Fission Products Silver, Palladium, and Cadmium identification in Neutron-Irradiated SiC TRISO Particles Using a Cs-Corrected HRTEM

I. J. van Rooyen^{1*}, E. J. Olivier² and J. H. Neethling²

¹Fuel Design and Development Department, Idaho National Laboratory

P.O. Box 1625, Idaho Falls ID, 83415-6188, USA

phone: +1-208-526-4199, isabella.vanrooyen@inl.gov

*Corresponding author

²Centre for High Resolution Electron Microscopy, Department of Physics,

Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

Abstract – Electron microscopy investigations of selected coated particles from the first advanced gas reactor experiment at Idaho National Laboratory provided important information on fission product distribution and chemical composition in the silicon-carbide (SiC) layer. Silver precipitates were nano-sized, and therefore high-resolution transmission electron microscopy (HRTEM) was used to provide more information at the atomic level. Based on gamma-ray analysis, this particle which was irradiated to an average burnup of 19.38% fissions per initial metal atom, may have released as much as 10% of its available Ag-110m inventory during irradiation. The HRTEM investigation focused on silver, palladium, and cadmium due to interest in silver transport mechanisms and possible correlation with palladium and silver previously found. Palladium, silver, and cadmium were found to co-exist in some of the SiC grain boundaries and triple junctions. This study confirmed palladium both at inter and intragranular sites. Phosphor was identified in SiC grain boundaries and triple points.

1. INTRODUCTION

A detailed understanding of the silver (Ag) transport mechanism in polycrystalline 3C-silicon-carbide (SiC) is important for design of advanced coated fuel particles for high-temperature reactors. A finding more than three decades ago, about Ag being released by intact tristructural isotropic (TRISO) particles has led to significant research efforts to determine an Ag transport mechanism in SiC, because out-of-reactor experiments did not reveal any significant Ag migration in SiC. Numerous Ag-110m transport mechanisms (e.g., grain boundary diffusion, surface diffusion or vapor transport through interconnected nano-pores or nano-cracks, and palladium [Pd]-assisted transport alongside grain boundaries) have been proposed from these out-of-pile experiments [1-10].

Researchers [5-7] annealed polycrystalline SiC in contact with a Pd-Ag compound out-of-pile and reported that Pd significantly enhanced the transport of Ag along grain boundaries in SiC. It was also reported that Ag or an Ag-Si compound did not penetrate polycrystalline 3C-SiC in the absence of Pd. Recent research by O'Connell and Neethling [10] reported enhanced Pd-Ag transport along grain boundaries in bulk (i.e., SiC grown by Rohm and Haas and irradiated at Oak Ridge National Laboratory) neutron-irradiated polycrystalline SiC annealed at 1000°C (out-of-pile) compared to Pd-Ag transport in unirradiated SiC. In addition, Pd was also observed inside (i.e., at a distance of about 100 μm from the grain boundary) SiC grains of high-fluence (9.4×10^{21} n/cm² at 1460°C) irradiated samples. The neutron irradiation of SiC at high temperatures leads to the introduction of voids in rows along the {111} planes, which was found to enhance the transport of Pd in the SiC grains. Void formation is aided by the presence of lattice faults such as stacking faults and twins that readily form in SiC on {111} planes.

Although these individual studies are relevant to specific experimental conditions, no experimental verification of the role of Pd in Ag transport in actual neutron-irradiated SiC layers of TRISO-coated particles, which could be used to validate these out-of-pile hypotheses [11-13], has been reported to date.

Therefore, the first direct observation of Ag in SiC grain boundaries of neutron-irradiated, TRISO-coated particles from the first Advanced Gas Reactor (AGR-1) experiment by van Rooyen and co-workers [13] provided motivation to confirm or rule out some of these Ag transport mechanism hypotheses. This work showed the co-existence of Ag and cadmium (Cd) in grain boundaries and the triple points of the neutron-irradiated SiC. Pd was found separately in different grain boundaries and inside the SiC grains. These results prompted the Idaho National Laboratory analytical electron microscopy investigation on Pd and Ag transport in SiC layers from TRISO-coated particles.

In this paper, analytical and high-resolution scanning transmission electron microscopy (STEM) was used to examine the microstructure and location of fission products (i.e., Pd, Ag, and Cd) in SiC irradiated to an average fast fluence of $4.13 \times 10^{25} \text{ n/m}^2$.

