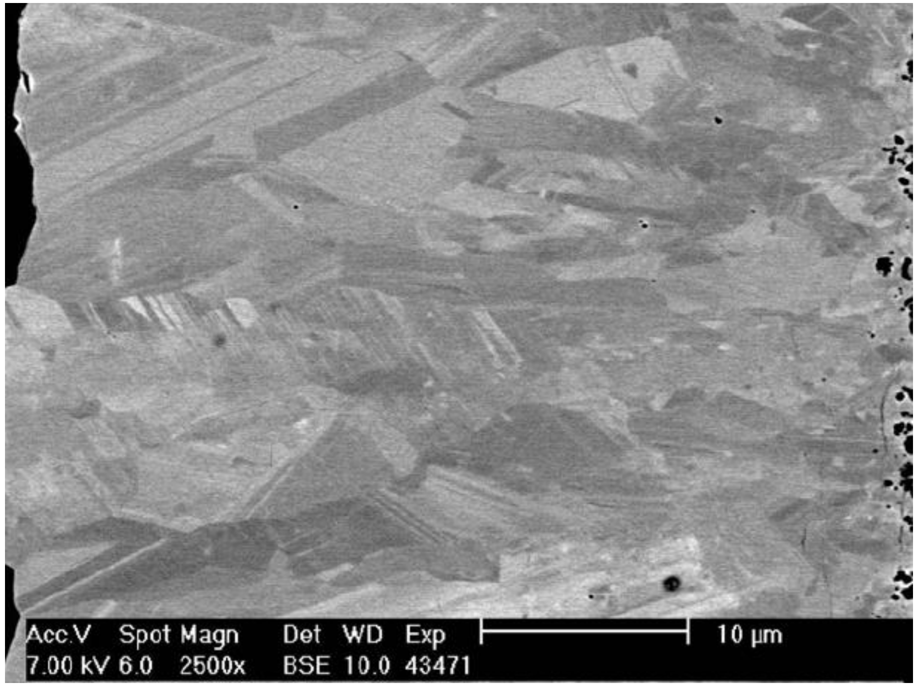
Parameter	German	JAERI HTTR	JAERI Advanced	U.S. LEU Fissile	U.S. Fertile	U.S. NPR	AGR
	Particle Design Parameters						
Kernel Composition	UO_2	UO_2	UO_2	UCO	UCO	UCO	UCO
Kernel Diameter (µm)	500	600	550	350	500	200	425
Buffer Thickness (µm)	95	60	100	100	65	100	100
IPyC Thickness (µm)	40	30	35	35	40	50	40
SiC Thickness (µm)	35	30	35	35	35	35	35
OPyC Thickness (µm)	40	45	40	40	40	40	40
Enrichment (%)	10.6	6	10	19.9	0.7	93	14.0
Burnup (% FIMA)	10	3.6	10	26	6	80	17
	Calculated Values						
Particle Diameter (µm)	920	930	970	770	860	650	855
Kernel volume (mm^3)	0.065	0.113	0.087	0.022	0.065	0.004	0.040
Buffer volume (mm^3)	0.107	0.082	0.134	0.065	0.065	0.029	0.088
Simple tensile stress metric	0.676	0.643	0.763	0.799	0.608	0.816	0.785
Normalized to German value	1.00	0.95	1.13	1.18	0.90	1.21	1.16

Draft RAI #2: SiC Microstructure

- AGR Program did not have a quantitative specification for SiC microstructure (e.g., grain size, grain orientation, etc.)
- Used a “visual standard” to avoid excessively large grain sizes and unfavorable orientations (e.g., columnar grains)
- Visual standard will be referenced in RAI response

