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The Influences of Neutron Irradiation on Aggregate Induced Degradation of Concrete

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ABSTRACT: Reactor cavity concrete, the primary support structure for the reactor pressure vessel (RPV), is exposed to neutron-and-gamma radiation during normal operation in nuclear power plants (NPPs). Neutron radiation can interact with the concrete's constituents, especially the mineral aggregates, and damage these, more so during Long Term Operation (LTO). Given the potential risks, and the paucity of knowledge therein [*], there exists a significant need to understand/quantify the impacts of irradiation on concrete degradation. This research develops new understanding of the evolutions, and manifestations of irradiation assisted aggregate (concrete) degradation caused by neutron exposure. Emphasis is placed on elucidating: (a) how aggregates can undergo volume changes, often expanding with increasing irradiation and the resultant implications on concrete microcracking and (b) how benign (innocuous) aggregates, up on neutron exposure, undergo atomic-scale disordering, thereby enhancing their reactivity, and chemical degradation. Rigorous insights into such processes is informed by molecular dynamics (MD) simulations, and nanoscale quantifications of mineral and aggregate dissolution rates in caustic aqueous environments. Simulations of ballistic collisions (of energetic particles with lattice atoms), and their impacts on altering the atomic topology/networks of minerals are used to explain and highlight the risks of mechanical and chemical degradation of aggregates, and concrete. New understanding of this nature is applied to develop an inclusive physics/chemistry/mechanics based degradation model for concretes exposed to neutrons, which considers aspects of: (i) chemical reactions (dissolution and precipitation), (ii) mass/ion transport, and (iii) microstructure-specific damage evolutions. The models developed are nested within GRIZZLY, a MOOSE application and benchmarked/validated/verified against expansion data acquired on concrete formulations experiencing alkali-silica reaction (ASR) – an analogous form of concrete degradation that occurs in the absence of irradiation. This work logically informs the sensitivity of minerals to irradiation, thus highlighting power-plant and concrete profiles that would be subject to such degradation risks.

OBJECTIVES: This research works towards three main objectives:

[1] To quantify the impacts of damage cascades, caused by irradiation on aggregate amorphization, and volume change in relation to the aggregate mineralogy, composition and radiation dosage,

[2] To correlate atomic-scale alterations/amorphization of aggregates, to the increase in their reactivity (dissolution) in high pH solvents at sub-boiling temperatures ($T<95°C$). This includes describing the rate/extent of precipitation of expansive products (e.g., Ca/Na/K-gels) following dissolution, and,

[3] To model the chemo-mechanical manifestations of aggregate dissolution and product precipitations in a microstructural reaction-transport environment, and describe evolutions of damage in concrete, e.g., similar to damaging alkali-silica reaction (ASR) that develops in traditional concrete.

The prediction tools developed will establish degradation risks of nuclear power plant (NPP) concretes, in relation to the aggregate mineralogy and nature of radiation exposure (i.e., incident energy and neutron fluence). Such platforms will enable owners, operators and regulators to assess/mitigate aging concerns.

* Graves, H., Le Pape, Y., Naus, D., Rashid, J., Saouma, V., Sheikh, A., and Wall, J., Technical Report: NUREG/CR-7153, ORNL/TM-2011/545. U.S. Nuclear Regulatory Commission, 2013