2038 Microsc. Microanal. 28 (Suppl 1), 2022
doi:10.1017/S1431927622007905

Laboratory-Based 3D X-ray Imaging of Neutron-Irradiated Ceramic Particle Nuclear Fuel

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High-temperature gas-cooled reactors (HTGR) are nuclear fission reactors which are graphite-moderated and helium-cooled with operating temperatures in the range of 300 °C – 900 °C. Tristructural isotropic (TRISO) coated fuel particles are a ceramic fuel system currently under investigation for use in HTGRs and are designed with three coating layers around the fuel particle to retain radioactive fission byproducts during normal and off-normal conditions [1]. These particles are consolidated into a cylindrical, graphitic resin matrix (i.e., compact), which can contain ~1000-2000 particles. In order to qualify TRISO coated particle fuel for licensing and operating in HTGRs, several neutron irradiation tests have been conducted on TRISO coated particle fuel-bearing compacts with Idaho National Laboratory's (INL) Advanced Test Reactor. In addition to these tests, post-irradiation examinations (PIE) are performed on both the consolidated compact and individual particles (liberated from the compact via a deconsolidation process). Traditionally, PIE of individual particles relies on destructive sample preparations for investigating the fuel using optical and electron microscopy and is performed with limited knowledge of regions or particles of interest.

In an interest to research and develop nondestructive characterization techniques for TRISO coated particle fuel-bearing compacts and individual TRISO coated fuel particles, the use of micro X-ray computed tomography (micro-XCT) has been investigated with these fuel systems [2]. Micro-XCT is an imaging modality that provides nondestructive three-dimensional (3D) surface and subsurface morphological information by acquiring several thousand X-radiographs as a function of sample rotation. The radiographs are then used to create a mathematical 3D reconstruction (i.e., tomogram) of the sample. However, the micro-XCT imaging of uranium-bearing materials is challenging due to uranium's high mass attenuation coefficient at X-ray energies that are typically accessible with laboratory-based X-ray sources [2,3]. Additional challenges include the sample preparation and handling of highly irradiated nuclear fuel (e.g., radioactive contamination and high energy radiation). To overcome these challenges, a commercially available laboratory-based X-ray microscope, located in INL's Irradiated Materials Characterization Laboratory (IMCL, a Hazard Category 2 nuclear facility), has been adapted for these studies.

This presentation will give an overview of micro-XCT imaging with the use of a laboratory-based X-ray microscope (a ZEISS Xradia 520 Versa) to nondestructively characterize neutron-irradiated TRISO coated particle fuel-bearing graphitic resin compacts and individual liberated TRISO coated fuel particles. Compacts were irradiated in INL's Advanced Test Reactor as part of the Advanced Gas Reactor (AGR) Fuel Development and Qualification Program. Individual TRISO coated fuel particles were deconsolidated from compacts irradiated during the second series of tests (i.e., AGR-2) whereas the TRISO coated particle fuel-bearing compacts imaged in this study are from the combined third and fourth series of tests (i.e., AGR-3/4). The results from quantitative analyses of the tomograms will be presented along with a proposed path forward for correlative 2D and 3D microscopy and imaging (e.g., neutron computed tomography, focused ion beam-scanning electron microscopy, and transmission electron microscopy).

This work was sponsored by the U.S. Department of Energy, Office of Nuclear Energy, through the Advanced Reactor Technologies Advanced Gas Reactor Fuel Development and Qualification Program. Idaho National Laboratory is operated by Battelle Energy Alliance LLC under contract number DE-AC07-05ID14517 for the U.S. Department of Energy.

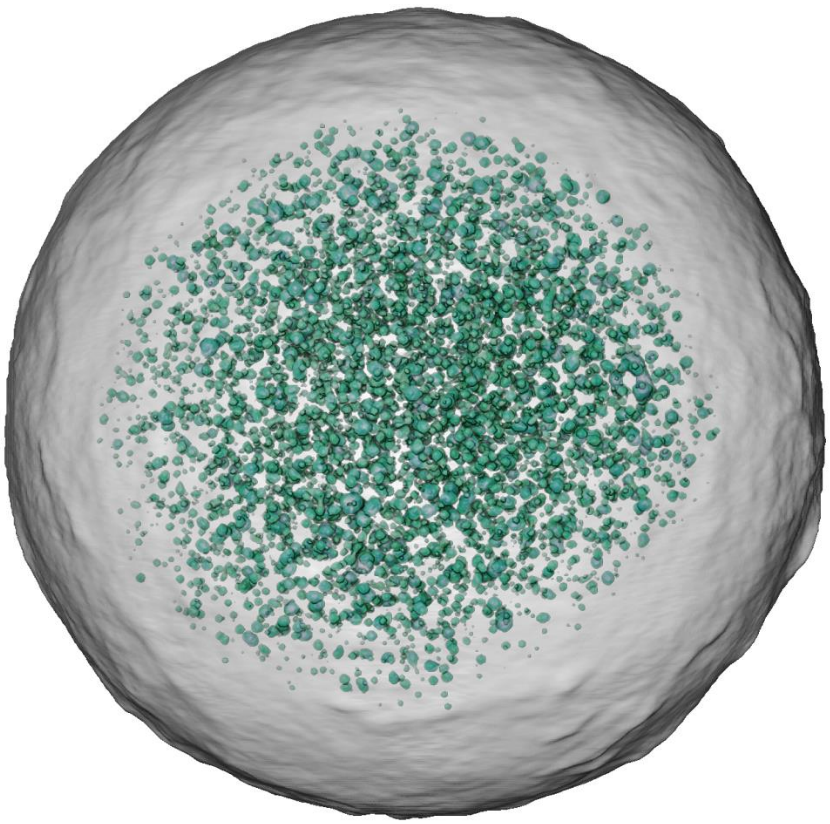

Figure 1. A transparent surface rendering of a neutron-irradiated TRISO coated particle fuel kernel and volume rendering of fission gas bubbles in the fuel matrix, derived from micro-XCT data. The equivalent spherical diameter of the kernel is ~ 454.6 µm [2].

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