Microstructural and Micro-Chemical Evolutions in Irradiated UCO Fuel Kernels of AGR-1 and AGR-2 TRISO Fuel Particles

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Abstract – AGR-1 and AGR-2 tristructural-isotropic (TRISO) fuel particles were fabricated using slightly different fuel kernel chemical compositions, modified fabrication processes, different fuel kernel diameters, and changed $^{235}$U enrichments. Extensive microstructural and analytical characterizations were conducted to correlate those differences with the fuel kernels’ responses to neutron irradiations in terms of irradiated fuel microstructure, fission products’ chemical and physical states, and fission gas bubble evolutions. The studies used state-of-the-art transmission electron microscopy (TEM) equipped with energy-dispersive x-ray spectroscopy (EDS) via four silicon solid-state detectors with super sensitivity and rapid speed. The TEM specimens were prepared from selected AGR-1 and AGR-2 irradiated fuel kernels exposed to safety testing after irradiation. The particles were chosen in order to create representative irradiation conditions with fuel burnup in the range of 10.8 to 18.6% fissions per initial metal atom (FIMA) and time-average volume-average temperatures varying from 1070 to 1287°C. The $^{235}$U enrichment was 19.74 wt.% and 14.03 wt.% for the AGR-1 and AGR-2 fuel kernels, respectively. The TEM results showed significant microstructural reconstructions in the irradiated fuel kernels from both the AGR-1 and AGR-2 fuels. There are four major phases: fuel matrix of UO$_2$ and UC, U$_2$RuC$_2$ and UMoC$_2$—in the irradiated AGR-2 fuel kernel. Zr and Nd form a solid solution in the UC phase. The UMoC$_2$ phase often features a detectable concentration of Tc. Pd was mainly found to be located in the buffer layer or associated with fission gas bubbles within the UMoC$_2$ phase. EDS maps qualitatively show that rare-earth fission products (Nd et al.) preferentially reside in the UO$_2$ phase. In contrast, in the irradiated AGR-1 fuel kernel, no U$_2$RuC$_2$ or UMoC$_2$ precipitates were positively identified. Instead, there was a high number of rod-shaped precipitates enriched with Ru, Tc, Rh, and Pd observed in the fuel kernel center and edge zone. The differences in irradiated fuel kernel microstructural and micro-chemical evolution when comparing AGR-1 and AGR-2 TRISO fuel particles may result from a combination of irradiation temperature, fuel geometry, and chemical composition. However, irradiation temperature probably plays a more deterministic role. Limited electron energy-loss spectroscopy (EELS) characterizations of the AGR-2 fuel kernel show almost no carbon in the UO$_2$ phase, but a small fraction of oxygen was detected in the UC/UMoC$_2$ phase.
1. Introduction

U.S. Advanced Gas Reactor (AGR) tristructural-isotropic (TRISO) fuel is the culmination of significant efforts to overcome high-temperature performance limitations historically observed in irradiations by using an optimized fuel fabrication process and dedicated accelerated in-pile irradiations [1, 2]. In TRISO-coated fuel particles, a multi-layer system consisting of outer pyrolytic carbon (OPyC), SiC, inner pyrolytic carbon (IPyC), and a porous carbon buffer layer provides the fuel with the thermal-mechanical strength to contain fission products. Based on post-irradiation examination (PIE) results for fuel compacts and individual fuel particles from the first and second AGR experiments (AGR-1 and AGR-2), the overall fuel performance is excellent, with extremely low fuel-failure rates, while the SiC layer exhibits low fission product permeability [3-5].

Achieving high-quality, low-defect TRISO-coated fuels is a key technical milestone in supporting the development, licensing, and operation of high-temperature gas-cooled reactors. Activities in the AGR fuel development and qualification program include fuel fabrication and irradiation, PIE and safety testing, and related fuel performance modeling. PIE and safety tests are conducted to evaluate fission product retention during normal operation and accident scenarios, the microstructural evolution of fuel kernels and coatings, and the causes of coating failures.

