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Integrated Chemical Effects Test Project: Consolidated Data Report

Los Alamos National Laboratory

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Principal Investigator: J. Dallman

Prepared by
J. Dallman, B. Letellier, J. Garcia, J. Madrid, W. Roesch
Los Alamos National Laboratory
Los Alamos, NM 87545

D. Chen, K. Howe
University of New Mexico
Department of Civil Engineering
Albuquerque, NM 87110

L. Archuleta, F. Sciacca
OMICRON Safety and Risk Technologies, Inc.
2500 Louisiana Blvd. NE, Suite 410
Albuquerque, NM 87110

B.P. Jain, NRC Project Manager

Prepared for
Division of Fuel, Engineering and Radiological Research
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
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INTEGRATED CHEMICAL EFFECTS TEST PROJECT: CONSOLIDATED DATA REPORT

ABSTRACT

Five tests conducted in the Integrated Chemical Effects Test (ICET) project apparatus attempted to simulate the chemical environment present inside a pressurized-water-reactor containment water pool after a loss-of-coolant-accident. The chemical environment within the tank included boric acid, lithium hydroxide, and hydrochloric acid. Trisodium phosphate, sodium hydroxide, or sodium tetraborate was added to each test. The tests were conducted for 30 days at a constant temperature of 60°C. The materials tested within this environment included representative amounts of submerged and unsubmerged aluminum, copper, concrete, zinc, carbon steel, and insulation samples (either 100% fiberglass or a combination of 80% calcium silicate and 20% fiberglass by volume). Representative amounts of concrete dust and latent debris were also added to the test solution. Water was circulated through the bottom portion of the test chamber during the entire test to achieve representative flow rates over the submerged specimens. Test solution pH ranged from just over 7 in Tests #2 and #3 to just over 8 in Test #5, and it reached almost 10 in Tests #1 and #4. Test solution chemistry varied from test to test, depending on the starting conditions and amount of material corrosion or leaching. Either particulate, flocculent, or film (webbing) deposits were observed in the fiberglass after each test. Visible changes were also seen on the metal coupons in each test. Corrosion was evident on both submerged and unsubmerged coupons. The amount of sediment recovered was directly proportional to the amount of particulate debris added to the test. Tests #3 and #4 had considerably more sediment than did the other tests, primarily because of the cal-sil dust added to the tank. The top layer of Test #3 sediment contained a gel-like material. When cooled to ambient temperature, test solution in Tests #1 and #5 contained precipitates. Test solution from those two tests also exhibited a non-Newtonian tendency for shear thinning with increasing strain rate when the solution was cooled to ambient temperature.

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FOREWORD

The U.S. Nuclear Regulatory Commission (NRC) is engaged in research activities related to resolving Generic Safety Issue (GSI) 191, "Assessment of Debris Accumulation on PWR Sump Performance." During a review of those staff activities, the NRC's Advisory Committee on Reactor Safeguards (ACRS) raised a concern that products attributable to chemical interactions between the emergency core cooling system (ECCS) containment spray water and exposed materials (such as metal surfaces, paint chips, and fiberglass insulation debris) could impede the performance of ECCS recirculation following a loss-of-coolant accident (LOCA) at a pressurized-water reactor (PWR).

In response to that concern, the NRC's Office of Nuclear Regulatory Research (RES) and the nuclear energy industry, represented by the Electric Power Research Institute (EPRI), jointly sponsored an integrated chemical effects test (ICET) program at the University of New Mexico, under the direction of Los Alamos National Laboratory. The objectives of that ICET program were to (1) determine, characterize, and quantify chemical reaction products that may develop in the containment pool in a representative post-LOCA PWR environment, and (2) determine and quantify any gelatinous material that could be produced during the post-LOCA recirculation phase. Toward that end, the ICET program consisted of five tests, with each test representing a unique environment. The intent was that each test would represent a portion of the commercial PWR plant, such that the entire series would broadly characterize containment pool conditions applicable to the existing nuclear fleet.

