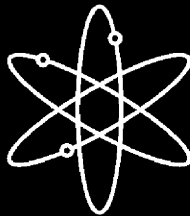




Integrated Chemical Effects Test Project: Consolidated Data Report



Los Alamos National Laboratory



**U.S. Nuclear Regulatory Commission
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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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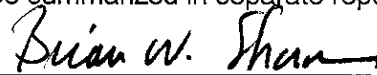
FOREWORD

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 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, Director
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission

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CONTENTS

ABSTRACT.....	iii
FOREWORD	v
EXECUTIVE SUMMARY	xix
ACKNOWLEDGMENTS	xxiii
ACRONYMS AND ABBREVIATIONS.....	xxv
1. INTRODUCTION	1
1.1. Objectives and Test Conditions	1
1.2. Information Presented in This Report.....	2
2. TEST PROCEDURES	5
2.1. Chemical Test Apparatus Functional Description	5
2.2. Pre-Test Preparation	6
2.2.1. Test Loop Cleaning.....	6
2.2.2. Test Coupons and Samples	7
2.2.3. Quality Assurance (QA) Program.....	11
2.2.4. Test Parameters.....	11
2.3. Test Operation.....	13
3. SUMMARY OF TEST RESULTS.....	15
3.1. Test #1.....	15
3.1.1. Water Samples	16
3.1.2. Insulation.....	17
3.1.3. Sediment	17
3.1.4. Coupons	17
3.2. Test #2.....	18
3.2.1. Water Samples	18
3.2.2. Insulation.....	19
3.2.3. Sediment	19
3.2.4. Coupons	19
3.3. Test #3.....	19
3.3.1. Water Samples	19
3.3.2. Insulation.....	20
3.3.3. Sediment	21
3.3.4. Coupons	22
3.4. Test #4.....	22
3.4.1. Water Samples	22
3.4.2. Insulation.....	23
3.4.3. Sediment	24
3.4.4. Coupons	24
3.5. Test #5.....	24
3.5.1. Water Samples	24
3.5.2. Insulation.....	26
3.5.3. Sediment	26
3.5.4. Coupons	26

4. COMPARISONS OF KEY RESULTS	29
4.1. Water Samples	29
4.1.1. Water Chemistry	29
4.1.2. Precipitates	43
4.2. Insulation	45
4.2.1. Fiberglass	45
4.2.2. Cal-Sil	70
4.3. Sediment	80
4.3.1. Test #1 Sediment.....	82
4.3.2. Test #2 Sediment.....	86
4.4. Coupons	98
4.4.1. Pre- and Post-Test Coupon Photographs	98
4.4.2. SEM/EDS.....	112
4.4.3. Passivation of Test #4 Submerged Al Coupons.....	123
4.5. Deposition Products.....	129
4.6. Gel Analysis.....	135
5. CONCLUSIONS.....	143
6. REFERENCES	145

APPENDICES

Appendix A.	ICET Background Information	A-1
Appendix B.	Materials Used in ICET Testing	B-1
Appendix C.	Test Plan.....	C-1

FIGURES

Figure 2-1.	Test loop process flow diagram.	6
Figure 2-2.	Coupon rack configuration in the ICET tank. The blue line represents the surface of the test solution.	8
Figure 2-3.	A typical loaded coupon rack in the ICET tank.....	8
Figure 2-4.	Fiberglass samples attached to a coupon rack.	9
Figure 2-5.	Solid pieces of cal-sil samples in SS mesh.	10
Figure 2-6.	Pulverized cal-sil insulation before addition to the ICET tank.	10
Figure 4-1.	ICET bench-top pH comparison.	30
Figure 4-2.	Day 1 turbidity.	31
Figure 4-3.	ICET 60°C turbidity	32
Figure 4-4.	ICET 23°C turbidity.....	33
Figure 4-5.	ICET Day-1 TSS.....	34
Figure 4-6.	ICET TSS.....	34
Figure 4-7.	ICET 60°C kinematic viscosity.....	35
Figure 4-8.	ICET 23°C kinematic viscosity.....	36
Figure 4-9.	ICET hydrogen concentration.....	37
Figure 4-10.	ICET Tests #1 and #5 unfiltered aluminum concentration.....	38
Figure 4-11.	ICET unfiltered calcium concentration.....	39
Figure 4-12.	ICET unfiltered copper concentration.	39
Figure 4-13.	ICET unfiltered zinc concentration.....	40
Figure 4-14.	ICET Tests #2, #3, and #5 unfiltered magnesium concentration.....	41
Figure 4-15.	ICET unfiltered silica concentration.	42
Figure 4-16.	ICET unfiltered sodium concentration.....	43
Figure 4-17.	Clean fiberglass before exposure to test chemicals.	46
Figure 4-18.	Day 15, sample #4 SEM image (#4037), magnified 2500 times; BSE close-up.....	48
Figure 4-19.	Day 30, sample #3 SEM image (#3003), magnified 250 times, of the fiberglass with surface coating.	49
Figure 4-20.	Day 30, sample #3 SEM image (#3007), magnified 500 times, of the film across the fibers.....	49
Figure 4-21.	Day 15, sample #4 counting spectrum (EDS 4-22) for the crust on the fiberglass, as shown in Figure 4-18.	50