Over the past 15 years, irradiation experiments on such fuels as AGR-1, AGR-2, and AGR-3/4 fuels were conducted in the Advanced Test Reactor, with PIE and safety tests on AGR-1/2 fuels completed with final advanced microscopy analysis currently still ongoing. Early lab-scale AGR-1 fuel demonstrated excellent in-pile performance with low fission-product release and very limited in-reactor coating failures. As opposed to AGR-1 fuel particles, AGR-2 fuel particles were produced in a pilot-scale coater. Systematic PIE microstructural and chemical characterization at scales spanning tens of microns to sub-nanometers is needed to fundamentally understand the impact of the fuel fabrication process and as-fabricated fuel properties on fuel performance during normal operation and accident conditions.

This paper presents microstructural characterization details from a safety-tested AGR-2 TRISO fuel kernel, offering a preliminary comparison of the microstructural and micro-chemical evolutions in irradiated fuel kernels of AGR-1 and AGR-2 fuels.

2. Experiment, sample description, and characterization methods

The TRISO fuel particle examined in this study was from Compact 2-2-2, irradiated in the AGR-2 experiment. Details of the AGR-2 irradiation experiment were reported by B. P. Collin [6]. After irradiation, Compact 2-2-2 was safety tested using the Core ConductionCooldown Test Facility (CCCTF). Table 1 lists the irradiation and safety-testing parameters, as well as the $^{110m}$Ag-retention ratio based on both measured and calculated $^{110m}$Ag activity. The absence of detectable Ag indicates that this particle released most of its $^{110m}$Ag inventory during safety testing.

| Table 1. Irradiated TRISO fuel particle AGR2-222-RS36, compact irradiation conditions, and subsequent safety-testing parameters. |
| Parameter | Measurement |
|-----------|-------------|
| Burnup (% FIMA) | 12.55 |
| Fast neutron fluence ($10^{25}$ n/m²), E > 0.18 MeV | 3.39 |
| Time-average volume-average temperature (°C) | 1287 |
| Time-average peak temperature (°C) | 1354 |
| Post-irradiation safety testing | 300 hours at 1600°C |
| $^{110m}$Ag retention | Not detectable |
| Kernel diameter (µm) | 426.7 ± 8.8 |
| Density (g/cm³) | 11.0 ± 0.030 |
| $^{235}$U enrichment (at.%) | 14.03 |
| As-fabricated chemistry, mole% | UO$_2$(71.4)/UC$_{1.86}$(12.3)/UC(16.4) |
Figure 1 shows a scanning electron microscope (SEM) image of the AGR2-222-RS36 particle, illustrating four TEM lamellae locations. These were specifically selected, as the fuel center and half-center have a higher temperature, the kernel edge zone may show the effects of fission fragment recoils, and the fuel kernel/buffer layer interface is of interest in showing fission product migration and the inter-diffusion behavior between the fuel kernel and the carbon-coating buffer layer.

TEM characterizations were conducted using a Talos F200X scanning/transmission electron microscope (STEM/TEM) located at the Irradiated Materials Characterization Laboratory (IMCL) at Idaho National Laboratory. The TEM is equipped with a super-X energy-dispersive x-ray spectroscopy (EDS) system and a Gatan’s Enfinium ER (977) spectrometer for electron energy-loss spectroscopy (EELS) analysis. The super-X EDS system provides superior sensitivity and rapid speed for EDS analysis and mapping down to the atomic scale. However, it should be noted that due to the inaccuracy of the absorption correction for light elements (atomic number below 11), quantification of C and O using EDS is inaccurate and unreliable. Microstructural characterizations, elemental analysis, and phase identification were conducted using conventional STEM/TEM imaging, EDS elemental mapping, and selected area electron diffraction. Limited EELS analysis was conducted to quantify the contents of C and O in phases of interest.