This six-volume report documents the results of this program. Volume 1 provides a summary and comparison of the important observations and measurements among all of the tests, while Volumes 2–6 provide detailed data reports for of each of the five tests. As documented herein, the ICET results indicate that (1) chemical reaction products with varied quantities, consistencies, attributes, and apparent formation mechanisms were found in each unique ICET environment; (2) containment materials (metallic, non-metallic, and insulation debris), pH, buffering agent, temperature, and time are all important variables that influence chemical product formation; and (3) changes to one important environmental variable (e.g., pH adjusting agent, insulation material) can significantly affect the chemical products that form.

This report provides some insights and initial understanding regarding the solution chemistry, as well as the types and amounts of chemical reaction products that may form in the ECCS containment pool. The observed chemical products may potentially contribute to both pressure losses across a debris-laden sump screen and performance degradation of ECCS components downstream of the sump screen. The regulatory application of data and insights gained from this study is to be determined independently by the NRC staff and industry. This report is intended to assist the NRC staff in conducting reviews of licensees' responses to Generic Letter 2004-02 (GL), "Potential Impact of Debris Blockage on Emergency Recirculation During Design-Basis Accidents at Pressurized-Water Reactors," dated September 13, 2004. The staff is conducting additional research to assess head loss implications for chemical products observed in this testing and, with an external peer review group, is identifying outstanding chemical effect issues. The findings from these activities will be summarized in separate reports.

Brian W. Sheron

Brian W. Sheron, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

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INTEGRATED CHEMICAL EFFECTS TEST PROJECT: CONSOLIDATED DATA REPORT

EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research has developed a comprehensive research program to support resolution of Generic Safety Issue (GSI)-191. GSI-191 addresses the potential for debris accumulation on pressurized-water-reactor (PWR) sump screens and the consequent loss of net-positive-suction-head margin in the emergency-core-cooling-system (ECCS). Among the GSI-191 research program tasks is the experimental investigation of chemical effects that may exacerbate sump-screen clogging.

The Integrated Chemical Effects Test (ICET) project was a joint effort by the U.S. NRC and the nuclear utility industry undertaken through the Memorandum of Understanding on Cooperative Nuclear Safety between the NRC and Electrical Power Research Institute, “Addendum on Integral Chemical Effects Testing for PWR ECCS Recirculation.” The ICET tests attempted to simulate the chemical environment present inside a containment water pool after a loss-of-coolant accident (LOCA) and monitored the chemical system for 30 days to identify the presence, composition, and physical characteristics of chemical products that formed during the tests. The ICET test series was conducted by Los Alamos National Laboratory at the University of New Mexico, with the assistance of professors and students in the Departments of Civil and Mechanical Engineering. The primary objectives for the ICET test series were (1) to determine, characterize, and quantify chemical-reaction products that may develop in the containment sump under a representative post-LOCA environment and (2) to identify and quantify any gelatinous material that might be produced during the post-LOCA recirculation phase.

This report volume presents the principal findings of the five tests conducted in the ICET test series. The five individual test data reports are included as additional Volumes 2–6. This volume consolidates observations and findings from the individual data reports and compares trends and key results.

All of the ICET tests were conducted in an environment that attempted to simulate containment pool conditions during recirculation. A Project Test Plan, jointly developed by EPRI and NRC, provides a complete rationale for the ICET test conditions. For Tests #1–#4, the initial chemical environment contained 2800 mg/L of boron, 100 mg/L of hydrochloric acid, and 0.7 mg/L of lithium hydroxide. (For some tests, the hydrochloric acid and a small portion of the boron and/or lithium hydroxide were added during the spray phase.) For Test #5, the initial chemical environment contained 2400 mg/L of boron, 43 mg/L of hydrochloric acid, and 0.3 mg/L of lithium hydroxide. Sodium hydroxide was added in Tests #1 and #4, trisodium phosphate was added in Tests #2 and #3, and sodium tetraborate was added in Test #5. All tests were conducted for 30 days at a constant temperature of 60°C. The materials tested within this environment included representative amounts of submerged and unsubmerged aluminum, copper, concrete, zinc, carbon steel, and insulation samples. Representative amounts of concrete dust and latent debris (dirt) were also added to the test solution. The tests included an initial 4-hour spray phase to simulate containment spray interaction with the unsubmerged samples. Water was circulated

through the bottom portion of the test chamber during the entire test to achieve representative flow rates over the submerged specimens.