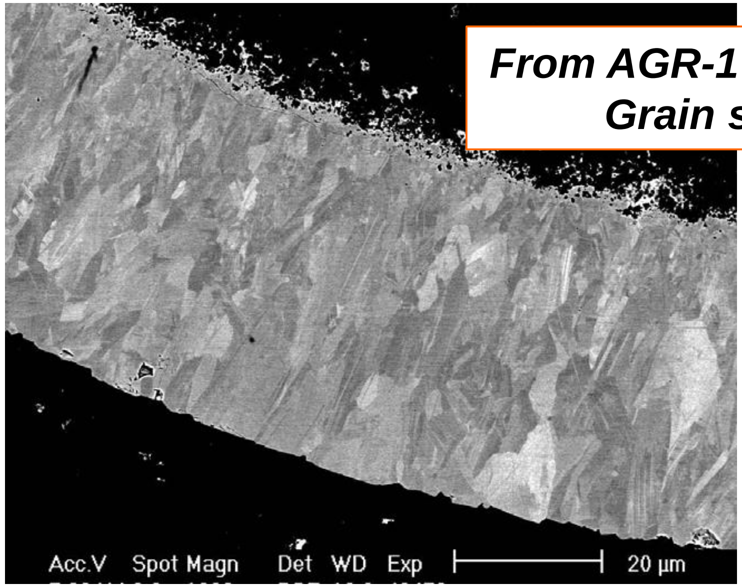


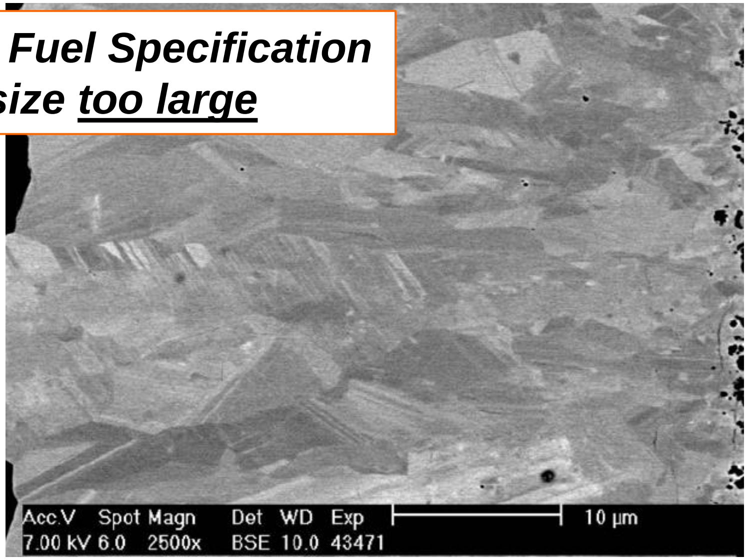
Reference micrographs of SiC with grains too large *(AGR-1 Fuel Product Specification, EDF-4380 Rev. 8, 2006)*

