Ceramic Materials for Nuclear Energy Applications

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Ceramic materials are essential to nuclear energy, which produces about 20% of the total electricity in USA and about 15% worldwide. Oxide nuclear fuels, such as UO_2 and mixed oxide (MOX), are the primary fuels used in the current commercial light water reactors; they are also fuel candidates in advanced reactors.¹ Various oxides that are similar to UO_2 in terms of crystal structure have been used as surrogates in research for fundamental fuel properties. Another important application of ceramics in nuclear energy is in the area of used fuel disposal for immobilizing and storing nuclear waste.² In addition, ceramics with superior mechanical properties and corrosion resistance at high temperatures, such as SiC, are promising candidates of fuel cladding for various fuels in various reactors, including accident-tolerant fuels in LWRs, TRISO fuel in high temperature gas-cooled reactors,³ and structural materials in fusion reactors.⁴ Ceramics can also be important for nuclear applications in an indirect way as corrosion products and impurities, such as carbides, in various structure materials. Given their critical technologic importance, extensive research efforts from both modeling and experimental sides have been paid to ceramics in nuclear energy applications, including fabrication, characterization, property measurement and prediction, as well as their performance in operation conditions.

This special topic presents several recent studies with a primary focus on the UO_2 fuel, including the anion diffusion properties in intrinsic UO_2 ,⁵ grain subdivision in UO_2 ,⁶ and the effects of second phase and fission gas on thermal transport.⁷ One study on the corrosion behavior of CrAlSiN coatings deposited on Zr alloy substrates⁸ is also included. Specifically, the following list summarizes the papers being published under the topic of “Ceramic

Materials for Nuclear Energy Applications.” To read or download any of the papers, follow the URL <http://link.springer.com/journal/11837/71/12/page/1> to the table of contents page for the December 2019 issue (vol. 71, no. 12).

- In the paper “Oxygen-18 Tracer Measurements of Anion Diffusion in Uranium Dioxide Thin Films” by Bernhardt et al.,⁵ the activation energy for anion diffusion in both textured and single crystal UO_2 thin films is measured using the O^{18} tracer. A much lower activation energy is obtained in unirradiated thin films than in stoichiometric bulk UO_2 . According to the authors, the low activation energy indicates that in these thin films, due to their hyper-stoichiometric nature, anion self-diffusion is dominated by the interstitial mechanism instead of the vacancy mechanism in stoichiometric bulk UO_2 . The effect of irradiation on anion diffusion in these thin films is also investigated.
- In the paper “Mesoscale Modeling of High Burn-Up Structure Formation and Evolution in UO_2 ” by Abdoelatef et al.,⁶ the authors present their phase-field model for modeling the formation of a high burnup structure (HBS) in UO_2 fuel, which is a grain subdivision process driven by accumulation of radiation-induced defects such as dislocation loops. According to the authors, the model considers the effects of dislocation density, grain boundary energy, and bubble properties on the HBS formation. The authors also use the model to predict the resulting grain size at high burnups.
- In their paper “An Experimentally Validated Mesoscale Model of Thermal Conductivity of a UO_2 and BeO Composite Nuclear Fuel,” a mesoscale model is developed by Badry et al.⁷ to describe the thermal conductivity of a UO_2 and BeO composite nuclear fuel. The effects of the second-phase (BeO) fraction and morphology, temperature, and interface thermal resistance were investigated. According to the authors, their model predicts that, with the

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same total volumetric fraction, the continuous second-phase configuration gives a higher effective thermal conductivity than the dispersed second-phase configuration. Good agreements with experimental data are shown in the paper. The work also calls for the need to quantify the Kapitza resistance of phase interfaces.

- Zhu et al.,⁸ in their paper “Effect of Cr/Al Atomic Ratio on the Oxidation Resistance in 1200°C Steam for the CrAlSiN Coatings Deposited on Zr Alloy Substrates,” studied the corrosion behavior of CrAlSiN coatings deposited on Zr alloy substrates by performing a steam oxidation test at 1200°C. According to the authors, a strong effect of the Cr/Al atomic ratio is identified. A Cr/Al ~ 3.1 coating was found to be able to provide effective protection for its Zr alloy substrate in 1200°C steam for 6 h, where a dense and homogeneous Cr₂O₃/α-Al₂O₃ bilayer scale was evidenced in the whole process. The protection effect degrades significantly with lower Ar/Al ratios of 1.3 and 0.6, pointing out the importance of the Cr/Al mass ratio.

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