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Separate Effects Testing in TREAT for ATF Fuels

G. Beausoleil, F. Cappia, and
L. A. Emerson

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Idaho National Laboratory
Originating Organization
Idaho Falls, Idaho 83415

http://www.inl.gov

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TEAM MEMBERS / COLLABORATORS

D. Murray, D. Sell, C. Christensen, A. Winston, D. Wahlquist, M. Bachhav, and B. Miller

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SUMMARY

This work performed examinations on high burnup UO_2 from commercial power plant with the intention of better understanding fission gas and fragmentation behavior. Fuel fragmentation, relocation, and dispersal (FFRD) is a major factor in fuel lifetime limits imposed on UO_2 by regulators, both domestic and foreign, and is a major area of interest by industry groups (e.g., Electric Power Research Institute [EPRI]). The characterization of the fuel focused on the differences in porosity between the high-burnup (rim) zone, the dark (intermediate) zone, and center zones of the fuel as well as the fission gas content of each region. Work involved thermal treatments to analyze fission gas and high resolution microscopy techniques to investigate pore structure.

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ACRONYMS

APT	atom probe tomography
CAES	Center for Advanced Energy Studies
EBSD	electron backscatter diffraction
EPRI	Electric Power Research Institute
FFRD	Fuel fragmentation, relocation, and dispersal
FIB	focused ion beam
HFEF	Hot Fuel Examination Facility
IMCL	Irradiated Materials Characterization Laboratory
INL	Idaho National Laboratory
LEAP	Localized Electron Atom Probe
LOCA	Loss of Coolant Accident
LWR	light water reactor
PFIB	plasma focused ion beam
SEM	scanning electron microscopy

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1. INTRODUCTION

This work performed examinations on high burnup UO_2 from commercial power plants with the intention of better understanding fission gas and fragmentation behavior. Fuel fragmentation, relocation, and dispersal (FFRD) is a major factor in fuel lifetime limits imposed on UO_2 by regulators, both domestic and foreign, and is a major area of interest by industry groups (e.g., Electric Power Research Institute [EPRI]). The characterization of the fuel focused on the differences in porosity between the high-burnup (rim) zone, the dark (intermediate) zone, and center zones of the fuel, as well as the fission gas content of each region. Work involved thermal treatments to analyze fission gas and high resolution microscopy techniques to investigate pore structure.

2. PROJECT DESCRIPTION

It is known that fuel pellet fragmentation appears to be largely driven by a rapid expansion of fission gas bubbles along grain boundaries, but quantitative assessment of the local gas inventory and related microstructural factors playing a major role in fuel fragmentation is still incomplete. The project focuses on the characterization of the initial local fission gas inventory and grain structure at different radial positions in high burnup fuel. This information is crucial to better interpret results from future integral Loss of Coolant Accident (LOCA) test planned on the same mother rod.

Fission gas measurement experiments will be used to assess the retained fission gas at different regions within the fuel. As UO_2 is irradiated within a reactor, the material forms three concentric zones with different appearance developed along the radius. These zones are referred to as the high burnup structure or the rim zone, the central zone of the fuel, and the intermediate zone between the rim and center, generally referred to as the ‘dark zone’ which can contain several sub-regions with variable bubble concentration. It is postulated that a significant amount of gas is retained in the dark zone and at intermediate radial positions, making these areas prone to fine fragmentation. The fission gas measurement experiment will utilize focused ion beam techniques to remove samples in radial increments so that the fission gas within each zone can be compared.

The fuel will also be characterized using scanning electron microscopy (SEM) techniques, including imaging and electron backscatter diffraction (EBSD) patterns as well as electron probe microanalysis (EPMA). The goal of this characterization will be to identify the fuel microstructure and porosity of each region. It is important to understand the statistics of the porosity, such as pore volume fraction and number density, so that the fission gas analysis can be meaningful. Understanding both enables researchers to analyze the pressures experienced by the fuel microstructure during an accident scenario.