2. MATERIAL AND METHODS

2.1 Material

Initial results of the high-resolution electron microscopy examination of a coated particle from Compact 4-1-1 from AGR-1 are described in this section. The unique identification number of Compact 4-1-1 is based on the specific capsule, level, and stack number for each compact. Fig. 1 identifies the stack and position (or level) numbers in a particular capsule. Compact 4-1-1 refers to the compact in Capsule 4 at Level 1 of Stack 1. Capsule design and details of the AGR-1 experiment have been described in previous reports [14].

Fig. 1. Numbering scheme for AGR-1 Compact 4-1-1.

Compact 4-1-1 contains Variant 3 fuel particles that were fabricated by changing the fuel carrier gas composition for the SiC layer vapor deposition from 100% hydrogen to a 50% argon, 50% hydrogen mixture and the deposition temperature was lowered relative to the baseline (from 1500 to 1425°C). This change was expected to reduce the potential for SiC defects formation resulting from uranium dispersion and provide a variation in SiC microstructure that may be less permeable to metallic fission products. The effect of the changed SiC fabrication parameters on the fission product transport and release is not yet fully determined as the advanced microscopy examination of the various variant fuel types are in progress. The fuel kernel is fabricated from low-enriched uranium oxycarbide with a diameter of approximately 350 μm and a U-235 enrichment of approximately 19.7%. Selected properties for the Variant 3 AGR-1 coated particles are shown in Table 1 [15]. Table 1. Selected properties (actual mean value $\pm$ population standard deviation) for the Variant 3 AGR-1 coated particles [15].

Coating Layer	Mean Value $\pm$ Population Standard Deviation	
	Thickness (μm)	Density (mg/m^3)
Buffer	104.2 ± 7.8	1.10 ± 0.04
Inner pyrolytic carbon (IPyC)	38.8 ± 2.1	1.904 ± 0.013
SiC	35.9 ± 2.1	3.205 ± 0.001
Outer pyrolytic carbon (OPyC)	39.3 ± 2.1	1.911 ± 0.008

Compact 4-1-1 was irradiated to 19.38% fissions per initial metal atom average burnup; 1072°C time-averaged, volume-averaged temperature; 1182°C time-averaged peak temperature; and an average fast fluence of $4.13 \times 10^{21} \text{ n/cm}^2$. Individual particles were gamma ray counted to measure the activity of various gamma ray emitting fission products. The retention of Ag-110m in each particle is estimated by comparing the measured inventory to the predicted inventory normalized by the relative Cs-137 activity to reduce the influence of different kernel sizes on overall distribution (see [15] for details).

The measured-to-calculated ratio for 58 gamma ray counted particles from Compact 4 ranged from 0.075 to 1.45. Coated particle AGR1-411-030 was selected because it exhibited an average retention of Ag-110m under irradiation with a measured-to-calculated Ag-110m ratio of 0.90 (Fig. 2). Deconsolidation-leach-burn-leach data [15] indicate that the particles from Compact 4-1-1 released, on average, approximately 3% of their inventory during irradiation, which was retained in the matrix. It has been concluded that, on average, there was relatively

low release of Ag from the particles in this compact. Decay-corrected activity (in Bq) for Ag-110m measured by gamma ray counting of the AGR1-411-030 particle is 6.45×10^4 [15].

Fig. 2. Distribution of measured-to calculated Ag-110m activity ratios, normalized by the Cs-137 activity to account for variations in fissile content and burnup.

2.2 Methods

The TEM specimens were prepared at the Electron Microscopy Laboratory at Idaho National Laboratory's Materials and Fuels Complex, using the dual-beam Quanta 3D field emission gun (FEG) focused ion beam (FIB) (Fig. 3). FIB lamellas at position 1b, 1c, and 2 were extracted from locations perpendicular to the SiC-IPyC interface. Lamellas 1b and 2 contain parts of both the IPyC and SiC layers, while FIB lamella 1c is from the outer interface between the SiC and OPyC layer, which is the furthest away from the IPyC-SiC interface. FIB lamella 1a contained only a small area of the SiC layer close to the IPyC-SiC interface and was cut parallel to the IPyC-SiC interface. Because lamella 1a contained only small areas of the SiC layer at the IPyC-SiC interface, it was not examined for this paper.

Fig. 3. Scanning electron microscope image showing the AGR1-411-030 FIB scanning electron microscope lamellas sectioned at positions 1b, 1c, and 2 as indicated on the cross section of the coated particle.