Figure 1. SEM image showing four TEM lamellae locations in the fuel particle AGR2-222-RS36: the fuel center, half-center, kernel edge zone with amorphous carbon, and the interface between the fuel kernel and the buffer layer.

3. Results

3.1. Irradiated AGR-2 Fuel Kernel

Fuel kernel center

Figure 2 shows bright-field (BF) TEM overview images, along with diffraction patterns from fission-product phases of interest. Figure 3 presents elemental maps and line scans across the phases and interfaces of interest. Based on the EDS analysis and SAEDs, there are four primary phases in the irradiated fuel center lamella: (1) the fuel matrix of uranium dioxide in the fluorite structure (UO$_2$ phase), (2) rock-salt structure UC with Zr in the solution, (3) tetragonal-structure (point group 4/mmm) Ru-rich U$_2$RuC$_2$ phase, and (4) orthorhombic-structure Mo-rich UMoC$_2$ phase. The crystal structures of the U$_2$RuC$_2$ and UMoC$_2$ phases are confirmed via the diffraction patterns shown in Figure 2 and their chemical compositions (atomic percentages) are shown in the EDS line scans Figure 3. The U$_2$RuC$_2$ phase was found to consistently precipitate within the Zr-rich UC phase. Our results also show that the UC phase is depleted of Pd and rare-earth elements (Nd, Pr, etc.). These rare-earth elements may form oxides that are in a solid solution in the UO$_2$ phase, similar to what is observed in traditional UO$_2$ fuels. The U$_2$MoC$_2$ phase shows a slight enrichment of Tc and often resides next to the UO$_2$ phase.
Figure 2. Overview of the fuel center lamellae and the diffraction from the fuel center.
Figure 3. TEM images, EDS maps (atomic concentration), and line scans across phases of interest: (a) low magnification over the fuel center lamella, (b) intermediate magnification showing a $\text{U}_2\text{RuC}_2$ particle, and (c) high magnification highlighting two $\text{UMoC}_2$ particles.
Fuel kernel half-center

Figure 4 shows the fuel half-center overview BF TEM images along with diffraction patterns, and Figure 5 shows the EDS maps and line scans across the phases of interest. The UC phase is consistently enriched with Zr. As the $^{235}$U atoms split into light elements, C combines with some fission products (FPs) to form carbides (e.g., ZrC and NdC). The metal-to-carbon bond is known to be significantly stronger than metal-to-metal bonds [7]. The C-Zr bonds are a combination of ionic and covalent bonds. Like most other transition metal carbides, ZrC is polar covalent [8], where the contribution of covalent bonding is significantly higher than that of ionic bonding, despite the considerable charge transfer (~0.42 e/pair) from Zr to the C atom [9]. Yasuo et al. [10] found that zirconium, niobium, and molybdenum monocarbides all have a NaCl-type structure and form a solid solution with UC. Many other studies on UC fuel also confirmed that the UC and ZrC are fully miscible [11-13]. With excess free carbon in the fuel kernels, production of Zr oxide is restrained. Carbothermal reduction of ZrO$_2$ to ZrC is often used by industry to synthesize ZrC. The phases of U$_2$RuC$_2$ and UMoC$_2$ are consistently identified in this fuel kernel half-center lamella, as well. Besides the fuel kernel, two UC$_2$ grains were identified, then highlighted using blue rectangles. The carbon map in Figure 5 (b) shows they have a relatively higher carbon content compared to neighboring grains.

**Figure 4.** Overview TEM images of fuel half-center lamellae and diffraction patterns from selected areas.
Figure 5. EDS maps (atomic concentration) and line scans across the phases of interest in the fuel kernel half-center TEM lamella: (a) top-right quarter, (b) top-left quarter, and (c) high magnification showing the submicron particles at the UO$_2$ grain boundaries.
Fuel kernel edge

Figure 6 and Figure 7 show BF TEM overview images, diffraction patterns of phases of interest, and the EDS maps and line scan from the fuel kernel edge zone. In the EDS maps, a high density of free carbon islands, shown in bright, can be clearly seen in the BF images. In contrast, no large pores were observed in this region—which is consistent with observations that the fuel edge has an appearance distinct from the rest of the fuel kernel, as shown in Figure 1. The U$_3$RuC$_2$ phase was found in the elongated shape shown in Figure 7 (a) of the Ru map.

