RESEARCH INFORMATION LETTER 0701

RESEARCH ACTIVITIES COMPLETED TO INFORM THE RESOLUTION OF GENERIC SAFETY ISSUE (GSI) 191

Abstract

This research information letter (RIL) describes a series of research projects, sponsored by the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), to study the effects of post-loss-of-coolant-accident (post-LOCA) containment pool environments on emergency core cooling system (ECCS) performance at pressurized-water reactor (PWR) power plants. Staff members from several national laboratories, private research facilities, and the NRC conducted the various research projects. The knowledge developed through these projects is used to inform the resolution of Generic Safety Issue (GSI) 191, "Assessment of Debris Accumulation on PWR Sump Performance."

The GSI-191 research focused on the ECCS performance phenomena of (1) chemical reactions occurring within post-LOCA containment building pools, (2) increase in sump screen head-loss attributable to chemical reaction products and/or particulates deposited on a fiberglass-laden sump screen, (3) downstream effects of insulation debris bypassing sump screens, and (4) transportability of coating debris. Ten research projects, culminating in seven NUREG-series reports and three letter reports, were conducted to characterize the post-LOCA chemical environment, identify the significant chemical reactions, study chemical effects on sump screen blockage, and document the peer-review of the chemical effects research. Four NUREG-series reports documented research on the accumulation behavior of insulation debris on sump screens, characterized the head-loss across fiberglass insulation (NUKON®) debris beds in combination with chemical precipitates, calcium silicate (CalSil) insulation, and/or coating chips and developed a calculation method for predicting head-loss across a fiberglass/CalSil debris bed. Two NUREG-series reports documented the research projects that examined the propensity for insulation debris to bypass the sump screen and studied the effect of the bypassed material on surrogate downstream throttle valve performance. In addition, one NUREG-series report documented the research project that characterized the water transport properties of chips prepared from five different coating systems that are typically used inside PWR containment buildings.

These research projects demonstrated that, under certain combinations of containment pool chemical and debris environments, ECCS performance may be adversely affected during sump pool recirculation.

Background

During the 1990s, a series of incidents at boiling-water reactor (BWR) nuclear plants resulted in degraded ECCS suction strainers, prompting the NRC to issue a number of bulletins requesting that BWR licensees implement appropriate measures to minimize the potential for clogging the ECCS strainers with accumulated debris following a LOCA. Subsequent research, conducted to support resolution of the BWR strainer clogging issue, raised questions concerning the adequacy of the PWR sump designs. In response to these questions, in 1996, the NRC opened GSI-191 to determine whether PWR ECCS sumps are adequate to ensure proper ECCS and containment spray system (CSS) operation in the recirculation mode during LOCAs or other high-energy line-break accidents for which sump recirculation is required. As part of the GSI resolution, the Advisory Committee for Reactor Safeguards (ACRS) recommended (in a letter dated September 30, 2003) that an adequate technical basis be developed to resolve sump performance issues related to chemical reaction products formed in the post-LOCA sump pool.

The technical assessment of GSI-191 concluded that, in general, PWR containment buildings contain a variety of insulating materials, metals, protective coatings, and concrete that interact in the post-LOCA containment pool to form products that can affect ECCS and CSS performance. Borated water, injected by safety systems and expelled from the reactor coolant system through a postulated break, can react with dislodged insulation materials, unprotected metals, coatings, concrete, and sump pool buffering agents to form various chemical byproducts in the sump pool, which can precipitate and transport to the sump screen. In addition, loose and eroded coating debris, miscellaneous latent debris, and dislodged insulation material can be transported to the sump screen where they can accumulate and block recirculation flow. Further, debris bypassing the screens can affect the performance of downstream components.

Therefore, after completing its technical assessment of GSI-191 in June 2003, the NRC issued Bulletin 2003-01, “Potential Impact of Debris Blockage on Emergency Recirculation at Pressurized-Water Reactors.” That bulletin requested an expedited response from PWR licensees regarding the status of their compliance with regulatory requirements based on a mechanistic evaluation of the ECCS and CSS recirculation functions. In addition, on September 13, 2004, the NRC issued Generic Letter (GL) 2004-02, “Potential Impact of Debris Blockage on Emergency Recirculation During Design-Basis Accidents at Pressurized-Water Reactors,” to request that all PWR licensees perform an evaluation to demonstrate acceptable performance of the ECCS and CSS during sump recirculation following a LOCA.