Insulation samples consisted of scaled amounts of NUKON™ fiberglass and calcium silicate (cal-sil) material. In Tests #1, #4, and #5, only NUKON™ fiberglass was included. In Tests #2 and #3, the samples were 80% cal-sil and 20% NUKON™ fiberglass by volume. In addition, the tank contained 373 metal coupon samples (40 submerged) and 1 submerged concrete sample. Process control consisted of monitoring online measurements of recirculation flow rate, test solution temperature, and pH. Flow rate and temperature were controlled to maintain the desired values of 25 gpm and 60°C. The value of 25 gpm was chosen to yield fluid velocities over the submerged coupons from 0–3 cm/s. Daily water samples were obtained for measurements of pH, turbidity, total suspended solids, kinematic viscosity, shear-dependent viscosity, and for chemical analyses. In addition, microscopic evaluations were conducted on water-sample filtrates, precipitates, fiberglass, cal-sil, metal coupons, and sediment.

Test preparation included heating a specified volume of water to 65°C, which was 5°C higher than the required test temperature to offset the 5°C heat loss that occurred when the test coupons were added. Upon reaching the desired temperature, test-specific chemicals were dissolved into the heated water. Latent debris, concrete, test coupons, and insulation samples were then placed in the tank. Once the solution temperature reached the required test temperature of 60°C, the test commenced with initiation of the tank sprays. During the 4-hour spray period, additional chemicals were added if required. After the addition of all chemicals, the test volume equaled 250 gal. The tests ran for 30 days, while the conditions were maintained within the accepted flow and temperature ranges, with only short periods of slight deviation. Water samples, insulation samples, and metal coupons were analyzed after the test. Sampling and analyses were conducted in accordance with approved project instructions.

Initial test solution pH was different in each test, and it varied from ~7.3 in Test #2 to ~9.8 in Test #4. The pre-determined amounts of chemicals were added for each test, and no attempt was made to control or alter the resulting pH. Solution samples from Tests #1 and #5 produced precipitates upon cooling to room temperature, whereas samples from Tests #2, #3, and #4 did not. The Test #1 precipitates occurred much more quickly and were present in greater quantities than the Test #5 precipitates. Except for precipitates seen on the first day of Test #3, no precipitates were visible in the test solution at the test temperature. Turbidity measurements were taken at 60^{o}C and 23^{o}C. In Tests #2, #3, and #4, measurements at both temperatures produced similar results. During the first 4 hours of Test #3, a large increase in turbidity was seen, which corresponded to the visible precipitates. In Tests #1 and #5, the turbidity at 23^{o}C rose higher than the 60^{o}C values. Total suspended solids (TSS) were also measured in each test. With the exception of Test #5, all tests reached a maximum TSS value by the first day and decreased to a value relatively close to the base-line measurement for the duration of the test. Test #5 TSS measurements varied between the baseline and the maximum value throughout the test. Measurements were made of suspended particles in the test solution. The particle size distribution in the Test #1 test solution indicated diameters <1 μm. For Tests #2–#5, the particle size ranged from 1 to 100 μm, and the size distributions within that range differed from test to test.

In all tests, daily measurements of the constant-shear kinematic viscosity revealed an approximately constant value at both the test and room temperatures. This was true for both filtered and unfiltered samples. Shear-dependent viscosity measurements indicated that the Tests #2, #3, and #4 solutions were representative of a Newtonian fluid. However, in Tests #1 and #5, shear thinning was observed when the solutions were cooled to room temperature.

