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Review

Material corrosion in a reactor containment sump following a loss-of-coolant accident

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A B S T R A C T

The present study conducts a critical review of relevant research that pertains to Generic Safety Issue 191 (GSI-191) and the chemistry and corrosion behavior of the various materials present in the containment sump of a pressurized water reactor (PWR). Thermodynamic simulations, integrated tests, and benchtop tests have determined the structure of the potential precipitates that may clog the sump strainer and cause a failure of the emergency core cooling system (ECCS). Based on this research, it was determined that the available research has been insufficient in terms of simulating the transient temperature behavior in the containment sump in the post loss-of-coolant environment. Research gaps are identified, and recommendations for future research are presented.

1. Introduction

In 1992, a loss-of-coolant accident (LOCA) occurred at the Barsebäck nuclear power plant in Sweden that led to degradation of the emergency core cooling system (ECCS) due to plugging of the sump pump (Potential Plugging, 1996). This accident led the U.S. Nuclear Regulatory Commission (NRC) to examine sump strainer performance in reactors in the United States. Initial research was conducted for boiling water reactors (BWRs) because the unit at Barsebäck was a BWR. It was found that the problem could be avoided by simply removing any fibrous material not rated to withstand LOCA conditions and enlarging the strainer surface area (Zigler et al., 1995).

Although BWRs were able to quickly address the problem, pressurized water reactors (PWRs) could not do so because of the major differences between BWR and PWR containment designs. This led the NRC to issue Generic Safety Issue 191 (GSI-191), Assessment of Debris Accumulation on Pressurized Water Reactor Sump Performance, several years later. In 2008, the NRC issued additional guidance as to how power plants should ensure further confirmatory research into the findings of GSI-191 (Fard and Reisi, 2011). This was due largely in part to the complexity of the problem. This confirmatory research will help establish an adequate technical basis so that the corrective actions can be deemed complete and sufficient for each affected power plant.

The confirmatory research included several integral tests aimed at validating thermodynamic simulations and truly describing the chemical effects present in this environment. The most in depth of these tests was the Integral Chemical Effects Test (ICET) loop, which was constructed at the University of New Mexico (UNM) and overseen by Los Alamos National Laboratory. This apparatus was later utilized for the Chemical Effects Head Loss Experiment (CHLE) (Howe et al., 2012).

Although the integral tests were imperative in generating experimental data, very little experimental work has been done to understand and validate the corrosion rates and chemical stabilities produced from thermodynamic simulations for each common containment sump material. In the present study, the status of GSI-191, including its relevant supporting research to understand the corrosion and chemistry of the various containment sump materials in the environment of the sump following a LOCA, is critically reviewed, and research gaps are identified for solving the complex problem of GSI-191 in a risk-informed manner.

2. Relevant research in support of GSI-191

The first major details of relevant data related to GSI-191 regard the description of the containment environment following a LOCA. Water from the primary systems of the reactor is ejected at temperatures of a maximum of 315 °C and at pressures of 15.17 MPa

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(2200 psi). In the transient process, the maximum sump temperatures can approach 130 °C and the maximum gauge pressures can reach 0.25 MPa (36 psi). Once the containment environment has reached equilibrium, temperatures of up to 55 °C and atmospheric pressures are observed (Rao et al., 2002). As for the water itself, PWRs utilize borated water in the primary loop for reactivity control. This boron is in the form of boric acid, so the initial water is slightly acidic. The pH of the primary water is balanced by the rate of boric acid and lithium hydroxide injection through the chemical shim system. In the event of a LOCA, the chemical shim system will not be functional, so the acidity needs to be controlled in a different manner within the containment. This containment pH control chemistry is plant specific, and may contain either lithium hydroxide or sodium hydroxide as the major pH controller, which is introduced via spray systems, or have buffers of either hydrated trisodium phosphate (TSP), or hydrated sodium tetraborate that exist as dissolvable powders in the sump (Dallman et al., 2006).

Various thermodynamic simulations were run to support GSI-191 research. These simulations were summarized by Jain et al. (2005, 2004) and McMurray et al. (2006). In general, the thermodynamic simulations were able to perform several calculations:

- Aqueous speciation and saturation calculations
- Precipitation reactions
- Calculations at standard and elevated temperatures
- Aqueous processes at ionic strengths up to 0.5
- Maintain fixed conditions if deemed necessary

These types of calculations can be performed by several different thermodynamic codes, so runs in each code were made and compared. Although there were differences in the code outputs, the order of magnitude for each output was usually similar. From these various simulations, the expected species expected to precipitate out of solution were determined. In addition to determining the type of solids produced, the amount of precipitate that could be dissolved in solution at a pH level of 10 was also calculated. The results are provided in Table 1. For plants using non-alkaline buffers, such as TSP, the species of precipitates was similar. The results for these plant types are provided in Table 2.