Furthermore, diffraction patterns from Figure 6 reveal that U$_3$RuC$_2$ and the UC matrix form a coherent interface. They have an orientation relationship of (001)$_{UC}$//(110)$_{U_3RuC_2}$. Qualitatively, there is a higher number density of U$_3$RuC$_2$ precipitates in the fuel edge than in the fuel kernel center and half-center. Consistently, rare-earth elements are depleted in the UC, U$_3$RuC$_2$, and UMoC$_2$ phases. As shown in Figure 7 (d), very fine fission gas bubbles appear in the Mo-rich phase, accompanied by enrichments of Ru and Pd. Some Widmanstatten-type UC$_2$ plates were expected within the UC matrix, as excessive carbon results from the interdiffusion between the fuel kernel and the carbon buffer layer. However, only Widmanstatten-type U$_3$RuC$_2$ was found based on our TEM characterizations.

![Figure 6. Overview of the fuel recoil zone lamellae and diffraction patterns from selected areas.](image-url)
Figure 7. EDS elemental maps (atomic concentration) with line scan from (a) the top-left quarter of the kernel edge lamella and (b) the bottom-left quarter, (c) elemental maps from the top-right quarter, and (d) high EDS maps from a selected area containing fission gas bubbles.
Buffer-kernel interface

Figure 8 and Figure 9 show the overview BF TEM images, the EDS maps, and the line scans from the interface lamella. Clearly, the interface between the carbon buffer layer and the fuel kernel survived the in-pile irradiation and safety test. The kernel side mainly consists of UO$_2$, free carbon, and Zr-rich phases. Iodine-rich particles are also identified, as shown in Figure 9 (b). One interesting observation is that Pd, Xe, and I are present together at the interface. Particles enriched with Xe and I are highlighted by the dashed circles in Figure 9 (a) and (b) (Note that there are iodine isotopes that are precursors to Xe isotopes). The HFR-EU1bis experiment [14] (UO$_2$ kernel) and limited electron probe micro-analyzer (EPMA) study (AGR-1 particle) [15] both showed that residual I, Xe, and Cs mainly resided within the fuel kernel edge and the buffer layer.

On the carbon buffer layer side (Figure 9 (c)), U along with other fission products such as Zr, Mo, Nd, Xe, Ag, and Pd as small particles dispersed in the buffer layer. The origination of the uranium-rich particles can be from the buffer layer coating process. Additional characterization of the carbon buffer layer region of the as fabricated TRISO fuel particle will provide clarification. However, it shows that Xe, Pd, and Ag might become immobile as they form compounds with other elements even though during the irradiation and safety test, the Ag-self becomes very mobile and majority of it was released from the compact.

![Figure 8](image-url)  
**Figure 8.** Overview TEM images of kernel-buffer interface lamellae.
Figure 9. EDS elemental maps (atomic concentration) with line scans from the (a) top-left quarter of the buffer-kernel interface lamella, (b) bottom-left quarter of the buffer-kernel interface lamella, and (c) the buffer layer zone that includes dispersed submicron particles (the thin layer on the far right contains both O and C based on the area integrated EDS spectrum and figure (b)).
3.2. EELS Characterization
Quantification of carbon and oxygen was attempted using EELS characterization. Figure 10 shows the EELS spectra and carbon/oxygen maps of the areas selected from the fuel kernel center and half-center, respectively. The relative atomic concentrations of C and O are listed in Table 2. In both the fuel center and half-center, the UO$_2$ phase consistently showed almost no carbon, whereas the UC/UMoC$_2$ phase contained a small fraction of oxygen. The presence of oxygen may be attributed to dissolved fission product oxides in the carbides. Unfortunately, the sample size was limited, as a large portion of the TEM lamellae was too thick for EELS characterization, preventing the C and O peaks from being clearly observed. In addition, the selected energy window was made too wide by considering short exposure times, causing accurate peak fitting to be very challenging. These initial EELS examinations provided lessons learned moving forward.

