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D.2.4.2.4 Microtherm

The Microtherm insulation recovered from the autoclave test vessel was composed of two distinct phases. The first was the fibers from the woven blanket containing the microporous particulate. The second phase was the microporous particles, which had reduced to a mud-like coating on the support screen. The quantity of material also suggested a significant loss of material to the solution during the testing, likely the result of both dissolution and dispersion of the fine particles in the water column. A photograph of the Microtherm after testing is shown in Figure D.2-24.

Figure D.2-24 Microtherm Insulation Recovered from the Autoclave



After collecting the residual material and drying it in a laboratory oven, the material was examined using optical stereomicroscopy. The optical images of dried material showed that the mud-like substance dried to a dark cake that covered the fibers. At higher magnification, clear / white patches of deposit were also noted on the fibers. Sample images from the optical microscope exam are provided in Figure D.2-25 and Figure D.2-26.

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Figure D.2-25 Optical Micrograph of Microtherm after Testing – Overview



Figure D.2-26 Close-up of Microtherm Showing Deposit



SEM/EDS analysis of the residual material showed the presence of two distinct phases, individual fibers covered with particulate. Micrographs of the fiber and particulate are provided in Figure D.2-27 and Figure D.2-28. An overview EDS spectrum of the particulate is provided in Figure D.2-29. As seen in the EDS spectrum, the primary constituents of the residual particulates are silicon and titanium, with traces of sodium, aluminum, and phosphorous. Given the lack of a calcium peak, it appears that the phosphorous was likely the results of residual TSP that dried on the fibers.



Figure D.2-27 SEM Micrograph of Microtherm Fibers after Testing





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Higher magnification SEM/EDS analysis of the particulate material clearly distinguishes between the silicon and titanium phases, as shown in Figure D.2-30 and Figure D.2-31. Additional analyses also indicate that the clear deposit noted during the optical microscope exam is likely dried boric acid.



Figure D.2-30 SEM Micrograph and EDS Spectra of Silicon Phase

00339









D.2.4.2.5 Latent Debris

A small amount of latent debris, composed of silica sand and sodium-form bentonite, was recovered from the autoclave following the test. The material was collected, dried, and examined using an optical microscope. Latent debris images are shown in Figure D.2-32 and Figure D.2-33.



Figure D.2-32 Latent Debris Recovered after Testing

Figure D.2-33 Latent Debris - Close-up



D.2.4.2.6 Suspended Particulate

At the conclusion of the test, a quantity of suspended particulate material, either precipitates or entrained Microtherm, remained distributed on the autoclave internals and entrained in the final solution as observed in Figure D.2-34 and Figure D.2-35. After all of the debris materials had been removed from their support screens, the autoclave internals were rinsed into a catch basin to collect the residual material. This rinse liquid and the final drained solution were filtered through 0.45 µm laboratory filters to collect the particulate material. The composition of the recovered material was compared with suspended particulate that was filtered from two samples collected during the test.



Figure D.2-34 Autoclave Internals after Testing



Figure D.2-35 Final Solution from Test

A micrograph and EDS spectra of a particulate sample collected during the test can be found in Figure D.2-36, Figure D.2-37, Figure D.2-38. The results of a second sample may be found in Figure D.2-39. The results of these analyses indicate that the suspended material in the autoclave during the test was primarily composed of silicon, presumably silicates, with distributed particles rich in titanium, presumably from the Microtherm insulation. Varying amounts of other materials, including sodium, aluminum, and phosphorous, potentially from precipitation, were also present.





00272 BSE



70µm

Element	Weight%	Atomic%
ОК	72.93	82.05
FΚ	3.37	3.19
Na K	2.34	1.84
Mg K	0.31	0.23
ALK	2.57	1.72
Si K	14.61	9.36
ΡK	0.85	0.49
Ca K	0.29	0.13
Ti K	2.05	0.77
Fe K	0.68	0.22
Totals	100.00	







Element	Weight%	Atomic%
O K F K Na K Al K Si K P K Ti K Fe K	60.24 1.74 1.11 0.39 35.87 0.35 0.12 0.19	72.22 1.75 0.93 0.28 24.49 0.22 0.05 0.05
Totals	100.00	





Point 3 Point 3 Ti F 1 2 3 4 5 6 7 Full Scale 27434 cts Cursor: 1.089 (880 cts) keV

Element	Weight%	Atomic%
O K F K Al K Si K Ti K	50.09 1.40 0.14 0.43 47.95	74.09 1.74 0.12 0.36 23.69
Totals	100.00	



Figure D.2-39 SEM Micrograph and EDS Analysis of Sample #2



Element	Weight%	Atomic%
O K Na K Mg K Al K Si K P K Ca K	42.19 2.83 0.17 2.12 2.47 4.43 0.67	67.59 3.16 0.18 2.02 2.26 3.67 0.43
FeL	45.12	20.71
Totals	100.00	

In addition to the mid-test samples, additional samples of the residual material collected at the end of the test were also examined using SEM/EDS. Two representative images and spectra are provided in Figure D.2-40 and Figure D.2-41 The results of these analyses indicate that the material recovered at the end of the test did not differ significantly from the suspended material present during the test. However, the material did appear to show a more equal distribution of titanium and silicon, indicating that a greater fraction may have been from Microtherm.

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50µm

[¬] Electron Image 1



D.2.4.2.7 Post-Test Weights of Debris Material

In addition to the post-test analysis performed on the debris material and simulated particulate, these materials were also weighed at the conclusion of the test. This data is presented in order to assist in preparing weight-loss corrosion values for the debris sources as part of the chemical precipitate generation calculation. The final mass of all the materials is provided in Table D.2-7.

Material	Final Mass (grams)
NUKON [®] Fibers	0.2451
Microtherm Insulation	0.7200
Aluminum Coupon	2.3732
Concrete Coupon	41.4978
Latent Particulate	0.3126
Recovered Precipitate / Particulate	0.7643

Table D.2-7	Final Mass	of all Recovered	Materials
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D.2.5 Conclusions

The objective of the chemical effects testing is to determine the types and approximate quantities of deposits that form as a result of the reaction of debris materials and buffering chemicals in the IRWST. The results of Section D.2.4 serve as input to the IRWST Sump Chemistry Modeling (Appendix D, Section D.3) for determining the chemical precipitate generation for the U.S. EPR plant.

Chemical effects testing utilized simulated debris materials at a loading that conservatively bounds the expected loading of an actual U.S. EPR plant. Because the details of the final debris loading of the U.S. EPR plant was not known at the time of testing, the test conditions were not designed to match a specific accident scenario. Therefore, the test results are normalized using the relative debris loading prior to their use in the design calculation to determine the chemical precipitate generation. The

deviation in the mass of NUKON[®] loading is also taken into account when evaluating the silicon releases from this test.

In addition to the detailed results presented in Section D.2.4, the following general conclusions are drawn from the chemical testing results.