To support the staff’s review of the anticipated licensee responses to GL 2004-02, the agency initiated research in technical areas where additional knowledge was thought to be required.

Research Initiatives

To better understand the effects of debris accumulation on PWR sump screens, the staff initiated research in the following four primary areas; (1) post-LOCA chemistry, (2) sump screen head-loss, (3) downstream effects, and (4) coating debris transport. The chemical research programs focused on characterizing and quantifying chemical reaction products that could form in a representative post-LOCA PWR containment environment, as well as evaluating the ability of commercially available computer codes to adequately predict the formation of byproducts of sump pool chemical reactions. The head-loss research evaluated the pressure drop across a sump screen attributable to the accumulation of fine particulates, insulation fibers, latent debris, and chemical byproducts observed in the chemical reaction tests. The downstream effects experiments examined the quantities of various sizes and types of insulation debris that could pass through the screen under a variety of flow conditions, and studied the effect of the debris on surrogate throttle valve performance and potential to clog. The coating debris transport test examined the settling and transport characteristics of coating debris in both stagnant water and water flowing at various velocities.

Conclusions

Chemical interaction experiments demonstrated that the dissolution of unprotected metals and CalSil insulation can occur in typical sump pool environments and can react with containment pool constituents to form precipitates that, in combination with debris, can increase the head-loss across the sump screens. Evaluation of five commercially available thermodynamic simulation codes demonstrated that extensive benchmarking is necessary to ensure that the predicted sump pool chemical reactions are accurate. More rigorous consideration of applicable kinetic effects is also required to improve the accuracy of the codes. Head-loss experiments revealed that calcium silica debris or small quantities (5 parts per million) of aluminum oxyhydroxide precipitates, in combination with a fiberglass debris bed, can cause significant pressure drop across the sump screen. The screen bypass experiments demonstrated that fiberglass, reflective metal, and CalSil insulation material can bypass the sump screens. Smaller, finer debris is substantially more likely to bypass the screens, regardless of the flowing water velocity under the conditions studied. Throttle valve head-loss experiments demonstrated that, under certain conditions, insulating materials resulted in partial or significant blockage of the surrogate throttle valve flow area even at high volumetric flow rates (75 gpm). In addition, coating transport experiments demonstrated that, at stream velocities of 0.06 m/s (0.2 feet/second) or less, the transport of coating chips is not significant.

The following sections briefly summarize the key findings for each of the research projects identified above. These summaries are grouped by research topic, and identified by the related NUREG-series or letter report.

Post-LOCA Chemistry

NUREG/CR-6868, "Small-Scale Experiments: Effects of Chemical Reactions on Debris-Bed Head-Loss," Los Alamos National Laboratory, March 2005

The small-scale tests conducted in this Los Alamos National laboratory (LANL) study addressed whether chemical interactions between the borated ECCS/CSS water, sodium hydroxide buffer, and exposed materials can affect post-LOCA debris generation and sump screen head-loss in PWR containment buildings. Notably, these tests confirmed that temperature-dependent corrosion of zinc metal can cause additional pressure drop across fibrous debris beds. In addition, the tests demonstrated that gelatinous material can transport to the PWR sump screen, where it can increase the head-loss across a fibrous debris bed. Despite these results, which demonstrated that harmful chemical products can form in the sump pool, the peer reviewers concluded that the results may not provide a complete understanding of sump pool chemistry because of the multitude of chemicals that are typically present in the sump pool. The Integrated Chemical Effects Test (ICET) research (NUREG/CR-6914) was initiated to address this peer review feedback.

NUREG/CR-6873, "Corrosion Rate Measurements and Chemical Speciation of Corrosion Products Using Thermodynamic Modeling of Debris Components to Support GSI-191," Center for Nuclear Waste Regulatory Analyses, April 2005

This report documents the results of experiments conducted by the Center for Nuclear Waste Regulatory Analysis (CNWRA) to determine corrosion rates for metals and leaching rates for concrete and fiberglass, which were used as input parameters to a thermodynamic model. The report also identifies the assumptions and simplifications considered in the simulation modeling.