Table 2. Relative carbon and oxygen concentrations in the three highlighted areas in the EELS spectra.

| Area | Element | Relative concentration (at.%) |
|------|---------|-----------------------------|
| A1   | C       | 0 ± 6 × 10$^{-6}$           |
|      | O       | 100.0 ± 5.0                |
| A2   | C       | 83.0 ± 4.0                 |
|      | O       | 16.5 ± 0.7                 |
| A3   | C       | 83.0 ± 4.0                 |
|      | O       | 16.5 ± 0.7                 |

Figure 10. EELS spectra and carbon/oxygen maps of selected areas from the fuel kernel center and half-center

4. Discussion

4.1. Fission Products’ Physical States in Irradiated TRISO Fuel Kernels
The presence of U$_2$RuC$_2$ and UMoC$_2$ in the irradiated UCO fuel kernel is consistent with the simulation studies, in that they are two ternary compounds in irradiated uranium carbide fuels [10, 11]. A higher number density of U$_2$RuC$_2$ precipitates was found in the fuel edge and interface zones than in the fuel kernel center or half-center regions. In the unirradiated UCO fuel kernel, UC$_2$ appears as thin plate within the UC phase [16]. It is suspected that the higher density of U$_2$RuC$_2$ precipitates is related to excessive UC$_2$ precipitates in the as-fabricated fuel kernel. The UC$_2$ plate may serve as a precursor phase for the U$_2$RuC$_2$ formation phase. However, this correlation needs to be proven through additional
characterizations of the unirradiated fuel kernels. Furthermore, previous thermodynamic studies of the U-C-Ru and U-C-Mo systems indicate that U$_3$RuC$_2$ and UMoC$_2$ are two primary solid phases in their ternary system [17, 18]. The high-temperature safety test probably promotes formation of U$_3$RuC$_2$. As there are very little U$_3$RuC$_2$ observed in the non-safety-tested AGR-2 UCO kernel irradiated to a similar burnup level [19]. Quite often in the UMoC$_2$ phase, a significant concentration of Tc is observed. The Tc probably forms a UTeC$_2$ phase that is soluble in the UMoC$_2$ phase, and they both have an orthorhombic structure with very close lattice parameters [20].

As shown in the previous sections, the UC phase is depleted of Pd and rare-earth elements (e.g., Nd). For the Pd, no ternary compounds are identified in the U-C-Pd system [21]. Pd metal, as well as the Pd-rich phase, was found in high vapor pressure regions and migrates to the colder region [22-25]. An abundance of rich particles only appears in the carbon buffer layer—which is consistent with other studies that show a high number density of Pd particles in the TRISO coating layers [26-28]. Compared with the UC phase, the UO$_2$ phase is slightly enriched with Pd, as shown in the EDS maps. This is consistent with our previous study using atom probe tomography [29]. However, the concentration of Pd in the UO$_2$ phase is too low to be quantified through EDS measurement. Its chemical and physical states are yet to be determined.