Throughout the ICET test series, daily water samples were taken for inductively coupled plasma (ICP) analysis of a standard list of elements (plus silica) to determine the composition of the solution. As expected, boron was present in high concentrations in all tests. In Test #1, aluminum and sodium were present in greater concentrations than were all other tested elements. In Test #2, silica and sodium were the dominant elements in solution. Silica, sodium, and calcium were present in the greatest concentrations with the Test #3 solution. In Test #4, silica, sodium, calcium, and potassium were present in solution in the greatest concentrations. Sodium, aluminum, calcium, and silica were the elements of highest concentration in the Test #5 solution.

Insulation debris, which was composed of fiberglass or a mixture of fiberglass and cal-sil, was analyzed after completion of each test. Fiberglass samples were present in all tests. Cal-sil samples were present in only Tests #3 and #4. Three types of deposits were found on the fiberglass samples by electron microscopy: (1) particulates deposited on the exterior of the insulation; (2) flocculence, which was more prevalent on the interior of the insulation (flocculence may have been formed by the chemical byproducts existing in the test or may have been caused by precipitation during the drying process, which was required for most analyses); and (3) film or webbing, which resulted from precipitation of soluble species from Tests #1 and #4 during the drying process. The amount of deposits seen on the fiberglass insulation varied from test to test because of differing solution chemistry. Comparisons revealed that the greatest degree of deposition occurred in Test #3, followed in order by Tests #1, #4, and #2. Test #5 samples had the fewest deposits. Analysis of the cal-sil samples showed large amounts of phosphorous on the exterior of samples obtained from Test #3, but the phosphorus did not penetrate to the interior of the samples.

The system effect on the metal coupons was different for each test. Test #1 experienced the largest amount of corrosion on the submerged coupons. Tests #2–#5 conditions did not cause significant submerged coupon corrosion. None of the tests showed significant corrosion on the unsubmerged coupons. The sediment on the tank bottom at the end of the tests also varied. Tests #3 and #4 had the most sediment, which consisted of chemical precipitate, as well as sediment attributable to the large amount of crushed cal-sil added to the tank. Tests #1, #2, and #5 produced the smallest amount of sediment, which was composed largely of materials from the insulation used (fiberglass) and debris added to the tank.

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ACRONYMS AND ABBREVIATIONS

ACRS	Advisory Committee on Reactor Safeguards (NRC)
BSE	Back Scattered Electrons
cal-sil	Calcium Silicate
CPVC	Chlorinated Polyvinyl Chloride
CS	Coated Steel
DAS	Data Acquisition System
DHR	Decay Heat Removal
ECCS	Emergency Core-Cooling System
EDS	Energy-Dispersive Spectroscopy
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESEM	Environmental Scanning Electron Microscopy
gpm	Gallons per Minute
GS	Galvanized Steel
GSI	Generic Safety Issue
HCl	Hydrochloric Acid
ICET	Integrated Chemical Effects Tests
ICP	Inductively Coupled Plasma
ICP-AES	Inductively Coupled Plasma—Atomic Emission Spectroscopy
IOZ	Inorganic Zinc
LANL	Los Alamos National Laboratory
LiOH	Lithium Hydroxide
LOCA	Loss-of-Coolant Accident
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
NTU	Nephelometric Turbidity Unit
PI	Project Instruction
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
QA	Quality Assurance
QC	Quality Control
RES	Office of Nuclear Regulatory Research (NRC)
RO	Reverse Osmosis
SEM	Scanning Electron Microscopy

SNL	Sandia National Laboratories
SS	Stainless Steel
TEM	Transmission Electron Microscopy
TOC	Total Organic Carbon
TSP	Trisodium Phosphate
TSS	Total Suspended Solids
UNM	University of New Mexico
US	Uncoated Steel
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence