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The particulate nature of the crud source term in light water reactors

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Abstract

Knowledge of the mechanism of crud deposition in light water reactors is key to modeling its growth and effects. Empirical and mechanistic models of crud exist throughout the literature, yet the argument persists whether the crud source term results from soluble or particulate species. Here it is shown that the crud source term must be principally particulate in nature, as soluble deposition mechanisms cannot account for crud thicknesses observed in reactors.

Keywords: crud, deposition, source term

Framing the Problem

The buildup of fouling deposits known as crud¹ continues to affect the light water reactor (LWR) industry by causing operational issues, some unexpected, others requiring fuel costs by up to \$2M per plant. Crud induces axial power shifts [2, 3] which can mandate power reductions as low as 70% [4], it can induce localized corrosion and fuel failure [5, 6], and increases radiation dose rates to primary side out-of-core surfaces [7]. Despite decades of changes in fuel loading patterns [8], detailed analysis of crud deposits in PWRs [9, 10] and similar experimental loops [11, 12], and advances in ultrasonic cleaning of fuel [13, 14], the issue of crud has not yet been eliminated. This is partially due to our lack of understanding of the mechanism of crud buildup, particularly in pressurized water reactors (PWRs). Arguments through the open literature [15, 16, 17] and in industry [18, 19, 20] abound as to whether crud is principally formed from soluble species in the PWR coolant, particulate oxide species, or both.

The coolant-facing surfaces of PWRs are comprised of nickel-based alloy steam generators (600 or 690) and iron-based alloy piping (typically 304 stainless steel) [21], containing much nickel, iron, and chromium. These materials are all passivating [22], rapidly growing a thin, dense, and protective layer of oxides slowing corrosion. However, passivated materials do not cease to corrode, they

simply corrode at a far lower rate. This slow corrosion rate, coupled with the high internal surface area in PWRs (up to 25,000 m² in the steam generators [23]), releases a non-negligible amount of metals into the PWR coolant. The roughly 138 m³ of water comprising the PWR coolant [21] serves as both the dissolution and the transport medium for these metals, most of which ultimately end up as crud deposits on the fuel rods [16].

The sub-cooled boiling occurring on PWR fuel rods causes microlayers of fluid to become trapped underneath vapor-filled bubbles [16, 18]. In this process, a rapidly expanding bubble traps a fluid microlayer which dries out, leaving behind any soluble and/or particulate species to deposit as crud. This process repeats, forming initial deposits of crud which evolve into the boiling chimneys most typical of crud deposits [11]. The density of nucleation sites, bubble departure frequencies, and concentrations of crud precursors in the fluid microlayers are what determine the growth rate of crud in this early stage. At later stages, an upper bound on the crud growth rate is set by the mass flux of water into the crud, itself determined by the evaporative heat flux of water within the crud. As the crud gets thicker, PWR coolant containing soluble species such as boric acid and crud precursors, both soluble and particulate, is continuously drawn into the crud [4, 16], with only water and some boric acid leaving due to its relatively high vapor pressure [24].

Rationale and Calculations

If crud were to deposit from soluble species alone, then the solubility of nickel and iron in the PWR coolant would be the rate limiting step in transporting metal from the PWR internals

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¹Crud is a backronym for Chalk River unidentified deposits. While its etymology was recently debunked [1], its deleterious consequences continue to affect the LWR industry.

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