Figure 4-22.	Day 30, sample #3 counting spectrum (EDS #3003) of the fractured coating, as shown in Figure 4-19.	50
Figure 4-23.	ESEM image, magnified 100 times, of raw fiberglass dipped in ICET Test #1 solution. (rft105.tif, 7/28/05).....	51
Figure 4-24.	EDS counting spectrum for the film on fiberglass, as shown in Figure 4-23. (rft106.tif, 7/28/05)	51
Figure 4-25.	ESEM image, magnified 100 times, of raw fiberglass dipped in ICET Test #1 solution and then washed with RO water. (DIfrg15.tif, 8/3/05)	52
Figure 4-26.	ESEM image, magnified 100 times, of raw fiberglass dipped in NaOH solution at pH 9.5. (OHFr07.tif, 8/3/05).....	52
Figure 4-27.	ESEM image, magnified 100 times, of raw fiberglass dipped in the solution containing 2800 mg/L boron and NaOH at pH 9.5. (Bofrg09.tif, 8/3/05).....	53
Figure 4-28.	ESEM image, magnified 300 times, of raw fiberglass dipped in the solution containing 2800 mg/L boron and NaOH at pH 9.5. (rftgbn03.tif, 8/5/05)	53
Figure 4-29.	EDS counting spectrum for the film on fiberglass, as shown in Figure 4-28. (rftgbn05.tif, 8/5/05).....	54
Figure 4-30.	ESEM image for a Test #2, Day 30, high-flow exterior fiberglass sample.	55
Figure 4-31.	Higher-magnification ESEM image of a Test #2, Day 30, high-flow exterior fiberglass sample.	55
Figure 4-32.	ESEM image for a Test #2, Day 30, high-flow interior fiberglass sample.....	56
Figure 4-33.	Higher-magnification ESEM image of a Test #2, Day 30, high-flow interior fiberglass sample.....	56
Figure 4-34.	Probe SEM image at 1000× magnification for a Test #2, Day 30, high-flow interior fiberglass sample. (T2D30_HiFlo023).....	57
Figure 4-35.	EDS counting spectrum for the deposits on a high-flow exterior fiberglass sample.....	57
Figure 4-36.	ESEM image of a Test #3, Day 30, exterior high-flow fiberglass sample, magnified 100 times. (t3hifx33, 5/11/05)	58
Figure 4-37.	EDS counting spectrum for the large masses of particulate deposits shown in Figure 4-36. (t3hifx34, 5/11/05).....	59
Figure 4-38.	ESEM image of a Test #3, Day 30, exterior fiberglass sample on the drain collar (away from the drain screen), magnified 1000 times. (t3dcex21, 5/6/05).....	59
Figure 4-39.	Comparison of EDS counting spectra between the light particle (EDS1, yellow) and the dark particle (EDS2, red) shown in Figure 4-38. (t3dcex24, 5/6/05).....	60
Figure 4-40.	ESEM image of a Test #3, Day 30, interior high-flow fiberglass sample, magnified 100 times. (T3HiFI36, 5/11/05).....	60