In well-studied Light Water Reactor UO$_2$ fuels, Nd and other rare-earth elements form oxide fission products and dissolve in the UO$_2$ fuel matrix [30]. In the UC phase, these rare-earth elements can form carbides, but with very low solubility [10, 12]. It was found that these rare-earth fission product carbides diffused to the colder region and deoxid in a carbide fuel matrix at high temperatures (> 1000°C) [12]. These carbide-forming rare-earth elements become oxide (RECO$_2$) at a relatively low oxygen potential compared to other carbide FPs (e.g., ZrC and NbC) from 1000°C to 1600°C. RECO$_2$ will diffuse and dissolve in the UO$_2$ phase [31]. Or, some carbides that form rare-earth elements will dissolve in the oxide fuel, depending on solubility limits. Our previous atom probe tomography studies showed that many lanthanide fission products tend to remain in solution of the UO$_2$ phase [29].

A simulation study by Yasuo et al. [10] showed that the principal condensed fuel matrix phases in an irradiated UC fuel should be UC and U$_2$C$_3$. However, U$_2$C$_3$ was not positively identified in unirradiated or irradiated UCO fuel kernels [29, 32, 33]. This is probably because of the presence of the UO$_2$ phase in the fuel matrix. It was also reported that U$_2$C$_3$ is a metastable phase at high temperature (> 1830°C), and decomposes to UC and C during the cooling process [34, 35]. At irradiation peak temperature, UC and UC$_2$ are completely soluble with each other [34]. Some UC$_2$ and/or UC will become oxides to balance the excessive free oxygen liberated from the irradiated UO$_2$ phase. As irradiation ends and the fuel starts to cool down, U$_3$RuC$_2$ rather than UC$_2$ will form Widmanstatten-type precipitates in the UC matrix. This explains why only few UC$_2$ grains were observed after irradiation at a burnup of 12.55% FIMA.

In this safety-tested irradiated AGR-2 fuel kernel, fission gas bubbles were only observed in the Mo-rich phase and are often accompanied by fine Pd and Ru-rich particles. The presence of Xe associated with the noble metal phase particles was also observed in the UO$_2$ spent fuel Zr cladding liner [36]. The exact chemical mechanisms governing this co-diffusion/co-precipitation behavior are yet to be understood. In the previous non-safety-tested AGR-1 fuel kernel, a large number of fission gas bubbles was found in the Zr-rich UC phase [29]. Most likely, the high-temperature safety testing removed the mobile fission gas bubbles, whereas the fission gas bubbles associated with Pd and Ru-rich particles survived.

4.2. Comparison between the Fuel Kernel Irradiation Responses of AGR-1 and AGR-2 TRISO Fuel Particles

Both the AGR-1 and AGR-2 UCO fuel particle kernels are a mixture of UO$_2$ and UC, but with a different nominal as-fabricated stoichiometry [37]. Table 3 lists the dimensions, $^{235}$U enrichment, and chemistry of the AGR-1 and AGR-2 UCO particle fuel kernels. AGR-1 UCO kernels have an overall composition of 67.9 mol%UO$_2$-31.7 mol%UC with only a trace of UC$_{1.86}$. In contrast, AGR-2 UCO fuel kernels have an overall composition of 71.4 mol%UO$_2$-12.3 mol%UC$_{1.86}$-16.4 mol%UC. The AGR-2 UCO particles have a larger fuel kernel diameter, but lower $^{235}$U enrichment compared to AGR-1 fuel particles. The AGR-2 UCO fuel kernels also have a noticeably different appearance, showing a very smooth, reflective surface and a greater homogeneity of chemistry and density [37].
The fuel kernel of the irradiated AGR-1-433-004 TRISO particle was examined in detail, and the microstructural evolution and fission product results were published in a journal article [38]. To better foster a one-to-one comparison, the irradiation conditions and safety testing are explained in [38].

Figure 11 shows a SEM image along with the TEM lamella locations in the irradiated AGR1-433-004 fuel particle. Compared with the AGR2-222-RS36 fuel particle kernel shown in Figure 1 the difference in pore structure is notable. Even though the AGR-1 fuel has a much higher burnup level, the pores are relatively small and evenly distributed. Although it seems that irradiation temperature plays a more pronounced role, as the time-average volume-average temperature for the AGR-2 compact is about 200°C higher than that for the AGR-1 fuel particle, it was found in other studies, that the pore structure can be significantly different from particles from the same compact [39]. High irradiation temperature also promotes a larger temperature gradient, as evidenced by the fact that the irradiated AGR-1 fuel kernel has a relatively homogeneous microstructure compared to the AGR-2 fuel kernel.