- The NUKON[®] insulation material behaved as expected during the test. The sample experienced a mass loss of 0.2361 grams, assumed to be due to the dissolution of silica in the simulated IRWST conditions. Based on the test data, the mass loss was gradual and approximately constant throughout the exposure period.
- The Microtherm insulation material presented an issue during testing. Based on the pre-test and post-test weights, there was a mass loss of 1.8725 grams from the sample. However, an unknown amount, believed to be a significant fraction of the mass loss, was due to distribution of the particulate throughout the autoclave during testing. Based on the dissolved silicon trend during the test, it is concluded that the amorphous silica dissolves readily under IRWST condition due to the small particle size. After approximately 24 hours of exposure, the rapid decrease in the silicon release rate indicates that the Microtherm source had been exhausted.
- The aluminum coupon experienced a mass loss of 0.0281 grams during the test. The initial corrosion / release rate of aluminum was higher than literature values suggested due to the active corrosion of the clean aluminum surface. After approximately 24 hours of exposure, the aluminum coupon had passivated, and the aluminum release rate decreased to a value more consistent with the literature.
- The concrete coupon exhibited a mass loss of 1.0295 grams during the testing, which is consistent with pre-test expectations. However, the quantity of calcium that would have been released from the coupon was not adequately accounted for in the post-test samples, either in the liquid samples or recovered particulate.

It was noted, however, that many of the samples contained minor amounts of calcium. It is concluded, based on the test data, that the calcium released from the coupon precipitated as calcium phosphate and distributed throughout the autoclave and sample surfaces. The distribution of the material over such a large area, and number of samples, made quantification of the recovered mass impractical.

D.3 IRWST Sump Chemistry Modeling

D.3.1 Purpose

The purpose of the IRWST sump chemistry modeling is to identify the specific compounds and quantities of materials that may precipitate within the U.S. EPR reactor containment sump pool following a LOCA. The sump chemistry modeling utilizes the results of the Chemical Effects Testing (Section D.2). The IRWST sump chemistry modeling results serve as a basis and input to the ECCS Strainer Performance Testing (Appendix E).

D.3.2 Methodology

Information in the public domain was used to develop the rate at which containment debris releases its constituent chemical species. The estimated chemical release rates were then validated and/or modified by simulating the LOCA event in a test facility recirculating autoclave (Section D.2 of Appendix D). The validated release rates are used to determine the chemical species released to the sump fluid over a 30-day period for input to a thermodynamic model.

Important features of the autoclave test are:

The amount of containment debris generated (NUKON[®] fiber, pulverized concrete, sand, clay, and Microtherm particulate) and concrete and aluminum surface areas exposed to the sump liquid were scaled from the minimum sump pool volume to the 7.5-liter autoclave volume. Table D.3-1 illustrates the scaling

factors that were applied. One exception to the values listed in the table was the amount of NUKON[®] fiber added to the autoclave. The total amount of NUKON[®] fiber added to the autoclave prior to the Chemical Effects Test was 0.4812 grams of prepared (baked and shredded) fiber instead of 0.0933 grams of prepared fiber and 0.0330 of virgin fiber. This change was evaluated and determined to be acceptable since the purpose of the Chemical Effects Test was to provide chemical release rate (corrosion) data for input to and verification of the thermodynamics model. The actual pretest weight of 0.4812 grams of NUKON[®] fiber was used in determining the post-test weight loss and associated chemical release rate.

- Trisodium phosphate dodecahydrate was added by circulating the autoclave liquid through a cylinder containing the scaled amount of dry chemical. Sample measurements of the fluid (pH, sodium, and phosphate concentrations) indicated that the chemical dissolved completely in approximately 2 hours.
- The IRWST temperature transient (as predicted at the time of the test) was simulated.
- The autoclave volume turnover rate was equivalent to the sump volume turnover rate.
- The autoclave was operated for 158.33 hours (approximately 6.5 days).

Constituent	Constituent Plant Input		NOTES Amount in 7.5 L	
Coolant	12,200 lb _m (Na ₃ PO ₄ ·12H ₂ O)	0.210 lb/ft ³	(3.36 g/l TSP p	+ boron @ 2800 pm)
Metallic Aluminum	3000 ft ²	0.005179 ft ² /ft ³	2.0 in ²	100% submerged
NUKON [®] fiber generated	6.62 ft ³	0.000114 ft ³ /ft ³	0.0330 g	100% submerged
Microtherm generated	40 ft ³	0.000691 ft ³ /ft ³	2.5888 g	100% submerged
Concrete (surface)	7400 ft ²	0.1277 ft ² /ft ³	4.87 in ²	100% submerged
	45 lb _m (NUKON [®] fiber)	0.000327 ft ³ /ft ³	0.0933 g	100% submerged
Latent Debris	255 lb _m (particulate sand, clay, and pulverized concrete)	0.00440 lb _m /ft ³	0.5290 g	100% submerged

Table D.3-1 Chemical Effects Ratio – Material Quantity versus IRWST Volume

Samples of the recirculating solution were taken periodically during the test and analyzed by inductively coupled plasma-mass spectroscopy (ICP-MS) to determine the concentration of the cations in solution as a function of time. Following the test, the autoclave was drained while hot, and the solution was allowed to cool before filtering to recover and weigh any particulates remaining in suspension. After the internal assembly was removed, available solid material remaining in the autoclave was collected and weighed. Finally, the simulated containment debris and concrete and aluminum coupons were weighed for comparison with pretest weights to determine corrosion weight loss.

D.3.3 Selection of Chemical Release Rates

A number of publicly available reports issued in support of GSI-191 were reviewed, and the applicable information was used to estimate the chemical release/corrosion rate for solid concrete, NUKON[®] fiber, Microtherm particulate, and aluminum Alloy 1100.

Pulverized concrete was assumed to release its constituent chemicals immediately because of the large particulate surface area. Sand and clay (bentonite) particulate were assumed to be insoluble. The approach used to determine the chemical release from the other materials is described in the following paragraphs.

D.3.3.1 Solid Concrete

Appendix B of Reference 1 provides the leaching rates for the elemental release of aluminum, calcium, and silicon from solid concrete as derived from linear fits to test data for borated containment water at pH 10 and temperatures of 140°F, 194°F, and 230°F. Table D.3-2 provides the elemental release rates for concrete. Although it was reported that tests were done at pH 7 as well, data was not included in Reference 1.

Temperature	AI	Ca	Si
°F	g/m²•hr	g/m²•hr	g/m²•hr
140	2.95E-02	7.29E-01	3.79E-02
194	5.93E-02	1.18E+00	1.12E-01
230	8.94E-02	2.20E+00	1.54E-01

Table D.3-2 Measured Release Rate for Concrete in Borated Water at
pH 10

Similar data was reported in Reference 2 for concrete in borated containment water at pH 8 and a temperature of 190°F. The ratio of exposed concrete surface area to solution volume was $15.72 \text{ m}^2/\text{m}^3$. Leachate concentrations for calcium and silica were reported for the 90-minute test as 38.3 ppm and 10.1 ppm, respectively. Aluminum was reported as less than detectable. These elemental concentrations can be converted to a release rate (RR) as follows:

RR =
$$(concentration)/(surface area ratio)/(time), g/m2·hr (1)$$

Applying Equation (1) to the reported values gives release rates of 1.62 and 0.428 g/m2h for calcium and silica, respectively. Based on this data, the release rates for

calcium and silica at pH 8 are 1.37 and 3.82 times higher than at pH 10. To determine the estimated release rates to be used for this study, the release rates in Table D.3-2 were multiplied by these factors and plotted in Figure D.3-1. The release rate expressions, based on a linear fit to the data points, are also shown in the Figure D.3-1 for elemental calcium and elemental silica. Linear, polynomial, and exponential fits of the calcium data points were compared. Because the linear fit more conservatively encompasses the middle of the temperature range where the bulk of the transient time is spent, it produced the most conservative releases. The extrapolation of the fit is deemed to be justified because

- 1. The solubility of CaCO₃ and SiO₂ does not change significantly over that temperature range.
- 2. In the absence of solubility changes, the corrosion kinetics are regular and predictable.
- 3. Any error introduced will have only a small impact on the results due to the short time spent above 230°F.