One notable simplification is that the model does not consider reaction kinetics, which may affect the types and amounts of chemical species that form. However, these initial thermodynamic simulation results indicate that (1) chemical interactions could lead to the formation of gelatinous products following a LOCA; (2) the important parameters for solid formation include solution pH and temperature (among others); and (3) the presence of low-density fiber insulation, aluminum, and concrete influences precipitation of chemical species. In addition, this report provides some initial understanding of the evolution of solution chemistry and the formation of solid phases in the ongoing ICET program. However, a better understanding of the impact of modeling assumptions and simplifications, including the effect of reaction kinetics, is necessary and could be obtained by comparing simulation results with ICET observations. The staff is conducting follow-on research to evaluate available analytical tools with the objective of gaining an understanding of their accuracies, uncertainties, and limitations within the sump environment. The insights presented in this report and recommendations from the follow-on research will assist the NRC staff in conducting safety reviews of licensees' responses to GL 2004-02.

NUREG/CR-6912, "GSI-191 PWR Sump Screen Blockage Chemical Effects Tests: Thermodynamic Simulations," Center for Nuclear Waste Regulatory Analyses, December 2006

This report by CNWRA documents computer simulation of containment pool chemical reactions using several existing chemical modeling software packages to assess their respective capabilities to predict whether secondary chemical precipitates would be likely to form in typical PWR post-LOCA containment environments. This study included benchmark simulations for the five ICET experiments conducted by LANL, as reported in NUREG/CR-6914. The results of the study are useful in broadly assessing chemical precipitate effects in a typical containment pool. However, limitations in the thermodynamic and kinetic database used to represent PWR containment environments inhibit the development of a robust, predictive model.

NUREG/CR-6913, "Chemical Effects Head-Loss Research in Support of Generic Safety Issue 191," Argonne National Laboratory, December 2006

This report documents head-loss tests conducted at Argonne National Laboratory (ANL) using chemical precipitates and other related tests to study precipitate formation. The head-loss tests included tests with calcium phosphate and aluminum-based precipitates, as well as fibrous debris and CalSil. The tests examined effects such as the arrival sequence of the precipitates with respect to the insulation debris and the formation of calcium phosphate. Additional subjects investigated included CalSil dissolution rates and calcium phosphate precipitate settling rates.

Overall, the test results indicated that (1) significant head-loss can result from chemical reaction products formed in pool environments buffered with trisodium phosphate or sodium hydroxide, as well as in pool environments containing significant quantities of dissolved aluminum; (2) pool environments buffered with sodium tetraborate did not exhibit head-loss attributable to chemical effects; (3) complete dissolution of CalSil insulation could take 1–4 days or more, depending on the dissolution rate of the trisodium phosphate buffer and the concentration of CalSil insulation; and (4) precipitates can agglomerate at higher dissolved calcium concentrations.

These results provide some initial understanding and insights regarding the head-loss attributable to chemical byproducts observed in the ICET program, as well as the other sump pool environments not examined in that program. In addition, insights gained from this report will be helpful to both the NRC staff and the nuclear power industry as it considers changes in plant design and operation that may help to resolve GSI-191.

NUREG/CR-6914, "Integrated Chemical Effects Test Project," Los Alamos National Laboratory, September 2006

LANL conducted a series of experiments in a closed-loop apparatus to characterize and quantify chemical reaction products and/or gelatinous material that could develop in a representative post-LOCA PWR containment environment. The tests addressed five ICET environments, designed to broadly characterize the PWR fleet by representing different buffering systems, insulation configurations, and other containment materials. The ICET experiments were conducted at a temperature of 60 °C (140 °F) for an extended period of time (30 days). Significant findings of the ICET program include the discovery that chemical products can form in representative post-LOCA PWR environments. In particular, calcium phosphate and amorphous aluminum-based precipitates formed under certain test conditions.

NUREG/CR-6915, "Aluminum Chemistry in a Prototypical Post-Loss-of-Coolant-Accident, Pressurized-Water-Reactor Containment Environment," Los Alamos National Laboratory, December 2006

Researchers at LANL also conducted small-scale experiments and a literature review to develop a more thorough understanding of the corrosion rates, precipitation mechanisms and precipitate characteristics of aluminum and aluminum compounds in alkaline solutions that are representative of post-LOCA PWR containment environments. This study helped explain the physical characteristics and behavior of the chemical precipitates that were observed in the ICET #1 and #5 test solutions, and provided information that can be used to predict the behavior of aluminum under various pH and temperature conditions that may exist in PWR containment pools following an accident.

