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Chemo-Mechanical Degradation of Nuclear Graphite in Molten Salt Reactors

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ABSTRACT:

Graphite is the second most abundant material (by volume) in the cores of Fluoride-Salt-Cooled High-Temperature Reactors (FHRs) and Molten Salt Reactors (MSRs). In addition to its favorable scattering and absorption cross sections, graphite has excellent mechanical and thermo-physical properties, which allow it to maintain structural integrity at very high temperatures compared to metals, yielding major benefits for reactor safety. Nevertheless, graphite properties are affected, in some cases irreversibly, by temperature transients, applied stresses, radiation, chemical environment, and their combinations. As a result, graphite components used in nuclear reactors are subject to continuous degradation mechanisms, which can impact their functional performance and shorten their lifespan.

Chemical reaction of defect-free, infinite graphite with fluoride salts at the target FHRs and MSRs redox potentials is not thermodynamically favorable. Nonetheless, there is evidence of fluorination of graphite upon exposure to fluoride salts at high temperature. These experiments show that, although most carbon atoms in graphite are inert, there exists a subset of reactive carbon sites (RCS) that can react with the major constituents and impurities in the salt. RCS consist of dangling carbon atoms at crystallite edges and crystallographic defects in the bulk and can be produced, among other ways, upon cracking under a mechanical load. At the same time, graphite's fracture can be impacted by the molten salt. Recent experiments demonstrate changes in mechanical behavior resulting from chemical reactions of the graphite with the fluorine species and from intrusion of salt in graphite pores. The changes in lubrication and intrusion-resistance in presence of reactive fluorides, oxygen, or moisture also suggest that graphite's chemo-mechanical behavior is impacted by the composition of the salt and the cover gas.

These instances demonstrate an interdependency of chemical and mechanical behaviors for graphite in salt. This interdependency is not unique to graphite and has been observed in other materials (especially metal alloys) and environments. Previous work on structural alloys has established a suite of standards and techniques to test and simulate the interconnected effects of stress and corrosion at high-temperature. Nevertheless, none of these studies, nor others in literature, discuss these coupled phenomena in graphite. This proposal aims to directly address this gap, investigating chemo-mechanical degradation of graphite in molten salts, leveraging methods previously developed to study structural alloys. Through a combination of experimental and modelling activities, we aim to answer four research questions:

1. How does graphite chemical reactivity towards species in the salt change under a mechanical load?
2. How are graphite mechanical properties impacted by the presence of the salt at high-temperature?
3. What is the effect of salt chemistry and cover gas composition on the coupled chemo-mechanical behavior?
4. How does chemo-mechanical degradation impact graphite components' lifespan in the reactor?