Because aluminum concentration was reported as less than detectable in the pH 8 test reported in Reference 2, its contribution was considered negligible, so no attempt was made to derive a similar release rate expression for aluminum.

The adjusted release rate expressions for calcium and silica were used to calculate a predicted weight loss for the solid concrete specimen exposed to the pH 7.4 autoclave test solution. As reported in Table D.3-6, the predicted weight loss was 0.971 grams, and the measured weight loss was 1.0295 grams. Considering the uncertainties inherent in experimental data, this reasonably close agreement was considered sufficient to validate the derived release rate expressions.



Figure D.3-1 Estimated Solid Concrete Release Rate at pH 8

D.3.3.2 Pulverized Concrete

Because of the very large surface area of the pulverized concrete particles, it is assumed that the chemical constituents of the powder were immediately released to the autoclave liquid. The amount of pulverized concrete added to the autoclave was 0.1757 grams. Scanning electron microscope / energy dispersive X-ray spectroscopy (SEM/EDS) analysis of the powder was conducted to determine the major chemical constituents. Table D.3-3 provides the SEM/EDS composition of the pulverized concrete.

Element	Weight %	Atomic %
O k	62.25	77.90
Na k	0.13	0.12
Mg k	1.61	1.33
Al k	1.59	1.18
Si k	11.21	8.00
S k	0.44	0.28
Κk	0.46	0.24
Ca k	21.07	10.53
Ti k	0.12	0.05
Fe k	0.81	0.29
Cu k	0.29	0.09
Totals	100.00	

Table D.3-3 Pretest SEM/EDS Composition of Pulverized Concrete

Note: The 'k' following each element indicates results based on k-shell electron emissions.

From this analysis, the weight of elemental calcium (Ca), silicon (Si), aluminum (AI), and magnesium (Mg) available in 0.1757 grams for release to the autoclave liquid would be 19.7 mg of Si, 37 mg of Ca, 2.8 mg of Mg, and 2.8 mg of AI. Dividing by the autoclave liquid volume of 7.5 liters gives the following concentrations: 2.6 mg/l of Si, 4.9 mg/l of Ca, and 0.37 mg/l of AI and Mg. These concentrations were assumed to be present in solution immediately on filling the autoclave.

D.3.3.3 NUKON[®] Fiber

Appendix B of Reference 1 also contains measured corrosion rates for NUKON[®] glass at pH 7 in 0.259 M boric acid as H_3BO_3 [2800 ppm B] at 140, 194, and 230°F. Trisodium phosphate [Na₃PO₄ · 12H₂O] was used to adjust the solution pH to 7. The measured corrosion rates in g/m²·hr reported in Reference 1 and a polynomial curve fit to the data are shown in Figure D.3-2 along with an expression for the corrosion rate. The curve fit is extrapolated up to 250°F to allow for the calculation of the corrosion for the short time where the IRWST temperature exceeds 230°F. Extrapolation is deemed to be justified because:

- 1. The solubility of SiO₂ does not change significantly between 230°F and 250°F.
- 2. In the absence of solubility changes, corrosion kinetics are regular and predictable.
- 3. Any error introduced will have only a small impact on the results due to the short time spent above 230°F.





The data that were linearly regressed in Reference 1 to determine corrosion rates are replotted in Figure D.3-3 to illustrate the change in release rate with time. The linear release rates shown in Figure D.3-2 are shown in Figure D.3-3 as dotted lines. The gradient of these curves, which is the fiberglass corrosion rate, decreases with time for

all three temperatures, suggesting that the corrosion rate of the NUKON[®] glass (in $g/m^2 \cdot hr$) becomes negligible after ~100 hours. This result was used to approximate the fiberglass corrosion rate as a first order function of time corresponding to the solution temperature for the first 80 hours of exposure. Based on the literature data shown in Figure D.3-3 and independent AREVA testing, discussed in Section D.2, the chemical releases from fiberglass are negligible after 80 hours of exposure, and therefore, the corrosion rate was set to zero for times >80 hours in the chemical debris calculation

One possible explanation for the decrease in release rate is a physical change initiating from the fiber outer diameter (OD) as the chemicals are released, similar to a dealloying mechanism in metals. As the chemicals leach from the glass, the outward diffusion path for the unaffected material increases in distance radially leading to a decrease in release rate. The physical changes that occurred during the test are seen in Figure D.3-4. Also, note the presence of a film on the OD of the fibers, bridging the two fibers shown. This film likely formed after the fibers were removed from the autoclave and the liquid evaporated.

Also, note in Figure D.3-3 that the linear release rates are a reasonable approximation up to 80 – 100 hours depending on temperature. For the present case, it is assumed that the corrosion/release rate is negligible after 80 hours of exposure.



Figure D.3-3 Mass Release Rate versus Time for NUKON[®] Fiber at pH 7



Figure D.3-4 Post-test Appearance of NUKON[®] Fiber

For the corrosion rates shown in Figure D.3-2 to be used in release rate calculations, it is necessary to know the volume and surface area of the fiber exposed to the sump fluid, as well as its chemical composition. Following the approach defined in Reference 1, the surface area A_{fg} of glass fiber per unit volume is determined from the following relationship:

$$A_{fg} = [(V_{NUKON\&} / V_w) \times \rho_{NUKON\&}) / (\rho_{fg})] \times A_{fg} / V_{fg}$$
(2)

where:

$V_{NUKON \mathbb{R}} / V_w$	= volume of NUKON [®] per volume of water, m ³ /m ³
O _{NUKON®}	= density of NUKON [®] , 38.1 kg/m ³
D _{fg}	= density of fiber glass, 2,500 kg/m ³
A _{fg} /V _{fg}	= surface area/volume ratio of glass fiber, $4.3 \times 10^5 \text{ m}^2/\text{m}^3$

The release rate of glass fiber in mol/liter hr is determined by multiplying the corrosion rate of NUKON[®] in Figure D.3-2 by the surface area, A_{fg} (Equation 2) divided by the molecular weight of NUKON[®] glass fiber, 60.71 g/mol. Finally, the release rate, RR_{*i*}, of component *i* is found by multiplying the release rate of glass fiber by its molecular weight (MW_{*i*}) and mole fraction:

$$RR_i = RR_{fg} \times MW_i \times (mole \ fraction)_i$$
(3)

The component molecular weights and mole fractions of NUKON[®] fiber insulation are shown in Table D.3-4.

NUKON®	Molecular Weight	Mole
Component	g/mol	Fraction
SIO ₂	60.084	0.637
Al ₂ O ₃	101.961	0.022
CaO	56.077	0.090
MgO	40.304	0.053
Na ₂ O	61.979	0.156
B ₂ O ₃	69.618	0.044

 Table D.3-4 Chemical Composition of NUKON[®] Fiber Insulation

For the autoclave test, 0.481 grams of baked and shredded NUKON[®] fiber were used. For this amount of fiber in 7.5 liters of solution, the release rates were calculated to be:

- SiO₂: RR = (5.361E-05) x T² (9.622E-03) x T + 3.794E-01
- AI_2O_3 : RR = (3.142E-06) x T² (5.639E-04) x T + 2.224E-02
- CaO : RR = (7.0695E-06) x T² (1.269E-03) x T + 5.003E-02
- MgO : RR = $(2.992E-06) \times T^2 (5.370E-04) \times T + 2.118E-02$
- Na₂O : RR = (1.354E-05) x T² (2.431E-03) x T + 9.585E-02
- B₂O₃ : RR = (4.291E-06) x T² (7.701E-04) x T + 3.037E-02

The above equations were used to calculate the release rates versus time for the first 80 hours of the autoclave test to confirm their validity for the U.S. EPR LOCA calculations.

D.3.3.4 Aluminum

At the buffered pH 7 expected for the U.S. EPR design basis LOCA, corrosion of the aluminum coupon is expected to be low. Figure D.3-5 illustrates the corrosion rate for A1100 calculated by OLI *CorrosionAnalyzer*[™] in the borated solution compared with the few data points published in the NUREG documents. As expected, the pH 9 corrosion rate data points plotted in Figure D.3-5 are much higher than the pH 7 corrosion rates.

The post-test measured weight loss for the aluminum coupon was 0.0281 grams, as indicated in Table D.3-6. Assuming a linear corrosion rate during the 158 hour test, the calculated average corrosion rate is:

Corrosion Rate = (weight loss/surface area/time)

= 0.0281 g / .00129 m² / 158 hr

This corrosion rate is much higher than would be predicted in Figure D.3-5 for aluminum at pH 7, but can be understood by considering the concentration of aluminum in solution as measured by ICP-MS and shown in Figure D.3-6. Assuming that the initially released aluminum is primarily from active corrosion of the aluminum coupon, the corrosion rate can be approximated with a linear fit of 0.95 g/m²·hr during the first 20 hours. Using this linear corrosion rate, the calculated weight loss after 20 hours would be 0.0245 grams, which is in very good agreement with the measured weight loss of 0.0281 grams.

Following this period of active corrosion, the rate of corrosion likely decreased as the aluminum in solution approached its solubility limit of approximately 5 ppm as noted in Reference 3, and/or until the surface became fully passivated. It is also possible that

the phosphate ions in solution reacted with the aluminum corrosion film forming augelite, $AI_2PO_4(OH)_3$, inhibiting further corrosion (Reference 4).







Figure D.3-6 Measured Concentration of Aluminum in Solution

From Figure D.3-6, it is evident that most of the aluminum released stayed in solution $\{as Al(OH)^{-4}\}$ at its solubility limit during the test.

For the U.S. EPR LOCA calculations, it is conservatively assumed that the aluminum metal exposed to the sump liquid actively corrodes at a rate of 0.95 g/m²·hr for the first 20 hours, and at a much lesser rate after 20 hours as determined by OLI *Corrosion Analyzer*TM (refer to Figure D.3-5) according to the following exponential curve fit:

Corrosion Rate = (8E-05) $e^{0.0283T}$

Where:

Corrosion Rate = metal released to solution in g/m^2 hr.

T = IRWST temperature in °F.

For the U.S. EPR sump calculations, it is assumed that any aluminum released from aluminum metal and from NUKON[®] fiber precipitates as it is released to the solution. This assumption defines the maximum amount of chemical (precipitate to use in sump screen testing.

D.3.3.5 Microtherm

Microtherm is a dense composite comprised of granular material and a small amount of fibrous material. For the autoclave test, it was assumed that the quilted material was torn open during the LOCA event, releasing the granular and fibrous material to the sump liquid.

Per the material safety data sheet, the granular material is composed of 35 to 70 percent amorphous silica, 20 to 60 percent titanium dioxide, and 0 to 25 percent aluminum oxide (Reference 5). Testing done by CNWRA (Reference 2) found Microtherm to be the most reactive insulation material tested, releasing significant quantities of silica while becoming enriched in titanium and exhibiting a marked change in surface appearance. EDS analysis of a sample of the granular material used in the autoclave test (refer to Table D.3-5) confirmed that silica and titanium were the major elements present. Assuming that the silica is present as SiO₂, the titanium as TiO₂, and the aluminum as Al₂O₃, the compound weight percentages in this sample analysis are 44.1 percent, 12.0 percent, and 0.3 percent, respectively. These results suggest that the aluminum oxide content was at the low end of the expected range and the silica content was within the expected range of 35 to 70 weight percent.

Element	Weight%
0	70.67
F	1.14
AI	0.16
Si	20.60
Ti	7.20
Fe	0.08
Cu	0.15
Total	100.00

Table D.3-5 Pretest SEM/EDS Composition of Microtherm

Review of the autoclave silica concentration as determined by ICP-MS analysis (refer to Figure D.3-8) suggests that there are at least two separate sources of silica (indicated by the dashed and solid lines) with markedly different release rates. Since Microtherm particulate is the most reactive material, a reasonable conclusion is that the amorphous SiO₂ available from Microtherm is the primary source of silica in solution during the first 20 hours of the test. Assuming that the 2.5925 grams of Microtherm added to the autoclave is 35 wt% SiO₂, there would be approximately 0.91 grams of SiO₂ (0.42 grams of Si) available for release. For an initial estimate of silica release from the Microtherm, it is assumed that all 0.91 grams of SiO₂ is released in 20 hours at a linear rate of 6 mg/liter·hr.



Figure D.3-7 Measured Silica Concentration

In developing the model for the sump calculations, the assumption was made that the Microtherm particulate material added to the autoclave was composed of 70 weight percent of SiO_2 and 25 weight percent of Al_2O_3 . The silica is assumed to be released at the rate of 6 mg/liter hr, as measured in the autoclave test. Although significant aluminum release from Microtherm was not seen during testing, the full content of Al_2O_3 is assumed to be released at 6 mg/liter hr. for calculating IRWST loading.

D.3.4 Validation of Chemical Release Rates

D.3.4.1 Comparison of Estimated Chemical Release Rates with Autoclave Test

The chemical masses released by each of the materials exposed to the autoclave sump liquid as a function of time were calculated using the relationships developed in Section D.3.3. Table D.3-6 summarizes the weight losses for these materials compared with the predicted weight losses. The largest difference between measured and predicted is for Microtherm. Because of Microtherm's very small particulate size, some quantity of the material was lost to the system and/or included in the material recovered from the

bottom of the autoclave following the test. The remaining predictions are reasonably close to the measured values or bound the measured values, and based on this agreement, the relationships developed in Section D.3.3 are considered valid for calculating the material release in the U.S. EPR LOCA event.

Material		Weight, g	Notes
	Pre-test	42.5273	
Conorata	Post-test	42.5837	
COncrete	Post-test	41.4978	After cleaning
	Weight Loss	1.0295	0.971 grams predicted
	Pre-test	2.4013	
Aluminum	Post-test	2.3848	Before cleaning (0.0165 grams weight loss)
	Post-test	2.3732	After cleaning
	Weight Loss	0.0281	0.0245 grams predicted
	Pre-test	0.4812	
	Post-test	0.5029	
NUKUN	Post-test	0.2451	After drying
	Weight Loss	0.2361	0.416 grams predicted
	Pre-test	2.5925	
Microtherm	Post-test	0.7200	
Wieretreim	Weight Loss	1.8725	Unknown quantity lost to system due to its small particle size
	Pre-test	0.5388	Pulverized cement : 0.1757 grams, bentonite: 0.1855 grams, sand: 0.1776 grams
Latent Debris	Post-test	0.3126	
Debris	Weight Loss	0.2262	Assume pulverized cement is dissolved quickly. Bentonite and sand are insoluble in water.
Recovered	Post test	0.4060	7% CaHPO ₄ ; 11-14% NaAlSi ₃ O ₈ ; balance: titanium
Precip.	Filtered	0.3583	Material collected on 16 filters
	Total	0.7643	Precipitated material & Microtherm particulates

Table D.3-6 Measured Weight Losses of Materials

OLI *StreamAnalyzer*[™] was used to calculate the at-temperature solution pH, the concentrations of aqueous species in solution, and the identity and quantity of precipitates formed for comparison with the measured data. The chemical species released to the solution during the autoclave test, calculated using the relationships

developed in Section D.3.3, and other test variables input to *StreamAnalyzer* are tabulated in Table D.3-7. The pH (at temperature) values (pH_T) shown in Table D.3-7 are the values calculated by *StreamAnalyzer*.

 Table D.3-7 Estimated Chemical Releases during Autoclave Test

				Cor	icrete & Al-1	100	Nukon™ & Microtherm						
time	Т	Na ₃ PO ₄	B(OH)₃	рН _{т(осі)}	Ca	AI	Si	SiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	B ₂ O ₃
hours	٩F	mg/l	mg/l		mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
0	110	0	16014	4.50	4.90E+00	3.75E-01	2.60E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.08	110.3	134	16014	6.25	4.91E+00	3.89E-01	2.60E+00	5.00E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.60	156.9	2688	16014	7.24	5.74E+00	6.43E-01	2.76E+00	9.89E+00	1.69E-02	3.79E-02	1.61E-02	7.26E-02	2.31E-02
3.62	188.6	3360	16014	7.25	7.50E+00	9.84E-01	3.12E+00	2.30E+01	7.27E-02	1.63E-01	6.93E-02	3.13E-01	9.93E-02
7.38	208.7	3360	16014	7.25	1.16E+01	1.63E+00	3.97E+00	4.82E+01	2.28E-01	5.14E-01	2.18E-01	9.83E-01	3.12E-01
9.10	214.4	3360	16014	7.27	1.35E+01	1.92E+00	4.39E+00	5.98E+01	3.07E-01	6.91E-01	2.92E-01	1.32E+00	4.19E-01
10.83	170.9	3360	16014		1.47E+01	2.22E+00	4.63E+00	7.07E+01	3.38E-01	7.59E-01	3.22E-01	1.45E+00	4.61E-01
13.58	215.6	3360	16014	7.27	1.79E+01	2.69E+00	5.30E+00	8.94E+01	4.66E-01	1.05E+00	4.44E-01	2.01E+00	6.37E-01
16.08	228.8	3360	16014		2.12E+01	3.13E+00	6.00E+00	1.07E+02	6.10E-01	1.37E+00	5.81E-01	2.63E+00	8.34E-01
17.33	229.9	3360	16014	7.29	2.28E+01	3.34E+00	6.35E+00	1.16E+02	6.84E-01	1.54E+00	6.51E-01	2.94E+00	9.34E-01
20.00	219.8	3360	16014		2.60E+01	3.80E+00	7.03E+00	1.34E+02	8.17E-01	1.84E+00	7.78E-01	3.52E+00	1.12E+00
24.08	209.8	3360	16014		3.06E+01	3.82E+00	7.99E+00	1.37E+02	9.90E-01	2.23E+00	9.42E-01	4.26E+00	1.35E+00
30.08	194.8	3360	16014	7.27	3.64E+01	3.84E+00	9.20E+00	1.40E+02	1.18E+00	2.65E+00	1.12E+00	5.08E+00	1.61E+00
40.08	190.2	3360	16014		4.58E+01	3.87E+00	1.11E+01	1.45E+02	1.47E+00	3.30E+00	1.40E+00	6.31E+00	2.00E+00
50.08	170.1	3360	16014	7.28	5.30E+01	3.89E+00	1.26E+01	1.48E+02	1.64E+00	3.68E+00	1.56E+00	7.05E+00	2.24E+00
57.08	164.8	3360	16014		5.77E+01	3.90E+00	1.35E+01	1.50E+02	1.74E+00	3.91E+00	1.66E+00	7.49E+00	2.38E+00
62.08	160.0	3360	16014	7.29	6.08E+01	3.91E+00	1.41E+01	1.51E+02	1.80E+00	4.05E+00	1.72E+00	7.76E+00	2.46E+00
80.00	160.0	3360	16014		7.21E+01	3.93E+00	1.63E+01	1.55E+02	2.03E+00	4.55E+00	1.93E+00	8.72E+00	2.77E+00
158.00	160.0	3360	16014	7.34	1.23E+02	4.05E+00	2.61E+01	1.55E+02	2.03E+00	4.55E+00	1.93E+00	8.72E+00	2.77E+00

The concentrations of silicon and aluminum ions in solution are available in the *StreamAnalyzer* output and are plotted in Figure D.3-9 for comparison with the measured concentrations. As discussed in Section D.3.4, the kinetics of precipitation for aluminum appears to be controlling, as the concentration of aluminum in solution remained at the solubility limit during the test period. To compare the predicted releases vs. the measured values, it was necessary to "turn off" the precipitation of aluminum species in the calculations. The resulting predicted and measured aqueous concentrations are shown in Figure D.3-8. The agreement between the predicted and measured values is further validation of the relationships for chemical release developed in Section D.3.3.



Figure D.3-8 Comparison of Agueous Concentrations Calculated with StreamAnalyzer with Measured Values (Aluminum Precipitation Turned Off)

If precipitation of aluminum species is allowed in the calculations, the concentration of aluminum immediately drops to zero as there is sufficient sodium and silica in solution to form sodium aluminum silicate, NaAlSi₃O₈. As indicated in Table D.3-6, the formation of NaAlSi₃O₈ was confirmed by SEM/EDS as present in the solid material collected from the autoclave following the test.

Figure D.3-9 shows the concentrations in solution when aluminum is allowed to precipitate. Note that the aluminum concentration in solution is zero and that the silica concentration is decreased by the formation of sodium aluminum silicate. In reality, as noted in the previous paragraph, some quantity of aluminum did precipitate as NaAlSi₃O₈ during the test, even though the kinetics are slow. For U.S. EPR LOCA calculations, it will be assumed that all aluminum released forms precipitates. For purposes of sump screen testing, this assumption is conservative.



Figure D.3-9 Comparison of Aqueous Concentrations Calculated with *StreamAnalyzer* with Measured Values (Aluminum allowed to Precipitate)

Another precipitate that was expected to form during the test was calcium phosphate, Ca₅(PO₄)₂. The major source of calcium is the concrete, and the release rate was assumed to be directly proportional to temperature and constant with time. As noted in Table D.3-6, the measured weight loss for the concrete coupon in the test correlated closely with the weight loss predicted using the estimated release rates for calcium and silica. The amount of calcium phosphate that should have precipitated during the autoclave test as determined by OLI *StreamAnalyzer* is approximately 2.1 grams. Only a small amount of calcium phosphate was detected by EDS (refer to Table D.3-6) in the solid material collected after the test. However, since minor amounts of calcium were detected in most solid samples, it is believed that the calcium phosphate was distributed throughout the autoclave and test loop, making quantification impractical. It is concluded that the release rate estimates for concrete developed in this document are

valid and can be used for the sump calculations. This approach should be conservative, based on the results of the autoclave test.

D.3.5 Key Assumptions

Using the release rates identified in Sections D.3.3 and D.3.4, identification and quantities of chemical precipitates formed and sump pH values were determined using the OLI Systems, Inc. *StreamAnalyzer* equilibrium thermodynamic Mixed Solvent Electrolyte (MSE) model (refer to section D.3.7). The following assumptions are implicit in the results:

- System transients and non-equilibrium conditions are not considered. Each phase (solid, liquid, and gas) is assumed to be in thermodynamic equilibrium with the surrounding phases.
- Kinetic reaction rates are not included in the model. As a result, all species that reach thermodynamic saturation are assumed to precipitate to reach equilibrium. In reality, some degree of supersaturation is required to prompt solid nucleation and initiate precipitation from solution. In particular, the precipitation of aluminum compounds such as AlOOH and Al(OH)₃ is complex, and some degree of supersaturation can persist for significant periods of time before precipitation occurs. As discussed previously, this was apparently the case in the autoclave test, where the concentration of aluminum ions in solution was constant during the test period at the solubility limit of aluminum.
- No species-specific interactions that could potentially influence crystal nucleation and growth are considered. As a result, reactions that inhibit precipitation are not replicated, thereby making the calculation results conservative.
- Chemical release rates were determined from published literature test results and were verified where possible by comparison with the autoclave test results.
- The thermodynamically favored form of calcium phosphate precipitate considered by *StreamAnalyzer* is hydroxyapatite, Ca₅(OH)(PO4)₃, which is a

metastable, poorly-crystallized phosphate. For the sump calculations, hydroxyapatite will not be allowed to form; instead, the precipitate allowed to form will be calcium phosphate, $Ca_5(PO_4)_2$.

- The multi-node calculation of the IRWST temperature provides data for the liquid temperature and containment pressure up to approximately 20 hours after the break. Because the duration of the chemical precipitate calculation is 720 hours, the temperature and pressure data from the previous revision was used for the remainder of the time. This approach is conservative because the temperatures in the two calculations converge at approximately 20 hours, with the multi-node calculation decreasing at a slightly greater rate.
- For conservativism regarding the effect of Microtherm insulation on the chemical precipitate generated in the IRWST, the following assumptions are made as part of the chemical release calculations.
 - The Microtherm insulation is assumed to contain the maximum listed silica concentration of 70 percent, which will be released to the IRWST at a rate of 6 mg/liter hr, as estimated from the autoclave testing.
 - Although the Mirotherm insulation that was utilized in the autoclave test did not contain a significant amount of aluminum oxide, the chemical precipitation calculation assumes that the maximum concentration of 25 percent is present. Because the aluminum release from Microtherm could not be determined during the autoclave test since there was little or no aluminum in the sample acquired, a release rate of 6 mg/liter hr will be assumed. Given the lower proportion of aluminum in the compound, this rate is conservative.
 - Because titanium dioxide will be inert under IRWST conditions, titanium will not be considered in the chemical precipitate calculation.

D.3.6 Calculation of Chemical Precipitates Formed During LOCA

The concrete surface area identified for the autoclave test was bounded by assuming that the entire heavy floor would be exposed to the recirculating flow. However, since the concrete is protected with an epoxy or equivalent coating and only the coatings within a LOCA blast radius would fail, the actual exposed surface area will be much smaller and depend directly on the location of the break. In addition, the quantity of debris generated by a LOCA blast and subsequent blowdown or High Energy Line Break (HELB) has been finalized in the debris generation evaluation for the U.S. EPR. This information was used to select the location that would generate the largest amount of debris. The resulting debris masses and exposed concrete surface area were then used to calculate the chemical precipitates that would form during the 30-day period following the break.

The results of the Debris Generation Evaluation (Appendix C) conclude that the fibrous insulation has been removed from the zone of influence of all analyzed breaks. However, for conservatism, the largest quantity of fibrous insulation previously determined, the RCS crossover leg piping at the steam generator (SG) 3 outlet nozzle, will be used in the calculation. Table D.3-8 lists the debris generated for the RCS crossover leg break at the SG3 outlet nozzle.

Sump Pool Volume: 57,916 ft3 (1.64x106 L)						
Class	Plant Input	Ratio				
Coolant	12,200 lb _m (Na ₃ PO ₄ ·12H ₂ O)	0.210 lb _m /ft ³				
NUKON [®] fiber generated	6.62 ft ³	1.143x10 ⁻⁴ ft ³ /ft ³				
Microtherm generated	1 ft ³	1.727x10 ⁻⁵ ft ³ /ft ³				
		6.475x10 ⁻⁴ lb _m /ft ³				
	10.2 lb _m (NOKON liber)	2.725x10 ⁻⁴ ft ³ /ft ³				
Latent Debris	139.8 lb _m (particulate sand, clay, and pulverized concrete)	3.67x10 ⁻³ lb _m /ft ³				

Table D.3-8 Debris Generation for RCS Crossover Leg Break at theSG3 Outlet Nozzle

As discussed in the Debris Generation Evaluation, the U.S. EPR heavy floor will be coated with epoxy having a spherical 4D zone of influence (ZOI) with a radius of 10.33 feet for a 31-inch RCS pipe diameter. This means that only the epoxy floor covering within 4 pipe diameters of the break will be potentially damaged by the water jet. To be conservative, it is assumed that the epoxy coating within this ZOI is completely removed, exposing the underlying concrete. The center of the ZOI sphere at the crossover leg connection to the SG3 nozzle is located at a building elevation of approximately 18'- 6". Since the heavy floor elevation is at 4'-11", the epoxy coating is approximately 3 feet (18'-6" – 4'-11") outside the 4D ZOI for this location and therefore would not be damaged. To be conservative, the crossover leg elevation of 10'-0 $\frac{1}{2}$ " is used to determine the exposed concrete surface area for calculation purposes.

The exposed surface area of the heavy concrete floor within the 4D ZOI sphere centered at the crossover leg piping elevation is calculated by first determining the radius (R_{HV}) of a planar circle intersecting the sphere at approximately 5 feet below its center and then the area. Figure D.3-10 illustrates the methodology for determining the exposed concrete surface area.



Figure D.3-10 Methodology for Determining the Exposed Concrete Surface Area

The radius, $R_{HF} = \sqrt{(R^2_{ZOI} - h^2)} = \sqrt{((10.33^2) - (5^2))} = 9.039$ feet

The heavy floor circular area, $A_{HF} = \pi R^2_{HF} = \pi (9.039)^2 = 256.7 \text{ ft}^2$

Based on these calculations, an exposed concrete surface area of 257 ft² is used to determine the chemical elements released from the heavy floor following the LOCA.

The surface area of metallic aluminum in the building assumed to be submerged by recirculating sump liquid is conservatively estimated at 3000 ft², as modeled in the autoclave test.

Using the relationships for chemical release established in Section D.3.3, the total amount of debris generated as listed in Table D.3-8, an exposed concrete surface area of 257 ft², and 3000 ft² of submerged aluminum metal, the chemicals released versus time were calculated and are listed in Table D.3-9. Note that the quantity of Microtherm was reduced by the designers following the autoclave test to 1 ft³ from the initial 40 ft³.

	Concrete & Al-1100			Nukon™ & Microtherm									
time	Т	Na ₃ PO ₄	B(OH) ₃	Са	Al	Si	Mg	SiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	B_2O_3
hours	٩F	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
0	122.0	0	16014	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.25	154.8	420	16014	2.72E+00	2.40E-01	1.45E+00	2.10E-01	1.50E+00	1.50E+00	6.43E-04	5.57E-04	1.23E-03	3.90E-04
0.58	178.8	974	16014	2.73E+00	2.94E-01	1.45E+00	2.10E-01	3.50E+00	2.16E+00	2.46E-03	2.13E-03	4.70E-03	1.49E-03
0.92	194.5	1546	16014	2.74E+00	3.49E-01	1.45E+00	2.10E-01	5.56E+00	2.16E+00	5.14E-03	4.46E-03	9.85E-03	3.12E-03
1.58	216.3	2654	16014	2.77E+00	4.55E-01	1.46E+00	2.10E-01	6.15E+00	2.17E+00	1.30E-02	1.13E-02	2.49E-02	7.89E-03
1.92	224.5	3226	16014	2.78E+00	5.10E-01	1.46E+00	2.10E-01	6.18E+00	2.17E+00	1.76E-02	1.53E-02	3.37E-02	1.07E-02
2.25	231.4	3360	16014	2.79E+00	5.63E-01	1.47E+00	2.10E-01	6.22E+00	2.17E+00	2.26E-02	1.96E-02	4.33E-02	1.37E-02
3.31	246.2	3360	16014	2.84E+00	7.35E-01	1.48E+00	2.10E-01	6.37E+00	2.18E+00	4.23E-02	3.67E-02	8.10E-02	2.57E-02
4.50	221.5	3360	16014	2.89E+00	9.27E-01	1.49E+00	2.10E-01	6.49E+00	2.19E+00	5.77E-02	5.01E-02	1.11E-01	3.50E-02
6.50	203.2	3360	16014	2.95E+00	1.25E+00	1.50E+00	2.10E-01	6.63E+00	2.19E+00	7.65E-02	6.64E-02	1.47E-01	4.64E-02
9.50	193.1	3360	16014	3.04E+00	1.73E+00	1.52E+00	2.10E-01	6.80E+00	2.20E+00	9.95E-02	8.64E-02	1.91E-01	6.04E-02
13.50	187.0	3360	16014	3.15E+00	2.38E+00	1.54E+00	2.10E-01	7.00E+00	2.22E+00	1.26E-01	1.10E-01	2.42E-01	7.67E-02
20.00	181.6	3360	16014	3.31E+00	3.43E+00	1.57E+00	2.10E-01	7.29E+00	2.23E+00	1.65E-01	1.43E-01	3.15E-01	9.99E-02
31.50	180.0	3360	16014	3.60E+00	3.45E+00	1.63E+00	2.10E-01	7.79E+00	2.26E+00	2.30E-01	1.99E-01	4.40E-01	1.40E-01
37.50	170.0	3360	16014	3.73E+00	3.46E+00	1.66E+00	2.10E-01	7.98E+00	2.27E+00	2.56E-01	2.22E-01	4.90E-01	1.55E-01
49.50	160.0	3360	16014	3.95E+00	3.48E+00	1.70E+00	2.10E-01	8.27E+00	2.29E+00	2.93E-01	2.54E-01	5.62E-01	1.78E-01
60.00	160.0	3360	16014	4.15E+00	3.49E+00	1.74E+00	2.10E-01	8.52E+00	2.31E+00	3.26E-01	2.83E-01	6.25E-01	1.98E-01
80.00	160.0	3360	16014	4.52E+00	3.52E+00	1.81E+00	2.10E-01	8.99E+00	2.33E+00	3.89E-01	3.37E-01	7.45E-01	2.36E-01
120.00	160.0	3360	16014	5.27E+00	3.57E+00	1.95E+00	2.10E-01	8.99E+00	2.33E+00	3.89E-01	3.37E-01	7.45E-01	2.36E-01
240.00	160.0	3360	16014	7.50E+00	3.72E+00	2.38E+00	2.10E-01	8.99E+00	2.33E+00	3.89E-01	3.37E-01	7.45E-01	2.36E-01
360.00	160.0	3360	16014	9.73E+00	3.87E+00	2.81E+00	2.10E-01	8.99E+00	2.33E+00	3.89E-01	3.37E-01	7.45E-01	2.36E-01
480.00	160.0	3360	16014	1.20E+01	4.02E+00	3.24E+00	2.10E-01	8.99E+00	2.33E+00	3.89E-01	3.37E-01	7.45E-01	2.36E-01
600.00	160.0	3360	16014	1.42E+01	4.17E+00	3.68E+00	2.10E-01	8.99E+00	2.33E+00	3.89E-01	3.37E-01	7.45E-01	2.36E-01
720.00	160.0	3360	16014	1.64E+01	4.32E+00	4.11E+00	2.10E-01	8.99E+00	2.33E+00	3.89E-01	3.37E-01	7.45E-01	2.36E-01

Table D.3-9 Estimated Chemical Release for the RCS Crossover LegBreak at the SG3 Outlet Nozzle

The parameters listed in Table D.3-9 were input to *StreamAnalyzer* to determine the pH at temperature versus time and both the identity and quantity of precipitates formed. The final results including pH(t), total elements released, and total solids formed are tabulated in Table D.3-10. Figure D.3-11 provides a plot of total solids versus time. At 720 hours (30 days) following the break, a maximum of 42.2 kg (92.8 lbs) of sodium aluminum silicate, 69.39 kg (152.6 lbs) of calcium phosphate, and 13.74 kg (30.2 lb) of aluminum hydroxide had precipitated from the recirculating sump liquid as the chemicals listed in Table D.3-9 were released from the exposed concrete and generated debris. *StreamAnalyzer* indicates that AlO(OH) will predominate over Al(OH)₃ early in the transient, with Al(OH)₃ favored after approximately 49.5 hours. Because the two compounds are expected to behave similarly in suspension and Al(OH)₃ has a higher molecular weight and will result in more precipitate per gram of aluminum available, the Al(OH)₃ value is used.

The *StreamAnalyzer* results indicate that some of the aluminum hydroxide would have begun to dissolve back into solution prior to reaching 720 hours. The maximum amount precipitated is listed for conservatism. Based on the break locations reviewed in the

Debris Generation Evaluation, these precipitate masses conservatively represent the

total quantity of solids formed by chemical precipitation.

Table D.3-10 Total Elements Released and Solids Formed from theRCS Crossover Leg Break at the SG3 Outlet Nozzle

					Total Elements Released		Total Solids				
time	Т	Na ₃ PO ₄	B(OH) ₃	pH _{T(OLI)}	Ca(+2)	AI(+3)	Si(+4)	NaAlSi ₃ O ₈	Ca ₃ (PO ₄) ₂	AIO(OH)	AI(OH)3
hours	٩F	mg/l	mg/l		kg	kg	kg	kg	kg	kg	kg
0	122.0	0	16014	4.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.25	154.8	420	16014	6.39	4.46	1.70	3.53	10.19	0.00	0.00	1.85
0.58	178.8	974	16014	6.72	4.48	2.36	5.06	15.10	7.92	1.74	0.00
0.92	194.5	1546	16014	6.91	4.42	2.40	6.53	20.01	10.27	0.72	0.00
1.58	216.3	2654	16014	7.14	4.56	2.63	7.11	21.53	11.33	0.53	0.00
1.92	224.5	3226	16014	7.23	4.58	2.72	7.13	21.61	11.52	0.51	0.00
2.25	231.4	3360	16014	7.25	4.60	2.81	7.18	21.72	11.62	0.53	0.00
3.31	246.2	3360	16014	7.26	4.71	3.10	7.31	22.00	11.95	0.78	0.00
4.50	221.5	3360	16014	7.24	4.81	3.42	7.42	22.54	12.10	1.88	0.00
6.50	203.2	3360	16014	7.23	4.93	3.95	7.54	23.04	12.28	3.16	0.00
9.50	193.1	3360	16014	7.22	5.10	4.75	7.71	23.60	12.62	4.89	0.00
13.50	187.0	3360	16014	7.22	5.31	5.83	7.89	24.21	13.09	7.20	0.00
20.00	181.6	3360	16014	7.22	5.62	7.56	8.16	25.09	13.80	10.88	0.00
31.50	180.0	3360	16014	7.22	6.17	7.62	8.64	26.58	15.19	10.67	0.00
37.50	170.0	3360	16014	7.22	6.42	7.64	8.84	27.23	15.62	10.63	0.00
49.50	160.0	3360	16014	7.22	6.82	7.69	9.13	28.17	16.41	0.00	13.74
60.00	160.0	3360	16014	7.22	7.19	7.73	9.39	28.98	17.35	0.00	13.60
80.00	160.0	3360	16014	7.22	7.87	7.79	9.86	30.45	19.11	0.00	13.36
120.00	160.0	3360	16014	7.22	9.10	7.88	10.09	31.17	22.28	0.00	13.38
240.00	160.0	3360	16014	7.22	12.76	8.12	10.80	33.36	31.72	0.00	13.44
360.00	160.0	3360	16014	7.22	16.41	8.37	11.50	35.56	41.16	0.00	13.50
480.00	160.0	3360	16014	7.22	20.14	8.61	12.21	37.76	50.77	0.00	13.56
600.00	160.0	3360	16014	7.22	23.75	8.86	12.93	40.00	60.08	0.00	13.60
720.00	160.0	3360	16014	7.22	27.35	9.11	13.63	42.20	69.39	0.00	13.66