### Table 3. Dimensions, $^{235}$U enrichment, and chemistry of AGR-1 and AGR-2 UCO particle fuel kernels [37].

|       | UCO fuel kernel | AGR-1   | AGR-2   |
|-------|----------------|---------|---------|
| Diameter (µm) | 348.4 ± 8.3   | 426.7 ± 8.8 |
| Density (g/cm$^3$) | 10.7 ± 0.026   | 11.0 ± 0.030 |
| $^{235}$U enrichment (at.%) | 19.74           | 14.03         |
| Chemistry | UO$_2$ | 67.9     | 71.4    |
| (mole%) | UC$_{1.86}$ | 0.4      | 12.3    |
| UC     | 31.7           | 16.4     |

### Table 4. Compact Irradiation and subsequent safety-testing parameters of the AGR1-433-004 fuel particle.

| Parameter                          | Value     |
|------------------------------------|-----------|
| Burnup (%FIMA)                     | 18.63     |
| Fast neutron fluence (x 10$^{25}$ n/m$^2$), E > 0.18 MeV | 4.16     |
| Time-average volume-average temperature (°C) | 1094 |
| Time-average peak temperature (°C)  | 1179     |
| Post-irradiation safety testing    | 300 hours at 1600°C |
| $^{110m}$Ag retention              | 98%       |

Figure 11. SEM image of the AGR1-433-004 fuel kernel, along with TEM lamella locations.
No U₄RuC₂ or UMoC₂ precipitates were positively identified in the AGR-1 fuel kernels. The absence of those two types of precipitates can be attributed to many possible factors, e.g. irradiation temperature, fuel kernel stoichiometry variation, and irradiation history [38]. As highlighted by dashed red circles in Figure 12, there is a large number of rod-shaped precipitates in the fuel center and edge zone of the AGR-1 fuel kernel. EDS maps showed that the precipitates are enriched with Rh, Ru, Tc, Pd, and/or Mo. However, this rod-like type of precipitate was not identified in the irradiated AGR-2 fuel kernel. In the buffer layer of the AGR-1 fuel kernel, there were large particles consisting of U, Nd, Rh, Zr, Mo, and other fission products.

**Figure 12.** High-angle annular dark-field STEM images of the lamellae from the irradiated AGR1-433-004 fuel kernel.

5. Conclusions
Systematic TEM characterizations show four primary phases in the safety-tested irradiated AGR-2 particle fuel kernel. They are fuel matrix UO₂ and UC, U₄RuC₂, and UMoC₂. The UMoC₂ phase often shows a detectable concentration of Tc. Zr and Nb form a solid solution in the UC phase. Pd was mainly found in the buffer layer or is associated with fission gas bubbles within the UMoC₂ phase. Two UC₂ grains were identified in the fuel kernel half-center lamella. Limited EELS characterizations show almost no carbon in the UO₂ phase, while a small fraction of oxygen was detected in the UC/UMoC₂ phase.

A comparison between the irradiated AGR-1 and AGR-2 fuel kernels shows distinguishable differences in their microstructural and micro-chemical evolutions upon irradiation. These differences may result from a combination of irradiation temperature, fuel geometry and chemical composition. However, irradiation temperature likely plays a more deterministic role.

Possible next activities include the benchmarking of the presence of high yield fission products like Sr vs the predicted fission product inventory generated during irradiation in compacts. However, by considering the fact that each fuel particle is out of 4000+ in a TRISO fuel compact, and there are considerable differences in irradiation temperature and initial fuel kernel microstructure. The reported results may not explicitly describe the average behavior of the whole TRISO fuel compact.

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