NUREG-1861, "Peer Review of GSI-191 Chemical Effects Research Program," NRC, December 2006

This report documents a peer review to evaluate the technical adequacy and uncertainty associated with the RES-sponsored chemical effects research. Toward that end, five reviewers with expertise in related fields critiqued the following chemical effects research programs:

- integrated chemical effects tests conducted at LANL (NUREG/CR-6914)
- chemical testing and analysis conducted at LANL (NUREG/CR-6915)
- chemical speciation prediction conducted through CNWRA at Southwest Research Institute (NUREG/CR-6912)
- accelerated chemical effects head-loss testing conducted at ANL (NUREG/CR-6913)

The peer reviewers identified additional chemical effects phenomena for consideration. NRC staff is evaluating these phenomena in a manner consistent with the general resolution of technical issues related to GL 2004-02. The results of that evaluation will be documented in a separate paper.

"Survey on Leaching of Coatings Used in Nuclear Power Plants: Letter Report," Argonne National Laboratory, August 2006

This letter report discusses a survey of information in the open literature addressing leaching characteristics of coatings used in nuclear power plants. This survey revealed the scarcity of available research information on the leaching of nuclear coatings in boric acid environments.

Technical Letter Report: "Supplementary Leaching Tests of Insulation and Concrete for GSI-191 Chemical Effects Program," Center for Nuclear Waste Regulatory Analyses, November 2006

This letter report documents bench-scale dissolution and precipitation experiments conducted on insulation and concrete samples to examine the assumption in Westinghouse WCAP-16530-NP that sample materials selected for testing from a group of similar materials adequately represents that group such that the dissolution characteristics could be generalized from the tested product to the other products in the same material group. (That is, the chemical properties of similar insulation products in a given material class are sufficiently similar that the leaching behavior of a single product is representative of all products in that class.) Overall, the test results reported by CNWRA supported that assumption.

"Technical Letter Report on Follow-On Studies in Chemical Effects Head-Loss Research: Studies on WCAP Surrogates and Sodium Tetraborate Solutions," Argonne National Laboratory, February 2007

In this study, ANL conducted a series of tests to evaluate (1) the head-loss performance of the surrogate precipitates recommended in Westinghouse WCAP-16530-NP, relative to the precipitates generated in NRC-sponsored chemical effects tests, and (2) the long-term solubility limits and head-loss characteristics of aluminum precipitates in sumps buffered with sodium tetraborate.

The WCAP surrogate tests demonstrated that aluminum precipitates prepared in accordance with the WCAP procedure were effective in creating head-loss when deposited on a sump screen laden with a fiber bed and, therefore, may be representative of precipitates formed in the containment pool. The quantity of precipitate required to generate high head-loss was equivalent to an aluminum concentration that is 5% above the solubility limit.

The sodium tetraborate buffer experiments demonstrated that the solubility limit for aluminum compounds in a sump pool buffered with sodium tetraborate at 27°C (80°F) appears to be 50 ppm. Consequently, aluminum concentrations above 50 ppm begin to precipitate as aluminum oxyhydroxides.

Sump Screen Head-Loss

NUREG/CR-6874, "GSI-191: Experimental Studies of Loss-of-Coolant-Accident-Generated Debris Accumulation and Head Loss with Emphasis on the Effects of Calcium Silicate Insulation," Los Alamos National Laboratory, May 2005

In this study, LANL used a series of closed-loop flume experiments to evaluate the sump screen accumulation of debris from PWR insulation materials, and measured the head-loss associated with CalSil insulation in combination with NUKON® fiberglass and MRI® metal reflective insulation materials. These experiments confirmed that CalSil insulation can disintegrate to a very fine particulate in the post-LOCA containment environment, and then be captured in a fibrous debris bed, which creates significant head-loss across the sump screen. To address the uncertainties associated with these test results, additional debris-bed head-loss testing was performed at Pacific Northwest National Laboratory (PNNL), as documented in NUREG/CR-6917.

NUREG/CR-6877, "Characterization and Head-Loss Testing of Latent Debris from Pressurized-Water-Reactor Containment Buildings" Los Alamos National Laboratory, July 2005

This study examined the ratio of fiber and particulate constituents in latent debris obtained from five PWR nuclear power plants and determined (through testing) the head-loss contribution from each of the constituents. The head-loss data were used to estimate conservative hydraulic parameters for latent debris over a range of sump flow velocities and particle-to-fiber ratios based on a correlation documented in NUREG/CR-6224, "Parametric Study of the Potential for BWR ECCS Strainer Blockage Due to LOCA-Generated Debris," issued October 1995.