3. ACCOMPLISHMENTS

In order to provide a thorough description of the as-irradiated microstructure, a combination of experimental techniques has been used to gather data from a polished cross section of LWR UO_2 fuel irradiated at 72 GWd/tHM average burnup. Detailed image analysis from SEM images acquired with a Backscattered Electron Detector has been performed along the pellet radius (Figure 1 & Figure 2). At the same time, EBSD patterns have been collected radially and correlated to the local gas inventory.

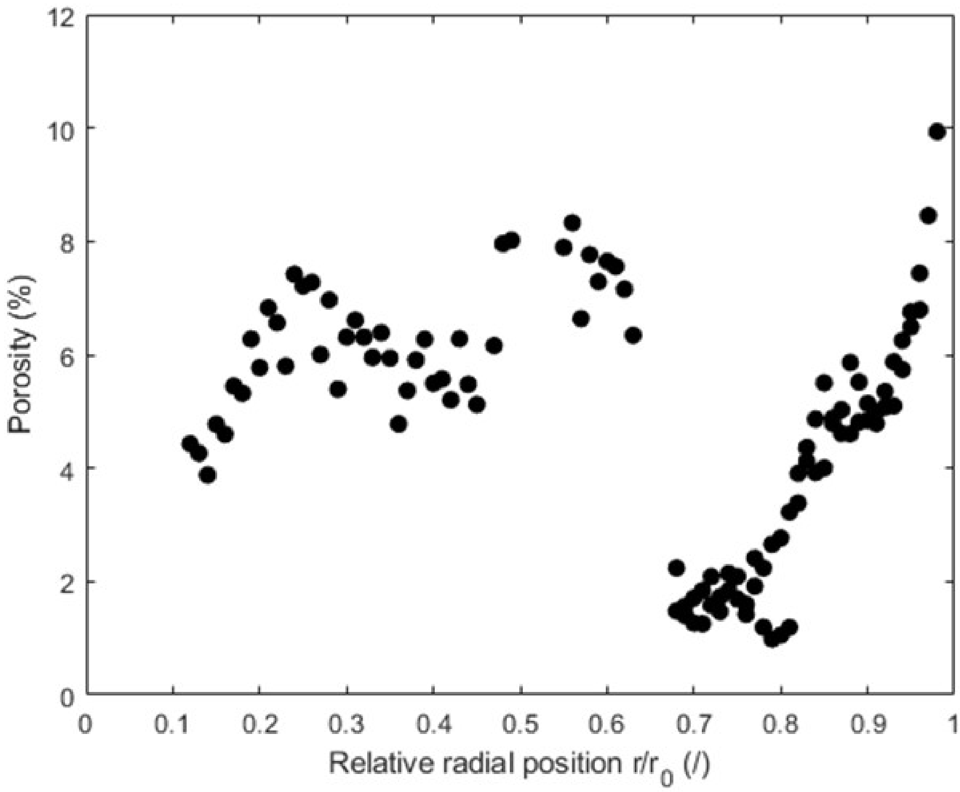

Figure 1. Measured radial porosity profile on a polished cross section. Fuel average burnup: 72 GWd/tHM.