High-resolution transmission electron microscopy (HRTEM) and high-resolution STEM (HRSTEM) investigations were performed at the Nelson Mandela Metropolitan University in South Africa, using a double Cs-corrected JEOL ARM 200F operated at 200 kV. This microscope is equipped with two CEOS spherical

aberration (Cs) correctors for correction in TEM and STEM modes and with an Oxford Instruments XMAX 80 electron dispersive spectroscopy (EDS) detector and Gatan quantum image filter with dual electron energy loss spectroscopy capabilities. The use of aberration corrected STEM in the analysis of the specimens arises from the relative increase in probe current density achieved as compared to uncorrected microscopes. Greater signal can be generated from a comparatively smaller area which results in the analysis of more localized areas in a shorter space of time.

Subsequent EDS analyses were performed with a JEOL Centurio EDS detector, which is a next-generation type Silicon Drift Detector (SDD) detector that has a chip area of 100 mm² and an enhanced detector design that allows for significant improvement (about 300%) in collection efficiency compared to previous detectors (such as the Oxford XMax 80). In the case of the JEOL Centurio, a collection angle of about 0.82 Sr is specified when using the JEOL ARM 200F fitted with an ultra high resolution (UHR) pole piece. The Oxford XMax 80 fitted on the same configuration has a collection angle of about 0.21 Sr. The improved collection efficiency leads to better counting statistics over a shorter time period, which allows the detection of low concentrations of elements during the shorter analysis time before sample modification or contamination issues by the electron beam arise. The electron dose experienced by the sample can also be limited because a smaller probe size can be used.

Imaging and analysis of the sample were done using a sub-angstrom-sized probe with a probe current of approximately 68 pA, which was found to give the best balance of resolution, count rate, and sample stability. EDS was mainly used for compositional analysis due to the relative accessibility of the higher energy K-lines for Ag and Pd, which enabled their easy identification due to sufficient separation between the respective x-ray peaks. Another distinct advantage of the microscope is simultaneous acquisition of both bright field (BF) and high-angle annular dark field (HAADF) STEM images. This aided in the identification of grain boundaries in conjunction with elemental atomic number contrast imaging. The main objective of this investigation was to detect very low concentrations of Ag, Pd and other fission products by using high resolution TEM/STEM and an EDS system with a high collection efficiency.

2.3. HRSTEM Investigation and Approach

The Cs-corrected HRTEM was operated in scanning transmission mode, which allows for simultaneous viewing of BF and HAADF STEM images. This mode of viewing enables easy differentiation between SiC and PyC areas, as well as identification of fission product agglomerates in the form of nodules inside the SiC layer. The BF image provides sufficient contrast to identify the positions of grain boundaries and the presence of defects (such as stacking faults), which can then be correlated with the position of fission products by using HAADF imaging that shows atomic number (Z) contrast. After HRSTEM imaging of the sites containing visible fission product agglomerates, EDS spot analysis was carried out on the fission products and surrounding areas to identify the elements present. Probe current conditions were chosen to optimize the beam current but, at the same time, minimize beam damage to the specimen.

3. RESULTS

3.1 SiC as Main Barrier to Fission Products

The effectiveness of the SiC layer as the main fission product barrier is illustrated by the HAADF STEM images in Fig. 4, where the accumulation of Pd at the IPyC-SiC interface is visible. Additionally, no significant Pd corrosion of SiC (i.e., only a few approximate 1-nm diameter corrosion pits) is observed at this high magnification, which confirms earlier SEM observations and proves that Pd can penetrate the SiC without corroding the surface significantly [11].

3.2 Co-Existence of Ag, Pd, and Cd at Grain Boundaries and Triple Junctions

BF and HAADF STEM images of fission product networks at SiC grain boundaries and triple points of specimen AGR-411-030 position 1b are shown in Fig. 5 (a) and (b), respectively. These fission product accumulations are visible as bright regions (i.e., high atomic number) in the HAADF STEM shown in Fig. 5 (b). Accumulations of Pd, Ag, and Cd were found to co-exist in the area indicated by the arrow marked 1 in the HAADF STEM image (b). The arrowed area 1 in Fig. 5(b) is shown at higher magnification in Fig. 6 as a BF STEM image of co-existing Pd-Ag-Cd accumulations at location 1 on a grain boundary between two SiC grains. Fig. 7 shows the EDS spectra at locations 1 to 3 in Fig. 6. The peaks for Ag and Cd passed the 2 sigma test as determined by the Oxford software. Thus the peaks are deemed to be statistically relevant. EDS analyses of locations 2 and 3 only indicated the presence of Pd.

