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Understanding Fission Gas Bubble Distribution and Zirconium Redistribution in Neutron-irradiated U-Zr Metallic Fuel Using Machine Learning

Fei Xu[1], Lu Cai[1], Daniele Salvato[1], Fidelma Dilemma[1], Jeffrey J. Giglio[1], Michael Benson[1], Daniel J. Murray[1], Cynthia A. Adkins[1], Joshua J. Kane[1], Min Xian[2], Luca Capriotti[1] and Tiankai Yao[1*]

[1.] Idaho National Laboratory, Idaho Falls, ID, USA.
[2.] University of Idaho, Idaho Falls, ID, USA.
* Corresponding author: tiankai.yao@inl.gov

U-10wt.% Zr (U-10Zr) based metallic fuel is the leading candidate for next-generation sodium cooled fast reactor in United States. Currently, Idaho National Laboratory (INL) has been the leading national laboratory for research, development, and demonstration (RD&D) on metallic fuel [1, 2]. Advanced post-irradiation characterization will help to understand fuel microstructure and property change during irradiation, benefiting fuel qualification for commercial application. Characterization capabilities ranging from sub-nanometer to micrometer, such as scanning electron microscopy (SEM), focused ion beam (FIB) sampling, transmission electron microscopy (TEM) characterization [1], and local thermal conductivity microscopy (TCM), have been utilized recently on irradiated U-10Zr fuel samples to gain a better understanding of nuclear fuel microstructure and property evolution inside a reactor.

The FIB/SEM coupled with energy dispersive X-ray spectroscopy (EDS) can capture the essential information to achieve better understanding of fuel behaviors. Inside a nuclear reactor, the phase and microstructure of U-10Zr is constantly changing under neutron bombardment. For example, the gaseous fission product atoms have a limited solubility inside fuel matrix and tend to precipitate out in bubble form, which not only contribute to fuel thermal conductivity degradation but also provide a shortcut for movement of fission products, i.e. lanthanides. The resultant deposition of lanthanides at the cladding inner surface will potentially trigger a chemical reaction/interaction between nuclear fuel and cladding at reactor operational conditions, threatening fuel integrity and safety. FIB/SEM coupled with EDS can provide the fission bubble information as well as probe into phase separation or Zr redistribution, which is fundamental to predict the fuel performance.

With high velocity image data generating method, such as FIB/SEM, an automatic way to extract the microstructural information quantitively can better serve the needs from post irradiation characterization. A trained machine learning model, named Decision Tree, is employed to generate a bubble classifier and to categorize bubbles into three categories: isolated bubble, connected without lanthanides, and connected with lanthanides bubbles[3]. This work presents a showcase of this approach on six regions of a fuel cross-section along the radial temperature gradient. We obtained distributions of bubble categories and porosity rates along the six regions. Moreover, a secondary phase U-Zr_2 was determined and found on regions 5 and 6. The secondary phase fraction was increasing from 15.61% in region 5 to 34.79% in region 6 based on this approach (Figure 1). This quantitative data offers insights into the lanthanide migration and potentially thermal conductivity degradation. This information from machine learning will be fed into fuel design code for better prediction of fuel performance.

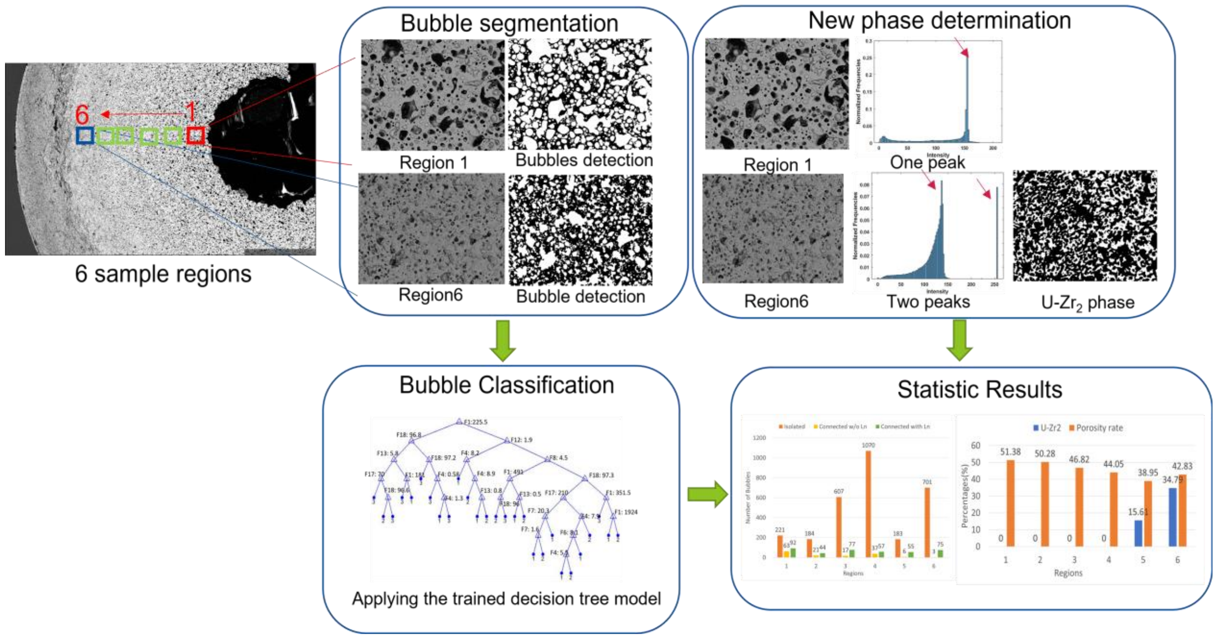

Figure 1. Workflow to obtain the quantitative microstructural information.

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[2] MT Benson et al., Journal of Nuclear Materials **544** (2021).
[3] L Cai et al., Materials Characterization **184** (2022), p. 111657.

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