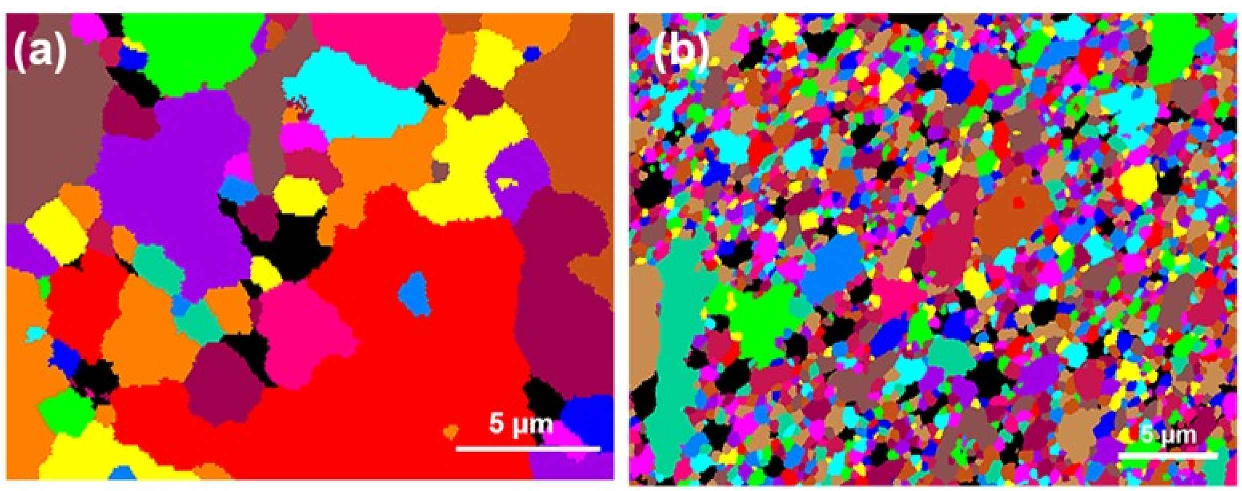

Figure 2. Selected EBSD maps at different radial locations: (a) pellet intermediate radial position (b) pellet rim.

The plasma focused ion beam (PFIB) at the Irradiated Materials Characterization Laboratory (IMCL) at Idaho National Laboratory (INL) was successfully used to mill out and remove large (~300 µm) cubes for fission gas examination. The team also successfully designed and fabricated air tight capsules capable of retaining the fuel samples during heat treatment. The cubes were placed within the capsules and subjected to 300°C heat treatments in both oxidizing and inert atmospheres. The oxidizing atmosphere was used to preferentially attack the grain boundaries of the samples and thus force the release of the grain boundary retained fission gas without inducing any significant transport or release of intra-granular retained fission gas. This was performed at the INL Hot Fuel Examination Facility (HFEF). After the heat treatments, the gas was collected and analyzed using gamma spectroscopy and gas mass spectrometry (Figure 3). That analysis is still ongoing.