Under certain imaging conditions, HAADF and BF STEM images are complementary; therefore, atom columns in dark field (DF) mode will change from bright spots to dark spots in BF mode. The dark spots at the grain boundary and at the triple points in Fig. 6 are due to the Pd, Ag, or Cd atoms. It is not possible to differentiate between these elements using BF STEM imaging. The EDS analyses caused slight damage to the atomic structure visible at the locations arrowed in Fig. 6.

Accumulations of Pd, Ag, and Cd co-exist in other areas of specimen AGR-411-030 position 1b, which was also confirmed by the HAADF STEM image shown in Fig. 8(a) with the corresponding EDS spectrum in Fig. 8

(d). Only Pd Pd-U or Pd were found in the adjacent larger triple point accumulations (points 2 (spectrum Fig. 8(b) and 4 (spectrum Fig. 8(c)) respectively) indicated by arrow Pd). Higher magnification BF STEM images of the Pd-Ag-Cd containing triple points are shown in Fig. 9. In the BF STEM image, the fission products in the grain boundary and the triple point are visible as dark areas.

Fig. 4. HAADF STEM images showing (a) accumulation of Pd at the IPyC-SiC interface, (b) showing no significant corrosion except for a few approximate 1-nm diameter corrosion pits only visible at this magnification, and (c) and (d) showing the presence of Pd in two spectra of associated areas in (a) .

Fig. 5. BF (a) and dark field (b) STEM images of fission product networks at grain boundaries and triple points of specimen AGR-411-030 position 1b.

Fig. 6. High-resolution BF STEM image Pd-Ag-Cd accumulations co-existing at location 1 at a SiC grain boundary of specimen AGR-411-030 position 1b. Only Pd was found at locations 2 and 3.

Fig. 7. EDS spectra showing (a) co-existence of Pd, Ag, and Cd at location 1 of specimen AGR-411-030 position 1b. The peaks for Ag and Cd passed the 2 sigma test as determined by the Oxford software. Thus the peaks are deemed to be statistically relevant, and showing that only Pd was found at locations 2 and 3 as shown in (b) and (c)

Fig. 8. Image showing (a) HAADF STEM image of specimen AGR-411-030 position 1b, showing a triple point where Pd, Ag, and Cd accumulations co-exist (point 5 in (a) and EDS spectrum in (d), Only Pd-U or Pd were

found in the adjacent larger triple point accumulations (points 2 (spectrum (b)) and 4 (spectrum (c)) respectively)

Fig. 9. BF STEM image (a) of a Pd-Ag-Cd containing triple point with the corresponding high-resolution BF STEM image (b).

Ag decay is suggested as the most likely primary source of Cd observed in the fission product nodules. Therefore, it is expected that at the end of irradiation, Cd will be present in close proximity to Ag. However, Cd is also a direct fission product (albeit one of lower yield and higher vapor pressure compared with Ag and Pd) and it is possible that some of the Cd observed could have been created by fission.

3.3 Intragranular Presence of Pd in SiC

Pd was also observed inside SiC grains in proximity to planar defects such as stacking faults or nano twins (see Fig. 10). This is an interesting observation because the majority of the Pd nodules are usually found along SiC grain boundaries. However, it is proposed that the same mechanism that governs the movement of Pd along SiC grain boundaries is responsible for the migration of Pd along planar defects in SiC. Grain boundaries contain high concentrations of dislocations due to the relative misorientation between adjacent grains; therefore, they have a comparatively open structure. This results in diffusivities for grain-boundary transport that are much larger than analogous values for lattice diffusion. Enhanced diffusion along dislocation cores will also occur. SiC grains containing high concentrations of stacking faults (or nano-twins) bounded by partial dislocations will also have a high concentration of easy diffusion paths created by the stacking faults and partial dislocation cores. This is consistent with the work of Kornilios et al. [16] who suggested that the observed diffusion of gold through a 2.8- μm thick 3C-SiC layer at 500°C for 500 hours was most likely along stacking faults extending through the layer.

As mentioned earlier, stacking faults and nano-twins also provide easy diffusion paths for atoms and may explain the presence of Pd at stacking faults (or nano-twins) inside the SiC grains observed in this study.