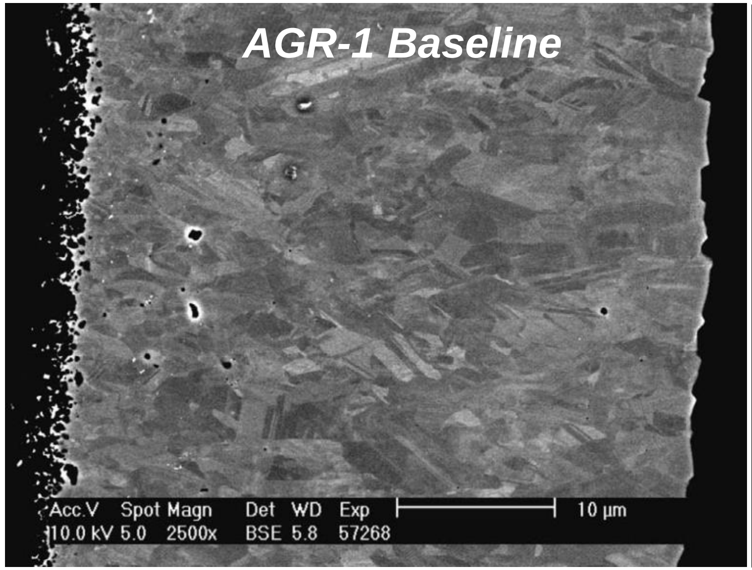


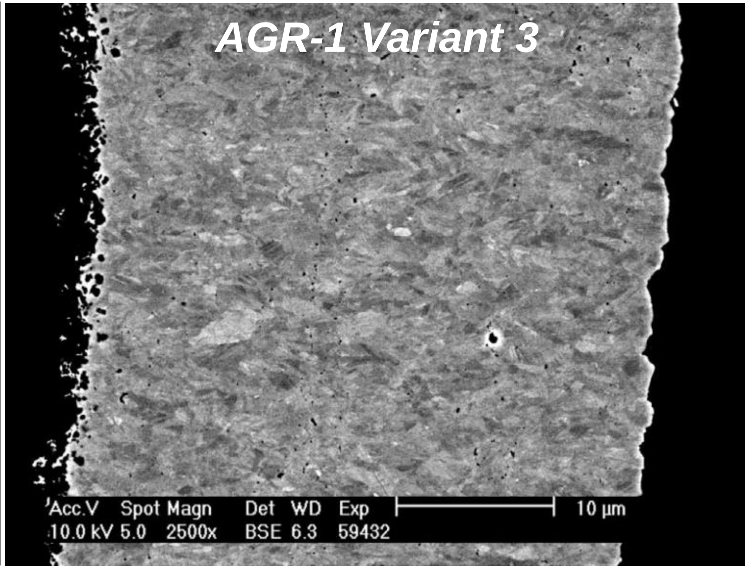
SiC Microstructure Comparison

From AGR-1 Fuel Specification
Grain size <u>too large</u>









SiC grain size of AGR-1 and AGR-2 fuel particles
(Data presented in Table 5-3)