Figure 4-41.	ESEM image of a Test #3, Day 30, interior high-flow fiberglass sample, magnified 1000 times. (t3hifi37, 5/11/05)	61
Figure 4-42.	ESEM image of a Test #3, Day 15, high-flow interior fiberglass sample, magnified 2000 times. (T3D15HI3, 4/22/05)	61
Figure 4-43.	EDS counting spectrum for the flocculent deposits between the fibers on the ESEM image shown in Figure 4-42. (T3D15HIA, 4/22/05)	62
Figure 4-44.	ESEM image, magnified 100 times, of a Test #4, Day 30, exterior high-flow fiberglass sample. (T4HFEx01.jpg).....	63
Figure 4-45.	ESEM image, magnified 500 times, of a Test #4, Day 30, exterior high-flow fiberglass sample. (t4hfex07.jpg).....	63
Figure 4-46.	ESEM image, magnified 100 times, of a Test #4, Day 30, exterior fiberglass sample on the drain collar (away from the drain screen). (t4dcox05.jpg)	64
Figure 4-47.	ESEM image, magnified 1000 times, of a Test #4, Day 30, exterior fiberglass sample on the drain collar (away from the drain screen). (t4dcox03.jpg)	64
Figure 4-48.	EDS counting spectrum for the large mass of particulate deposits on fiberglass shown in Figure 4-47. (t4dcox04.jpg).....	65
Figure 4-49.	ESEM image, magnified 100 times, of a Test #4, Day 30, interior high-flow fiberglass sample. (t4hfin01.jpg)	65
Figure 4-50.	ESEM image, magnified 500 times, for a Test #4, Day 30, interior high-flow fiberglass sample. (t4hfin04.jpg)	66
Figure 4-51.	ESEM image, magnified 100 times, of a Test #4, Day 30, interior high-flow fiberglass sample. The sample was gently pre-rinsed with RO water. (T4Rnd01.jpg).....	66
Figure 4-52.	ESEM image, magnified 500 times, for a Test #4, Day 30, interior high-flow fiberglass sample. The sample was gently pre-rinsed with RO water. (t4rnd05.jpg).....	67
Figure 4-53.	ESEM image, magnified 100 times, of a Test #5, Day 30, high-flow exterior fiberglass sample. (T5D30HX1.jpg).....	68
Figure 4-54.	ESEM image, magnified 500 times, of a Test #5, Day 30, high-flow exterior fiberglass sample. (t5d30hx3.jpg).....	68
Figure 4-55.	ESEM image, magnified 100 times, of a Test #5, Day 30, high-flow interior fiberglass sample. (T5D30HI4.jpg)	69
Figure 4-56.	ESEM image, magnified 500 times, of a Test #5, Day 30, high-flow interior fiberglass sample. (t5d30hi6.jpg).....	69
Figure 4-57.	ESEM image, magnified 500 times, of a Test #5, Day 30 high-flow interior fiberglass sample in a nylon mesh.	70
Figure 4-58.	EDS counting spectrum for the deposits between the fibers shown in Figure 4-57.....	70
Figure 4-59.	SEM image, magnified 1000 times, of an unused, unbaked cal-sil sample. (T3~RawCal_Sil008).....	72
Figure 4-60.	SEM image, magnified 1000 times, of an unused, baked cal-sil sample. (T3~BakedCal~Sil011).....	72

Figure 4-61.	XRD results for the unused, unbaked cal-sil sample.	73
Figure 4-62.	XRD results for the unused, baked cal-sil sample.	73
Figure 4-63.	Annotated ESEM image, magnified 1000 times, of the exterior of a Test #3, Day 30, submerged high-flow baked cal-sil sample. (t3bcal40).....	75
Figure 4-64.	EDS counting spectrum for the light particles (EDS1) shown in Figure 4-63. (T3bcal41).....	75
Figure 4-65.	EDS counting spectrum for the dark particles (EDS2) shown in Figure 4-63. (t3bcal42).....	76
Figure 4-66.	Annotated ESEM image, magnified 500 times, of the exterior of a Test #3, Day 30, unbaked cal-sil sample submerged in the birdcage. (T3Calx22).....	76
Figure 4-67.	EDS counting spectrum for the particles shown in Figure 4-66. (t3calx23)	77
Figure 4-68.	Annotated ESEM image, magnified 500 times, of the interior of a Test #3, Day 30, unbaked cal-sil sample submerged in the birdcage. (T3Call25).....	77
Figure 4-69.	EDS counting spectrum for the particles shown in Figure 4-68. (T3cali26)	78
Figure 4-70.	ESEM image, magnified 500 times, of a Test #4, Day 30, low-flow exterior baked cal-sil sample. (t4bcex08.jpg).....	79
Figure 4-71.	EDS counting spectrum for the whole image shown in Figure 4-70. (t4bcex09.jpg).....	79
Figure 4-72.	ESEM image, magnified 500 times, of a Test #4, Day 30, low-flow interior baked cal-sil sample. (t4bcin11.jpg)	80
Figure 4-73.	EDS counting spectrum for the whole image shown in Figure 4-72. (t4bcin12.jpg).....	80
Figure 4-74.	Sediment from south quadrant of tank after Test #1.....	83
Figure 4-75.	SEM overview image, magnified 40 times, of a Test #1, Day 30, sediment sample.	83
Figure 4-76.	SEM image with a higher magnification on a Test #1, Day 30, sediment sample.....	84
Figure 4-77.	SEM image, magnified 1000 times, of a Test #1, Day 30, sediment sample.....	84
Figure 4-78.	XRD result on a Test #1, Day 30, mixed-sediment sample.....	85
Figure 4-79.	Picture of a Test #2, Day 30, sediment sample.....	86
Figure 4-80.	SEM image of a Test #2, Day 30, sediment sample.	87
Figure 4-81.	Higher-magnification SEM image of a Test #2, Day 30, sediment sample.	87
Figure 4-82.	EDS counting spectrum for the porously structured material shown in Figure 4-81.....	88
Figure 4-83.	XRD results for Test #2, Day 30, mixed sediment.	88
Figure 4-84.	Sediment removed from the tank after Test #3.....	89
Figure 4-85.	ESEM image of a Test #3, Day 30, pink sediment, magnified 100 times. (t3pnkp31, 5/6/05).....	90

Figure 4-86.	EDS counting spectrum for the pink sediment shown in Figure 4-85. (t3pnkp30, 5/6/05).....	90
Figure 4-87.	ESEM image of a Test #3, Day 30, yellow sediment, magnified 100 times. (t3ylwp34, 5/6/05).....	91
Figure 4-88.	EDS counting spectrum for the particles shown in Figure 4-87. (t3ylwp35, 5/6/05).....	91
Figure 4-89.	XRD results for the Test #3, Day 30, mixed sediment.	92
Figure 4-90.	Sediment removed from the tank after Test #4.....	93
Figure 4-91.	Annotated SEM image, magnified 500 times, for a Test #4, Day 30, sediment sample at the bottom of the tank. (T4D30SEDMT027.bmp)	93
Figure 4-92.	EDS counting spectrum for the white snow-like deposits (EDS1) shown in Figure 4-91. (T4D30SEDMT16.jpg)	94
Figure 4-93.	EDS counting spectrum for the dark deposits (EDS2) shown in Figure 4-91. (T4D30SEDMT17.jpg).....	94
Figure 4-94.	XRD results for the possible matching crystalline substances in the Test #4, Day 30, sediment.	95
Figure 4-95.	Sediment sample removed from the tank after Test #5.	96
Figure 4-96.	SEM image, magnified 70 times, of the Test #5, Day 30, sediment at the bottom of the tank.	96
Figure 4-97.	EDS counting spectrum for the big particulate deposit shown in Figure 4-96.	97
Figure 4-98.	XRD results for the possible matching crystalline substances in Test #5, Day 30, sediment.	97
Figure 4-99.	ICET Test#1 Al-91 post-test (left); ICET Test#2 Al-96 post-test (right).....	98
Figure 4-100.	ICET Test#3 Al-155 submerged, post-test (left); ICET Test#4 Al-237 submerged, post-test, (right).	98
Figure 4-101.	ICET Test #5 Al-93 submerged, post-test.	99
Figure 4-102.	Unused Al coupon.....	99
Figure 4-103.	ICET Test #1 GS-328 submerged, post-test (left); ICET Test #2 GS-335 submerged, post-test (right).	99
Figure 4-104.	ICET Test #3 GS-468 submerged, post-test (left); ICET Test #4 GS-130 submerged, post-test (right).	100
Figure 4-105.	ICET Test #5 GS-332 submerged, post-test.	100
Figure 4-106.	Unused GS coupon.	100
Figure 4-107.	ICET Test #1 IOZ-77 submerged, post-test (left); ICET Test #2 IOZ-79 submerged, post-test (right).	101
Figure 4-108.	ICET Test #3 IOZ-156 submerged, post-test (left); ICET Test #4 IOZ-233 submerged, post-test (right).	101
Figure 4-109.	ICET Test #5 IOZ-310 submerged, post-test.....	102
Figure 4-110.	Unused IOZ-coated coupon.	102
Figure 4-111.	ICET Test #1 CU-80 submerged, post-test (left); ICET Test #2 CU-105 submerged, post-test (right).	102

Figure 4-112. ICET Test #3 CU-207 submerged, post-test (left); ICET Test #4 CU-100 submerged, post-test (right).	103
Figure 4-113. ICET Test #5 CU-100 submerged, post-test.	103
Figure 4-114. Unused CU coupon.	103
Figure 4-115. ICET Test #1 US-8 submerged, pre-test (left); ICET Test #2 US-7 submerged, post-test (right).	104
Figure 4-116. ICET Test #3 US-11 submerged, post-test (left); ICET Test #4 US-17 submerged, post-test (right).	104
Figure 4-117. ICET Test #5 US-14 submerged, post-test.	104
Figure 4-118. Unused US coupon.	105
Figure 4-119. ICET Test #1 Conc-6 submerged, post-test (left); ICET Test #2 Conc-2 submerged, post-test (right).	105
Figure 4-120. ICET Test #3 Conc-5 submerged, post-test (left); ICET Test #4 Conc-4 submerged, post-test (right).	105
Figure 4-121. ICET Test #5 Conc-003 submerged, post-test.	106
Figure 4-122. Unused concrete coupon.	106
Figure 4-123. Test #1 Al-42 unsubmerged (left); Test #2 Al-101 unsubmerged (right).	107
Figure 4-124. Test #3 Al-159 unsubmerged (left); Test #4 Al-3 unsubmerged (right).	107
Figure 4-125. Test #5 Al-247 unsubmerged.	108
Figure 4-126. Test #1 GS-223 unsubmerged (left); Test #2 GS-366 unsubmerged (right).	108
Figure 4-127. Test #3 GS-503 unsubmerged (left); Test #4 GS-33 unsubmerged (right).	108
Figure 4-128. Test #5 GS-167 unsubmerged.	109
Figure 4-129. Test #1 CU-76 unsubmerged (left); Test #2 CU-196 unsubmerged (right).	109
Figure 4-130. Test #3 CU-291 unsubmerged (left); Test #4 CU-584 unsubmerged (right).	109
Figure 4-131. Test #5 CU-587 unsubmerged.	110
Figure 4-132. Test #1 IOZ-48 unsubmerged (left); Test #2 IOZ-26 unsubmerged (right).	110
Figure 4-133. Test #3 IOZ-199 unsubmerged (left); Test #4 IOZ-275 unsubmerged (right).	110
Figure 4-134. Test #5 IOZ-356 unsubmerged.	111
Figure 4-135. Test #1 US-1 unsubmerged (left); Test #2 US-10 unsubmerged (right).	111
Figure 4-136. Test #3 US-13 unsubmerged (left); Test #4 US-16 unsubmerged (right).	111
Figure 4-137. ICET Test #5 US-18 unsubmerged.	112
Figure 4-138. Unused aluminum coupon (left); Test #1 submerged aluminum coupon (right).	114
Figure 4-139. Test #2 submerged aluminum coupon (left); Test #3 submerged aluminum coupon (right).	115
Figure 4-140. Test #4 submerged aluminum coupon (left); Test #5 submerged aluminum coupon (right).	115
Figure 4-141. Test #1 unsubmerged aluminum.	115
Figure 4-142. Test #2 unsubmerged aluminum (left); Test #3 unsubmerged aluminum (right).	116

Figure 4-143. Test #4 unsubmerged aluminum (left); Test #5 unsubmerged aluminum (right).	116
Figure 4-144. Unused copper coupon (left); Test #1 submerged copper coupon (right).	117
Figure 4-145. Test #2 submerged copper coupon (left); Test #3 submerged copper coupon (right).	117
Figure 4-146. Test #4 submerged copper coupon (left); Test #5 submerged copper coupon (right).	117
Figure 4-147. Test #1 unsubmerged copper.	118
Figure 4-148. Test #2 unsubmerged copper (left); Test #3 unsubmerged copper (right).	118
Figure 4-149. Test #4 unsubmerged copper (left); Test #5 unsubmerged copper (right).	118
Figure 4-150. Unused galvanized steel coupon (left); Test #1 submerged galvanized steel (right).	119
Figure 4-151. Test #2 submerged galvanized steel (left); Test #3 submerged galvanized steel (right).	119
Figure 4-152. Test #4 submerged galvanized steel (left); Test #5 submerged galvanized steel (right).	119
Figure 4-153. Test #1 unsubmerged galvanized steel.	120
Figure 4-154. Test #2 unsubmerged galvanized steel (left); Test #3 unsubmerged galvanized steel (right).	120
Figure 4-155. Test #4 unsubmerged galvanized steel (left); Test #5 unsubmerged galvanized steel (right).	120
Figure 4-156. Unused carbon steel coupon (left); Test #1 submerged carbon steel (right).	121
Figure 4-157. Test #2 submerged carbon steel (left); Test #3 submerged carbon steel (right).	121
Figure 4-158. Test #4 submerged carbon steel (left); Test #5 submerged carbon steel (right).	122
Figure 4-159. Test #1 unsubmerged carbon steel.	122
Figure 4-160. Test #2 unsubmerged carbon steel (left); Test #3 unsubmerged carbon steel (right).	122
Figure 4-161. Test #4 unsubmerged carbon steel (left); Test #5 unsubmerged carbon steel (right).	123
Figure 4-162. Aluminum concentration in ICET Test #1 and Test #4 daily water samples.	124
Figure 4-163. Silica concentration in ICET Test #1 and Test #4 daily water samples.	125
Figure 4-164. SEM image, magnified 100 times, of a Test #4, Day 30, submerged aluminum coupon sample. (T4D30AlSubm004.bmp)	125
Figure 4-165. Annotated SEM image, magnified 1000 times, of a Test #4, Day 30, submerged aluminum coupon sample. (T4D30AlSubm006.bmp)	126
Figure 4-166. EDS counting spectrum for the deposits (EDS3) on the coupon surface shown in Figure 4-165. (T4D30AlSubm03.jpg)	126
Figure 4-167. EDS counting spectrum for the flat coupon surface (EDS4), as shown in Figure 4-165. (T4D30AlSubm04.jpg)	126