Tables 1 and 2 indicate that the major contributors to potential sump clogging are due to silicates, phosphates and hydroxides. Jain's simulations also showed that the pressure transient caused no significant differences in these predictions because little difference was observed between high and low pressure tests (Jain et al., 2005).

In addition to simulations, a number of integral chemical effects tests were conducted. Several of the most in depth of these tests were run using the ICET loop at UNM. These tests were able to recreate the containment sump environment at the post-LOCA steady state conditions of 55 °C and atmospheric pressure. Corrosion was facilitated and various precipitates could be identified. In fact, a gel-like substance was found at the bottom of the reaction tank following tests that incorporated TSP as the main pH buffer. It was determined that this gel was mainly composed of $Ca_3(PO_4)_2$ (Dallman et al., 2006). In general, the majority of the precipitates that were found were from the fiberglass insulation itself, or from the aluminum. It was also determined that the silicon and calcium from the fiberglass inhibited corrosion in the aluminum, thus limiting precipitate formation in the high-pH tests (Dallman et al., 2006). In addition to characterizing the chemistry of the solution following 30 days of tests, the particle size distributions in solution were also analyzed. The distributions were in the range of 1–100 μm, and the mean particle size varied with each test.

Table 1
Expected precipitates in alkaline solutions at various temperatures (Jain et al., 2004) (McMurray et al., 2006).

Precipitate chemical formula	Percent in solid phase at 60 °C (%)	Percent in solid phase at 90 °C (%)	Percent in solid phase at 110 °C (%)
$NaAlSi_3O_8$	90.2	84.2	79.7
$Ca_2Mg_5Si_8O_{22}(OH)_2$	8.7	15.6	16.8
$Fe_3Si_2O_5(OH)_4$	26	N/A	N/A
$ZnO\cdot Fe_2O_3$	0.03	N/A	N/A
Fe_3O_4	N/A	12	N/A
Zn_2SiO_4	0.36	0.09	0.66
Mg	100	100	100
Al	100	100	100
Si	35	32	32
Ca	8	17	19
Zn	63	39	81
Fe	75	87	98

Table 2
Expected precipitates in neutral solutions at various temperatures (Jain et al., 2004) (McMurray et al., 2006).

Precipitate chemical formula	Percent in solid phase at 60 °C (%)	Percent in solid phase at 90 °C (%)	Percent in solid phase at 130 °C (%)
$NaAlSi_3O_8$	28	26	25
$Ca_5(OH)(PO_4)_3$	67	64	63
$Fe_3Si_4O_{10}(OH)_2$	N/A	9	1
$Fe_3(PO_4)_2\cdot 8H_2O$	5	N/A	N/A
$ZnO\cdot Fe_2O_3$	N/A	N/A	4
Fe_3O_4	N/A	N/A	10
Mg	0	0	0
Al	100	100	100
Si	29	36	29
Ca	96	99	99
Zn	0	22	72
Fe	38	82	96

Experimental tests were also conducted in small benchtop loops to measure the potential head loss across the sump strainer. Pacific Northwest National Lab (PNNL) operated multiple tests to relate any chemical effects to the measured pressure drop (Enderlin et al., 2006). At most, the pressure drop was measured to be 15 kPa (2.2 psi), with minimum drops of 2 kPa (0.3 psi). It was found that these pressure drops were extremely dependent on the material preparation, what order the debris material is placed on the screen, and the amount of material placed on the screen. The approach velocity also played a large role in the variability of the pressure drop. Although a pressure drop was measured, the drop (15 kPa) is very small, and may not lead to an ECCS failure like that seen at the Barsebäck plant.

Based on the results, or rather lack thereof, from the ICET and PNNL experiments, some major factors could have been overlooked in the past NRC funded reports. Since most of the tests have been isothermal, it is postulated that the temperature transient seen during a LOCA could be such a missing factor.

3. Chemistry and corrosion of reactor sump materials

Corrosion, in its various forms, has been studied since the early 1900s, with most interest coming during and after the 1950s and 1960s. Thus, the basic thermodynamics of corrosion are well understood. However, corrosion that takes place in extreme and complex environments, like that of the containment sump following a LOCA, is not well known. In fact, many of the materials present in the containment sump have little experimental data on corrosion for the post-LOCA environment; most of the current data are obtained from running thermodynamic simulations.

As the materials in the containment sump corrode, it is possible for the corrosion products to chemically react in the solution and