Fig. 10. BF STEM image in (a) showing the position of the Pd accumulation at a stacking fault in a SiC grain with ahigh resolution BF STEM image in (b) with the corresponding EDS spectrum in (c).

3.4. Penetration Depth and Compositional Identification of Fission Products in the SiC Layer

Because significant Ag was released from this particle, it was our aim to identify locations of Ag through the the SiC layer in an attempt to correlate the locations with local microstructure (e.g., grain size and grain boundary character). Determination of the maximum penetration depth in SiC is challenging because the Pd nodules that are clearly visible at low magnification are not visible at the maximum penetration depth. (This is specifically a limitation when SEM analysis is used to determine the fission product depth.) When the magnification is increased, smaller hairline (i.e., about 1 to 2-nm thick) networks of Pd become visible and extend further into the SiC than the larger nodules that are easily observed at lower magnification. EDS analyses of these hairline networks also become challenging when the concentration of Pd or Ag is of the same magnitude as the EDS detection limit. From this depth and deeper into the SiC, atomic migration along the grain boundaries below the STEM and EDS detection limits is possible and quite likely.

Pd was found to be present in nodule networks throughout FIB lamellas 1b, 1c, and 2 (work by Lillo et al. [17] shows networks of Pd through the total SiC layer thickness for a particle from Compact 6-3-2 irradiated to 11.4% fissions per initial metal atom). In this particle, Ag is found at a distance of about 6.7 μm from the IPyC-SiC interface (Fig. 11 and Fig. 12 for higher magnification of this area) in this specific lamella 1b (no Ag was measured in lamella 1c). This value should be considered as a lower (i.e., detectable) limit for the current irradiation conditions of the TRISO particle and electron microscopy techniques employed for this investigation. However, Ag has only been found together with Pd and Cd. Although electron energy loss spectroscopy has a better spatial resolution than EDS, it is not ideal in this case for analysis of Ag due to edge overlap.

Fig. 11. BF STEM image of SiC showing the penetration depth of Ag measured in this specific SiC lamella 1b (no Ag was measured in lamella 1c).

Fig 12 BF STEM image of SiC showing the penetration depth of Ag at higher magnification. At this larger magnification, more fission product triple points are visible.

3.5. EDS Analysis Using the JEOL Centurio EDS Detector

More detailed EDS analysis was performed on AGR1-411-030 using a next generation EDS detector. In the area shown in Figure 13, Ag was found to be co-existing with Pd at EDS points 1 through 4 and was corresponding to grain boundaries and triple points. Figure 14 shows the presence of Ag at location point 4. Neither Ag nor Pd were found at points 5 and 6, which were inside the SiC grains. However, phosphorus (P) was detected in association with Pd and Ag at the SiC grain boundary at point 1 while in contrast no P was detected in the SiC grain at positions 5 and 6 (Figure 15). Further analysis on grain boundaries at an additional site revealed also P on grain boundaries as shown in Fig. 16, specifically at points 1 and 2. This suggests segregation of P at the boundaries and triple points. The software identifies and quantifies it to be within a 3 sigma level. This is the first finding of P, which is usually produced by neutron transmutation of silicon, in the SiC layer grain boundaries of neutron-irradiated, TRISO-coated particles.

Fig. 13. Selected HRSTEM image showing the six locations where EDS analysis was completed using the new higher-resolution EDS detector.

Fig. 14. HRSTEM-EDS spectrum at point 4 showing the co-existence of Ag and Pd.

Fig. 15. HRSTEM-EDS spectra at points 1(a) and 5(b) showing the presence of P (as indicated by the arrow) at the grain boundary but not in the SiC grain respectively.

Fig. 16. Selected HRSTEM image (a) showing the four locations where EDS analysis was completed using the new higher-resolution EDS detector. HRSTEM-EDS spectra at points 1(b) and 2(c) showing the presence of P (as indicated by the arrow) at the grain boundary triple points.

4. DISCUSSION AND CONCLUSIONS

This paper describes some of the first analytical HRSTEM results obtained from examination of a particle from Compact 4-1-1, which was irradiated to an average burnup of 19.38% fissions per initial metal atom; a time-averaged, volume-averaged temperature of 1072°C; a time-averaged peak temperature of 1182°C; and an average fast fluence of 4.13×10^{21} n/cm². Based on gamma ray analysis, it is estimated that this particle may have released as much as 10% of its available Ag-110m inventory during irradiation.