Figure 4-168. SEM image, magnified 300 times, of a Test #1, Day 30, submerged aluminum coupon sample. (Test1submAl015.bmp).....	127
Figure 4-169. SEM image, magnified 1000 times, of a Test #1, Day 30, submerged aluminum coupon sample. (Test1submAl016.bmp).....	128
Figure 4-170. EDS counting spectrum for the light spot (EDS1) on the coupon surface shown in Figure 4-169. (T1AIEDS10.tif).....	128
Figure 4-171. EDS counting spectrum for the grey coupon surface (EDS2) shown in Figure 4-169. (T1AIEDS11.tif).....	128
Figure 4-172. SEM image at 650× magnification of a Test #2, Day 30, sample of fine powder on a vertical piece of the submerged PVC rack. (T2D30_Cor_Prod003_Fine Powder).....	130
Figure 4-173. SEM image at 1000× magnification of a Test #2, Day 30, sample of fine powder on a vertical piece of the submerged PVC rack. (T2D30_Cor_Prod002_Fine Powder).....	130
Figure 4-174. EDS counting spectrum for the entire SEM image shown in Figure 4-173. (T2D30EDS1-Fine Powder)	130
Figure 4-175. SEM image (130×) of a Test #2, Day 30, sample of white residue on a horizontal piece of the submerged CPVC rack. (T2D30_Cor_Prod004_White Powder on Rack).....	131
Figure 4-176. EDS counting spectrum for the white residue shown in Figure 4-175. (T2D30EDS2).....	131
Figure 4-177. SEM image, magnified 200 times, of a Test #3, Day 30, powder on the submerged rack. (T3~RackPowder013)	132
Figure 4-178. EDS counting spectrum for the powder on the submerged rack shown in Figure 4-177. (T3RackPowder09).....	133
Figure 4-179. SEM image, magnified 1000 times, of a Test #4, Day 30, fine powder on the submerged rack. (T4D30RackPowder030.bmp).....	133
Figure 4-180. EDS counting spectrum for the particles (whole image) shown in Figure 4-179. (T4D30RackPowder18.jpg)	134
Figure 4-181. SEM image, magnified 100 times, of the Test #5 Day 30, fine yellow powder on the submerged rack. (T5D30YellowDeposits001.bmp)	134
Figure 4-182. Annotated SEM image, magnified 1000 times, for the Test #5, Day 30, fine yellow powder on the submerged rack. (T5D30YellowDeposits003.bmp).....	135
Figure 4-183. EDS counting spectrum for the particulate deposit shown in Figure 4-182. (T5D30yllw~partcl02.jpg)	135
Figure 4-184. Stainless steel mesh covered with gel-like material.	136
Figure 4-185. Gel-like material recovered from the bottom of the tank.	136
Figure 4-186. SEM image of a Test #3, Day 30, white gel-like material from the top of the birdcage, magnified 100 times. (T3D30GelMaterial003, 5/9/05)	137
Figure 4-187. SEM image of a Test #3, Day 30, white gel-like material from the top of the birdcage, magnified 1000 times. (T3D30GelMaterial004, 5/9/05)	138

Figure 4-188. EDS counting spectrum for the white, gel-like material (whole image) shown in Figure 4-187. (T3D30Gel02, 5/9/05)	138
Figure 4-189. ESEM image of a Test #3, Day 30, white gel-like material from the top of the birdcage, magnified 1000 times. (t3Gel08, 5/6/05).....	139
Figure 4-190. EDS counting spectrum for the white, gel-like material shown in Figure 4-189. (t3geled6, 5/6/05)	140
Figure 4-191. XRD results for a Test #3, Day 30, white gel-like sample.	141

TABLES

Table 1-1. Test Series Parameters	2
Table 2-1. Quantity of Each Coupon Type in Every Test.....	7
Table 2-2. Material Quantity/Sump Water Volume Ratios for the ICET Tests.....	12
Table 2-3. Physical Parameters for the ICET Tests	12
Table 2-4. Chemical Parameters for the ICET Tests.....	12
Table 4-1. Test Conditions in the ICET Tests.....	29
Table 4-2. Composition of Precipitates from Test #1	44
Table 4-3. Composition of Precipitates from Test #5	44
Table 4-4. Distribution of Main Elemental Components of Precipitates from Tests #1 and #5	44
Table 4-5. Relative Amounts of Particle Deposits in Fiberglass	47
Table 4-6. Dry Mass Composition (%) of Unused Cal-Sil Samples by XRF Analysis.....	74
Table 4-7. Elemental Composition of the Sediment Samples from Different Tests Based on XRF Analysis	81
Table 4-8. Elemental Composition of the Fiberglass Samples Based on XRF Analysis.....	82
Table 4-9. Mean Weight Gain/Loss Data for Submerged Coupons (g).....	106
Table 4-10. Mean Gain/Loss Data for Unsubmerged Coupons (g)	112
Table 4-11. Standard Redox Potential of the Metals Used in the ICET Tests.....	113
Table 4-12. Elemental Compositions (by Mass %) of the Deposits and the Aluminum Coupon Surface, as Shown in Figure 4-163	127
Table 4-13. Elemental Compositions (by Mass %) of the Light and Grey Coating on the Aluminum Coupon Surface, as Shown in Figure 4-167	129
Table 4-14. Elemental Composition of Deposition Products Collected from Horizontal Surfaces on CPVC Coupon Racks after Tests Were Complete.....	132
Table 4-15. The Chemical Compositions for Figure 4-188	139
Table 4-16. Dry Mass Composition (%) of a Test #3 Day 30, White Gel-Like Sample by XRF Analysis.....	140

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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°C and 23°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°C rose higher than the 60°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