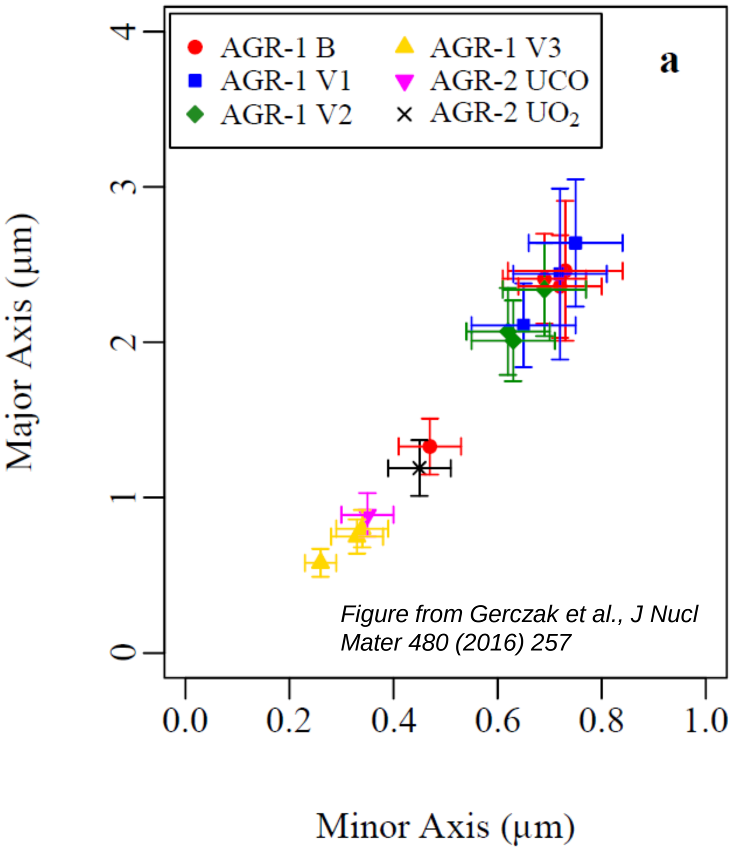
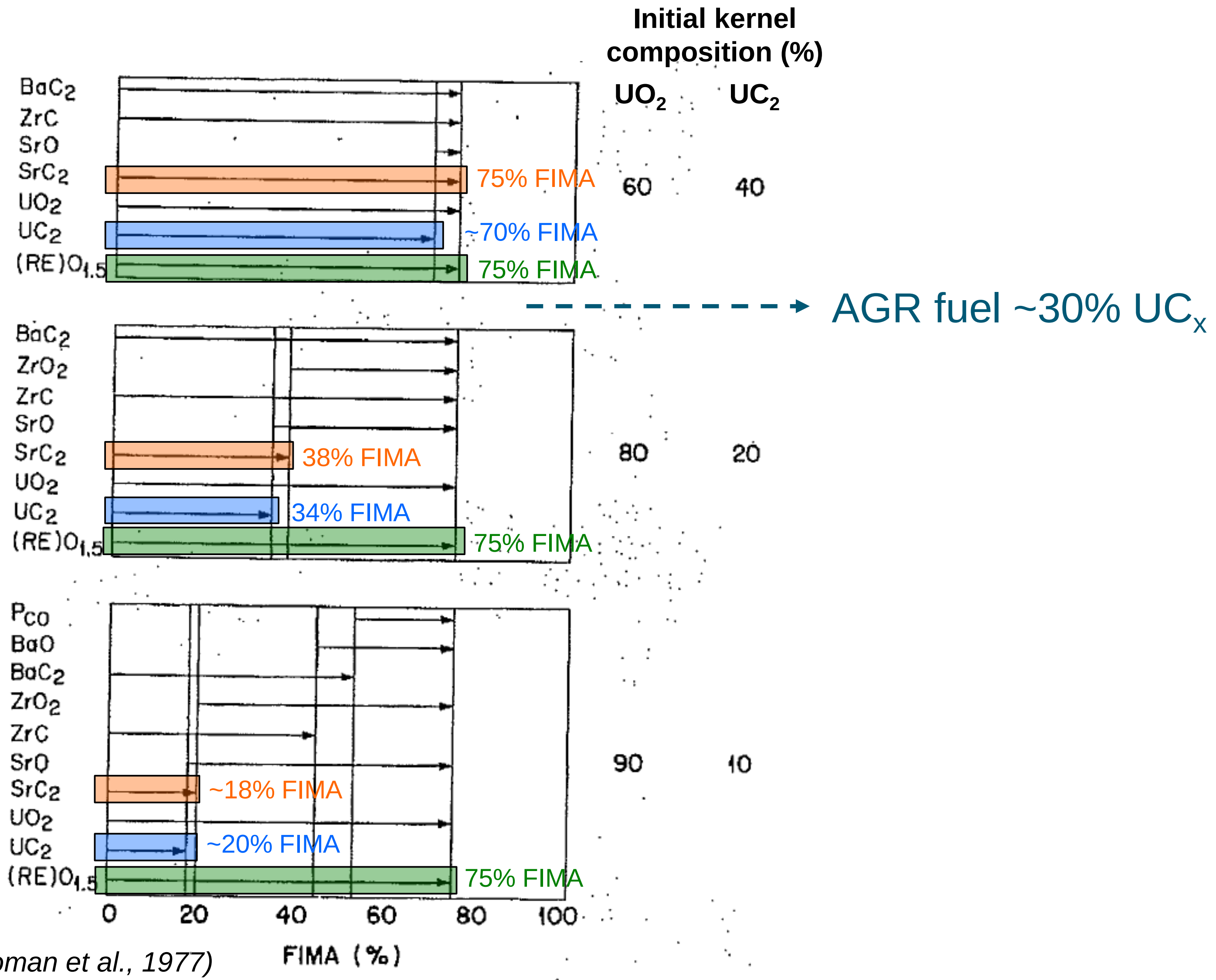


Figure from Gerczak et al., J Nucl Mater 480 (2016) 257

Draft RAI #2: UCO Kernel Stoichiometry



(Homan et al., 1977)

- Thermochemical calculations indicate oxide/carbide stability in UCO kernels as a function of starting UO_2/UC_2 content and burnup
- Calculations indicate that UC_x content as low as 10% is sufficient to maintain UC_x present in the kernel up to ~20% FIMA
- AGR-1 and AGR-2 fuel have ~30% UC_x content, indicating large margin of excess carbide for burnup ≤ 20% FIMA
- Recent thermochemical calculations suggest that as low as 5.5% UC_x is sufficient for acceptable performance of LEU TRISO up to ~16% FIMA (McMurray et al., 2017)