NUREG/CR-6917, "Experimental Measurements of Pressure Drop Across Sump Screen Debris Beds in Support of Generic Safety Issue 191," Pacific Northwest National Laboratory, January 2007

This report documents a series of tests conducted at PNNL to study the head-loss across a NUKON® glass fiber bed, in combination with particulates. The researchers examined various parameters, including approach velocity, water temperature, debris arrival sequence, debris preparation techniques, and debris quantities. The tests applied sophisticated techniques for measuring in situ debris bed heights and masses of debris constituents in the retrieved beds, providing NRC staff with the data required to develop a revised head-loss correlation (NUREG-1862).

The tests performed in this project with NUKON® and CalSil debris beds demonstrated that particulate in combination with a fiber bed can result in increased head-loss across ECCS sump screens. Further, the test demonstrated that the arrival sequence of the various debris constituents can significantly influence the magnitude of the head-loss.

NUREG-1862, "Development of a Pressure Drop Calculation Method for Debris-Covered Sump Screens in Support of Generic Safety Issue 191," NRC, January 2007

This project derived a head-loss correlation, with an improved theoretical basis (compared to previous correlations) for NUKON® and CalSil debris beds. It also compared the predicted results (obtained using the derived correlation) to NUKON®/CalSil head-loss data obtained in the PNNL and LANL experiments, and to predictions obtained using the calculation methods prescribed in NUREG/CR-6224. When compared to actual test results, the correlation presented in this report conservatively predicts head-loss in 70% of cases and under-predicts head-loss in 30% of cases. Over-predictions of head-loss were as high as 300% of actual measurements, and under-predictions were less than 25% of actual measurements.

Downstream Effects

NUREG/CR-6885, "Screen Penetration Test Report," Los Alamos National Laboratory, October 2005

This LANL study examined the propensity of various types of insulation debris (fibrous, CalSil particulate, and reflective metallic insulation) to penetrate PWR sump screens. The variables under consideration included the size of the screen openings; the size, shape, and type of debris; the flow velocity upstream from the screen; and the manner in which the debris reaches the screen.

The test results indicated that, under certain conditions, significant quantities of debris can bypass the screens. Researchers observed that significant amounts of particulate CalSil debris can pass through screen openings of 3–6 millimeters (⅛ – ¼ inch). In addition, NUKON® debris, arriving at the screen in finely separated fibers, can pass through the screen, as can suspended metal reflective insulation.

NUREG/CR-6902, "Effects of Insulation Debris on Throttle-Valve Flow Performance," Los Alamos National Laboratory, March 2006

These LANL tests assessed the potential for LOCA-generated insulation debris to block the high-pressure safety injection throttle valve after passing through the sump screen (as determined in the study reported in NUREG/CR-6885). Data from tests with single slugs of individual debris types showed that, in general, greater debris mass and larger sizes (relative to valve opening) resulted in the highest levels of valve blockage. For equivalent mass loadings, valve blockage was greater for RMI® than for NUKON® debris. In addition, mixtures of larger NUKON® and RMI® debris with smaller CalSil debris appeared to increase valve blockage (compared to the results obtained in tests with a single type of similar debris).

Coating Debris Transport

NUREG/CR-6916, "Hydraulic Transport of Coating Debris," Naval Surface Warfare Center, Carderock Division, December 2006

This study included experiments to characterize the hydraulic transport of coating chips generated from five coating systems that are considered to be broadly representative of coatings used in PWR power plants. The coating chip transport tests included (1) time-to-sink tests, (2) terminal settling velocity tests, (3) tumbling velocity tests, and (4) suspension transport tests. The parameters examined during the testing were chip properties (e.g., size, shape, density, thickness, presoaking, thermal-curing) and fluid velocity. The test results indicated that, in general, hydraulic transport of coating chips is not a significant concern at the typical flow velocities in the post-LOCA containment pool. These results may inform licensees' plant-specific coating debris transport evaluations.

Regulatory Use

The knowledge gained through these research efforts will inform the review of licensee submittals in response to GL 2004-02. The NRC has made the results of these research projects available to the public, including the nuclear industry. This information may be helpful to licensees when performing their GL 2004-02 evaluations, and when selecting appropriate mitigation strategies to eliminate or reduce the volume of in-containment problematic materials to mitigate the sump screen head-loss.