With STEM imaging, Pd accumulation at the IPyC-SiC interface was observed, which is an indication that Pd diffuses rapidly through the PyC layers until it reaches the SiC, where transport is much slower. This confirms the effectiveness of the SiC layer and the morphology of the IPyC/SiC interlayer as the main fission product barrier. Additionally, no significant Pd corrosion of SiC was observed, which confirmed earlier SEM observations and indicated that Pd can penetrate the SiC without significantly corroding the surface.

BF and HAADF STEM images of fission product networks at SiC grain boundaries and triple points of specimen AGR-411-030 indicated that accumulations of Pd, Ag, and Cd co-existed at grain boundaries and triple points. At some locations, EDS analyses only indicated the presence of Pd. However, the possible presence of Ag or Cd at these locations in concentrations below the EDS detection limit cannot be ruled out. Ag decay is most likely the primary source of the Cd observed in the fission product nodules. Therefore, Cd is expected to be present in close proximity to Ag at the end of irradiations. If Cd accumulations were observed without any Ag, it could have indicated a source of Cd was fission in the kernel.

Pd was also observed inside SiC grains in proximity to planar defects such as stacking faults or nano twins. This is an interesting observation because the majority of Pd precipitates are usually found along SiC grain boundaries. Previous STEM work by Van Rooyen et al. [13] showed the presence of spherical nano Pd precipitates inside grains as well; it was not possible to provide more positional information of these Pd precipitates inside the SiC grains, although evidence of fission products were found comparing HAADF with corresponding BF images (it was not possible to obtain compositional quantification and identification of these precipitates due to its low concentration). This HRTEM study provides this new information. It is proposed that the same mechanism that governs movement of Pd along SiC grain boundaries is responsible for migration of Pd along planar defects in SiC. Grain boundaries contain high concentrations of dislocations due to relative misorientation between adjacent grains; therefore, they have a comparatively open structure. This results in diffusivities for grain-boundary transport that are much larger than analogous values for lattice diffusion. Enhanced diffusion along dislocation cores will also occur. SiC grains containing high concentrations of stacking faults (or nano-twins) bounded by partial dislocations will also have a high concentration of easy diffusion paths created by the stacking faults and partial dislocation cores.

Furthermore, the transport of Pd in SiC is proposed to be mediated by a silicide formation mechanism at temperatures in the range of 1000°C. At temperatures above the melting point of the silicide (i.e., about 980°C for Pd/Si), Si atoms will diffuse into the Pd nodule via an exchange mechanism with Pd atoms, which will release more Pd atoms to penetrate the SiC and react with Si atoms at the grain boundaries. For this reason, migration of Pd is seen to occur preferentially along grain boundaries. As mentioned earlier, stacking faults and

nano-twins also provide easy diffusion paths for atoms and may explain the presence of Pd at stacking faults (or nano-twins) inside the SiC grains observed in this study. Earlier work on irradiated TRISO-coated particles [11] also revealed the alignment of voids at the grain boundaries in the vicinity of fission product precipitates.

With increased magnification, smaller hairline networks of Pd become visible and extend deeper (i.e., frequently up to 8 μm) into the SiC than the larger nodules that are easily observed at lower magnification. From this depth and deeper into the SiC, atomic migration along the grain boundaries, below the STEM and EDS detection limits, is possible and quite likely.

However, Ag has only been found together with Pd and Cd for samples from this specific compact and the current irradiation conditions. Ag being found inside SiC at grain boundaries only in the presence of Pd is consistent with the Pd-assisted transport mechanism proposed by Neethling and co-workers [5]. This may also explain why the majority of the out-of-pile experiments carried out to determine the diffusion coefficient of Ag in SiC did not reveal any significant Ag migration in SiC. The first finding of P in the SiC layer of neutron-irradiated, TRISO-coated particles is reported in this work. P is usually produced by neutron transmutation of silicon. No direct link between the presence of P and Ag transport could be made from this study.

Although the results of this analytical HRSTEM study are consistent with a Pd-assisted Ag transport mechanism along grain boundaries, more research is needed to elucidate the effect of neutron irradiation damage (and irradiation temperature) on fission product transport at the nano and atomic level, which is one of the research focus areas at Idaho National Laboratory.

5. ACKNOWLEDGEMENTS

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