Draft RAI #2: UCO Kernel Stoichiometry (cont'd)

- AGR-1 had fuel specification for mean and critical limits for C:U ratio
- AGR kernel chemistry measured in aggregate, not for individual kernels
- Supporting study based on optical examination of AGR-1 kernels indicated wide variability in oxide/carbide ratio (suggested that critical limits not met, but data analysis method deemed unreliable). AGR-1 C:U could range from ~0.15 to 0.46.
- Critical limit removed for AGR-2 spec and tolerance on the mean tightened

	Mean	Critical Limits	Measured
AGR-1	0.5 ± 0.2	≤1% below 0.2 ≤1% above 0.8	0.325 (~32% UC_x)
AGR-2	0.4 ± 0.1	None	0.392 (~29% UC_x)

Draft RAI #2: Uninterrupted Coating

- Uninterrupted process is the de facto standard in modern TRISO fabrication
- Most historic data sets involve fuel fabricated with this process
- AGR-1 and AGR-2 used this process
- Uninterrupted coating is considered a process requirement when applying the results of this topical report

Draft RAI #3: Acceptable Fuel Parameter Ranges

- The TR states that "fuel particles tested in AGR-1 and AGR-2 exhibited property variations…with remarkably similar excellent irradiation and accident safety performance results. The ranges of those variations in key characteristics of the kernels and coatings are reflected in measured particle layer properties provided in Table 5-5 from AGR-1 and AGR-2." Table 5-5 provides a set of characteristics for both tested fuel and specified ranges for "acceptable" fuel, both for mean values and extremes. The specification range is large[r] than the tested fuel range, sometimes substantially. Based on the provided data, there is a clear basis for use of the measured values in Table 5-5, but the basis for the specified range and especially the Maximum Allowable Fraction Beyond the Critical Limit(s) is not clear. Additionally, the table references the AGR-1 and -2 dataset separately in some cases. Provide a table with a clear requested range for each property for approval to be referenced in the conclusions. Further, provide a basis for useage of the values in this table for ranges beyond the tested ranges, paying particular attention to Maximum Allowable Fraction Beyond the Critical Limit(s), where the allowed particles may be substantially "worse" than those tested.

- *(Note that the highlighted text is only true in certain instances)*

Draft RAI #3

- In many cases, statistical analyses indicate that a substantial percentage (i.e., >1%) of fuel particles resided outside of the range specified for the mean
  - True in most cases for layer thicknesses
- In other cases, the particle population resides almost entirely within a range more narrow than the specified mean range
  - Most cases for layer densities
  - All cases for PyC anisotropy
- Data can be reformulated as mean +/- 2 or 3 σ to demonstrate the total range of values that were irradiated

Table 5-5. Particle layer property 95% confidence values on means and dispersion limits

Particle Property	Sample Population	Specified Range of Mean [a]	Measured Mean Confidence Extrema [b]	Maximum Allowable Fraction Beyond the Critical Limit(s) [c]	Measured Dispersion Extrema [d]
Buffer thickness (µm)	AGR-1	85 – 115	96.5 – 105.0	1% ≤ 55	1% ≤ 82.5
	AGR-2			1% ≤ 58	1% ≤ 74.9
IPyC thickness (µm)	AGR-1	36 – 44	38.6 – 41.1	1% ≤ 30 1% ≥ 56	1% ≤ 33.0 1% ≥ 47.2
	AGR-2			1% ≤ 30 1% ≥ 52	1% ≤ 33.3 1% ≥ 47.5
SiC thickness (µm)	AGR-1	32 – 38	34.4 – 36.1	1% ≤ 25	1% ≤ 32.0
	AGR-2			1% ≤ 23	1% ≤ 31.7
OPyC thickness (µm)	AGR-1, -2	36 – 44	39.1 – 44.3	1% ≤ 20	1% ≤ 34.0
Buffer density (g/cm³)	AGR-1	0.88 – 1.18	1.08 – 1.12 [e]	Not specified	
	AGR-2	0.95 – 1.15	1.04 [f]		
IPyC density (g/cm³)	AGR-1, -2	1.85 – 1.95	1.851 – 1.914	1% ≤ 1.80 1% ≥ 2.00	1% ≤ 1.822 1% ≥ 1.951
SiC density (g/cm³)	AGR-1, -2	≥ 3.19	≥ 3.204	1% ≤ 3.17	1% ≤ 3.198
OPyC density (g/cm³)	AGR-1, -2	1.85 – 1.95	1.895 – 1.914	1% ≤ 1.80 1% ≥ 2.00	1% ≤ 1.881 1% ≥ 1.935
IPyC anisotropy (BAF_{True}) [g]	AGR-1	≤ 1.035	≤ 1.023	1% ≥ 1.06	1% ≥ 1.044
	AGR-2	≤ 1.045	≤ 1.026		
OPyC anisotropy (BAF_{True}) [g]	AGR-1, -2	≤ 1.035	≤ 1.020	1% ≥ 1.06	1% ≥ 1.038
Aspect Ratio [h]	AGR-1, -2	Not specified		1% ≥ 1.14	1% ≥ 1.098