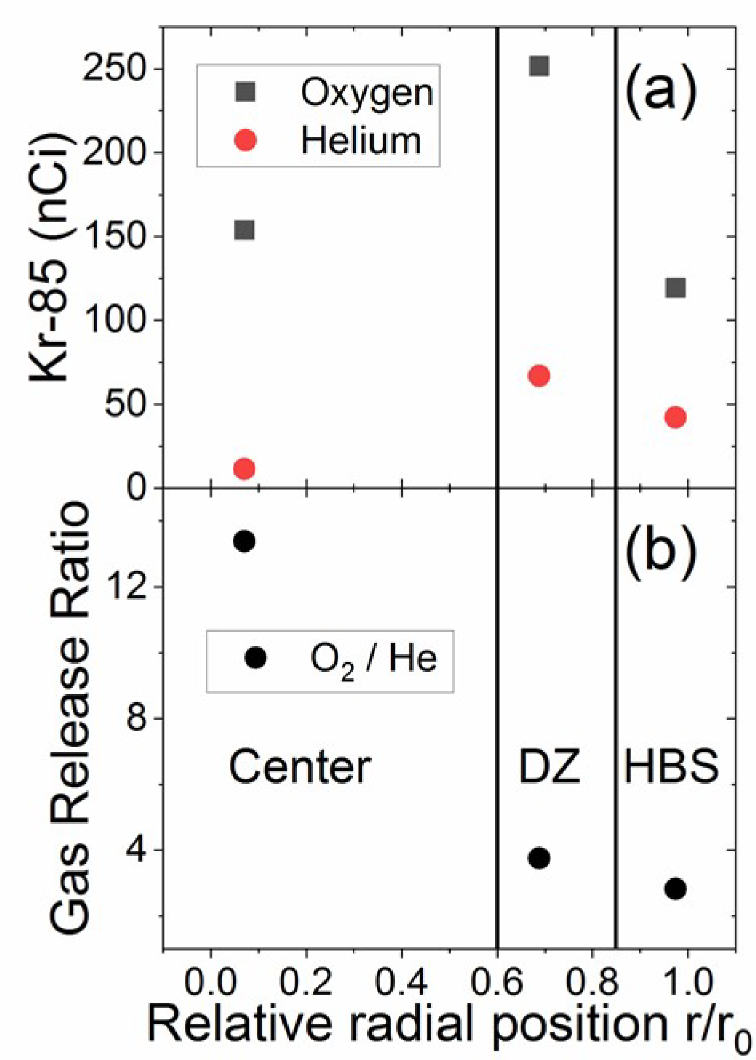

Figure 3. Kr-85 measured from oxidation study: (a) shows the comparison between capsules heat treated with O_2-He mixture and pure He. (b) shows the relative difference in the release quantity. The lines indicate the relative separation between the HBS, DZ, and center regions.

Radial composition and burnup characterization was also attempted using atom probe tomography (APT). The shielded FIB at IMCL was used to remove APT tips, and APT was performed using the LEAP system at the Center for Advanced Energy Studies (CAES). Performing APT on highly irradiated fuel is exceptionally challenging as porosity within the sample can cause the tip to fail catastrophically during mounting or measurement. A few tips were successfully measured from all three regions; however, additional investigation is required in order to corroborate present results and confirm identification of fission products. The presence of many fission products causes significant overlaps in the spectra collected, and the thermal tails in the fissile materials make signal deconvolution challenging (Figure 4).

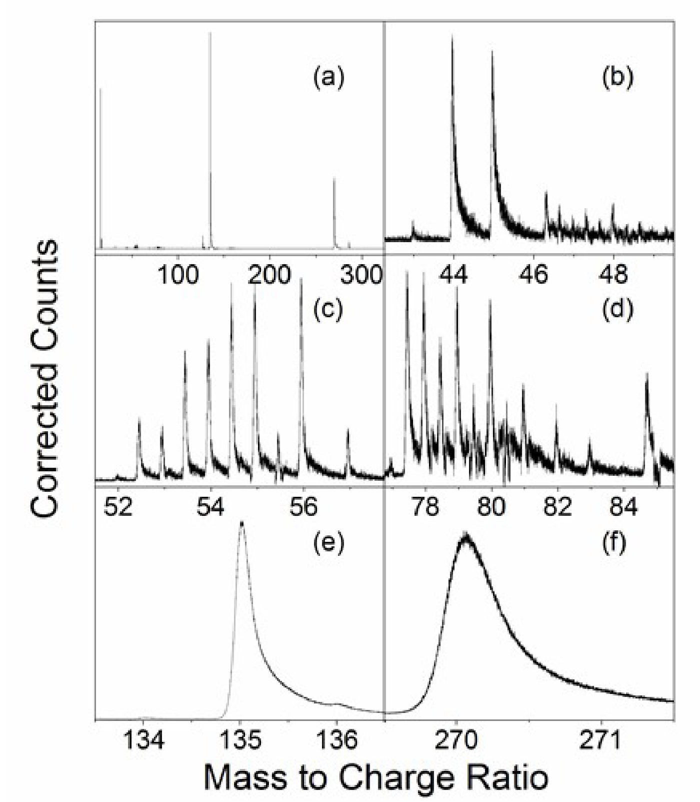

Figure 4. APT count corrected spectrum: (a) shows the full mass to charge spectrum (excluding hydrogen peaks). (b) through (d) shows fission product and U/Pu peaks. (e) & (f) shows UO & UO_2 peaks.