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Multiscale Modeling and Experiments for Investigating High Burnup LWR Fuel Rod Behavior Under Normal and Transient Conditions

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ABSTRACT:

The main objective of this work is to achieve a mechanistic understanding of and to develop a predictive model for LWR fuel rod behavior at high burn-up (HBU) under both normal and transient conditions. To improve economy and efficiency of electricity production, the U.S. nuclear industry is considering increasing the fuel peak burnup (BU) beyond the current regulatory limit of 62 GWD/MTU. The Nuclear Regulatory Commission (NRC) will likely require nuclear power plants (NPPs) to analyze a number of design basis accidents (DBAs) and their potential consequences before such extension can be approved. A major factor in analyzing such scenarios is the behavior of fuel rods at HBU. It is well-established that for LWR fuels, the fission gas release rate and probability of fuel fragmentation increase considerably at HBU, particularly during thermal transients associated with DBAs. *This occurred across all reactor types, vendor supplied fuel and fuel cycle management*. This results in an increase in fuel rod internal pressure that triggers ballooning and rupture of claddings. Moreover, fuel fragments may escape from the rupture opening, complicating the cooling process and potentially worsening the radiological consequences of an accident. Nonetheless, the underlying mechanisms by which these processes take place are still poorly understood. Nevertheless, there is a consensus that the drastic change of microstructure across the fuel pellet during normal operation through the transient holds the key for understanding these mechanisms. *By combining multiscale modeling and quantitative characterization and measurements, this project will investigate the effects of the pellet heterogeneous microstructure and transient conditions on the performance of fuel rods at HBU*. The research outcomes are expected to i) provide novel data on the pellet microstructure at HBU, ii) develop an experimentally validated multiscale model that accounts for the effects of microstructure and transients on the enhanced fission gas release and fuel fragmentation at HBU, iii) advance the fundamental understanding of the change of fuel rod internal pressure with burnup, and iv) advance the fundamental understanding of the change of fuel fragment size with burnup. *The predictions of this multiscale approach will be validated using data generated in this project and from open literature on same HBU fuel rods before and after loss-of-coolant accident (LOCA) testing*. These outcomes will improve the predictions of existing fuel relocation and dispersion models and cladding ballooning and rupture models. Hence, this *study will provide the nuclear industry with validated, physics-based criteria for fuel fragmentation thresholds and rod mechanical integrity limits.*

While this project will mainly focus on the current UO_2 and Zircaloy fuel-clad system, *primary investigations of the* Cr_2O_3*-doped* UO_2 *and Cr-coated Zircaloy accident tolerant fuel (ATF) concept will also be conducted*. These investigations will, however, be limited in scope to parametric studies focusing on identifying the safety margin of this new concept. This will guide future modeling and experimental efforts for ATF concepts to focus on determining the most influential parameters.