Coating Property Variation Examples: IPyC Thickness and Density

OPyC Thickness	AGR-1 (B)	AGR-1 (V1)	AGR-1 (V2)	AGR-1 (V3)	AGR-2 UCO
Smpl Mean	41	41.1	39.8	39.3	43.4
Smpl Std Dev	2.1	2.4	2.1	2.1	2.9
≤LL = 36	0.9%	1.7%	3.5%	5.8%	0.5%
≥UL = 44	7.7%	11.3%	2.3%	1.3%	41.8%

- Substantial portion of particles reside outside of the range specified for the mean (36 – 44 µm)

OPyC Density	AGR-1 (B)	AGR-1 (V1)	AGR-1 (V2)	AGR-1 (V3)	AGR-2 UCO
Smpl Mean	1.907	1.898	1.901	1.911	1.907
Smpl Std Dev	0.008	0.009	0.008	0.008	0.007
≤LL = 1.85	0.00%	0.00%	0.00%	0.00%	0.00%
≥UL = 1.95	0.00%	0.00%	0.00%	0.00%	0.00%

- Relatively small distribution of values results in very few particles outside of the range specified for the mean (1.85 – 1.95 g/cm^3)

B = Baseline
V*n* = Variant *n*

Draft RAI #4: Fission Product Release Data Applicability

- TR conclusion 3 states "fission product release data and fuel failure fractions, as summarized in this report, can be used for licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope defined by measured particle layer properties in Table 5-5." The phrases "as summarized in this report" and "can be used for licensing of reactors" lack specificity, though the subsequent discussion is relatively clear.
  - (a) Consider revising to more specifically reference the data presented, and narrow the scope of the request "can be used for licensing of reactors" to something more appropriate for the TR.
  - (b) Conclusion number 3 further states that the aggregate AGR-1 and AGR-2 fission product release data and fuel failure fractions can be used for licensing of reactors employing UCO TRISO-coated fuel particles that satisfy the parameter envelope detailed in the topical report. The staff notes that while the topical report supports fission gas release rates for most isotopes, it does not cover short-lived isotopes which decayed away before the particles discussed in EPRI-AR-1(NP) could be characterized. Therefore, the data set does not cover all of the fission gas release data necessary for licensing. Provide justification to support the statements in conclusion number 3 or limit the conclusion to the isotopes covered by the topical report.
  - (c) (Draft QA RAI) – TBD, under separate interactions with QA branch.

Draft RAI #4: Applicability of Fission Product Release Data

Applicability of Data

- The text "can be used for licensing of reactors" can be revised to "can be used to <u>support</u> licensing of reactors"
  - It is not intended to imply that the data are sufficient for this purpose without additional data

Short-lived isotopes

- No data is presented in the report on short-lived isotopes, therefore Conclusion 3 does not apply
- Conclusion 3 only applies to fission products specifically referenced in the report
- Additional data are being collected on short-lived fission product release (AGR-3/4)

QA Questions

- Discussion of these will be deferred until January 2020