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D.3.7 Computer Output

For the chemical effects studies, the OLI *StreamAnalyzer* was used to create configuration files for each single analysis or multipart analyses. These configuration files can be used by the *StreamAnalyzer* software to re-analyze or to re-create a previous analysis or analyses. The software was dedicated for use in this application in accordance with AREVA NP quality assurance procedures.

D.3.8 Summary

The U.S. EPR chemical effects studies were performed for the purpose of identifying the specific compounds and bounding quantities of materials that may precipitate within

the U.S. EPR reactor containment sump pool following a design basis accident such as a LOCA. These studies consisted of:

- developing relationships for estimating the rate at which containment debris and exposed concrete release constituent chemical species to the sump liquid based on information in the public domain
- validating and/or modifying these release rates by simulating a design basis accident in a recirculating autoclave
- using these release rates and the thermodynamic model StreamAnalyzer to calculate the pH of the sump liquid and the identity and bounding quantity of precipitates formed during the 30-day period following a design basis accident.

Results of the chemical effects studies are summarized as follows:

- 1. The estimated chemical release/dissolution rates for Microtherm, NUKON[®] fiber, and concrete developed from literature data were validated by the autoclave test data. The equilibrium corrosion rates reported in the literature for aluminum under-predicted the overall corrosion rate and were subsequently increased for the first 20 hours of exposure to represent the development of a passive corrosion film on the surface. The modified aluminum corrosion rates closely predicted the aluminum coupon weight loss.
- 2. The chemical release/dissolution rates validated in the autoclave test were used to calculate the pH at temperature and the total solids formed following a break in the RCS crossover leg pipe at the SG3 outlet nozzle location.
- 3. At 720 hours (30 days) following a break at the crossover leg, a maximum of 42.2. kg (92.8 lb_m) of sodium aluminum silicate, 69.39 kg (152.6 lb_m) of calcium phosphate, and 13.74 kg (30.2 lb_m) of aluminum hydroxide precipitated from the recirculating sump liquid as the chemicals were released from the exposed concrete and generated debris.

The chemical precipitates formed during a LOCA serve as input the chemical debris amounts for ECCS Strainer Performance Testing.

D.3.9 References

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- C.B. Bahn, et.al, "Aluminum Solubility in Boron Containing Solutions as a Function of pH and Temperature," NRC Contract #J-4149, Argonne National Laboratory, September 19, 2008.
- Tamara, Petrova and Pavel, Nikolaev, "Behavior of aluminium corrosion products in water-steam cycle of power plant," ICPWS XV, Berlin, September 8-11, 2008.
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Appendix E ECCS Strainer Performance Testing for the U.S. EPR

E.1 Introduction

Appendix E documents the process and results for the U.S. EPR ECCS strainer testing, which confirms the performance of the U.S. EPR ECCS strainer following a postulated loss of coolant accident (LOCA). Strainer testing is based on guidance specified in NEI 04-07 Volumes 1 and 2 (References 1 and 2) and the March 2008 testing guidance (Reference 3) and input from Appendix C Debris Generation Evaluation for the U.S. EPR and Appendix D Chemical Effects Evaluation for the U.S. EPR. Tests 1D, 1E, 2E, and 2F comprise the design basis testing for the U.S. EPR design configuration.

E.1.1 Background

During a postulated LOCA inside containment, pipe and equipment insulation and coatings can be fragmented by the jet forces emitted from the break location. Chemical precipitant debris may be created from coolant system fluid and the buffering agent solutions interacting with the generated debris. This mixed debris potentially transports from the area of the break to the IRWST. The generated debris consists of latent fiber, particulates (from destructed paint coatings, latent dirt and dust, and microtherm), reflective metallic insulation (RMI), miscellaneous debris, and chemical precipitates. A strainer is installed upstream of the ECCS pumps to prevent debris from entering the pump suction. Debris that transports to the IRWST must not cause a strainer head loss that impacts net positive suction head (NPSH) and satisfactory operation of the ECCS pumps during a LOCA condition. The overall head loss attributable to the strainer is a combination of the debris deposited on the strainer and the head loss associated with the clean strainer.

Strainer performance testing was performed at the Alden Research Laboratory, Inc. (ALDEN). Initial U.S. EPR strainer testing was performed in December 2009. The December testing demonstrated debris transport characteristics of RMI and other debris, such as coating chips. This testing also illustrated the need to re-model the retaining basket to the prototypical height to support other additional type tests. Following the December testing, the test apparatus was re-constructed with the retaining basket built to full scale height. In addition, selected debris generation amounts were adjusted.

Following re-construction of the test apparatus, subsequent U.S. EPR strainer testing was performed during the week of February 22, 2010 with one additional test performed on March 5, 2010. The testing was conducted with a modified test flume. The strainer performance test plans contain the debris requirements, flume description with detailed measurements, data recoding methods, test set-up, detailed testing steps, calibration records, and data collected while testing. Additional testing was performed in July and August 2010.

Testing performed in January and February of 2011 utilized the same test loop configuration and scaling but modified filtration media to determine the optimum filter for the U.S. EPR strainer and retaining basket design. The testing was performed in accordance with the AREVA NP quality assurance program.

E.2 Scope and Objective

The objective of the U.S. EPR ECCS strainer performance testing is to determine the head loss (differential pressure) across the U.S. EPR strainer based on prototypical water flow and debris mix conditions expected in the U.S. EPR containment following a postulated LOCA.

The ECCS strainer test program consists of two phases.

Phase 1 tests were performed between February and August 2010. These tests were performed with a higher fiber debris source term:

• Debris Transport Test - Test No. 5.

Four other tests were run:

- Design Basis Debris L oaded Strainer Head Loss Test Test 2.
- Fibrous Debris Only Test Test 3.
- Thin Bed Head Loss Test Test 4.
- Clean Strainer Head Loss Test Test 1.

These tests were performed at a higher fiber debris source term than the Phase 2 tests. Because of this, all the tests were performed again in Phase 2 except for the debris transport test. The debris transport test is not dependent on total fiber load. These tests provide guidance for follow-on Phase 2 tests.

Phase 2:

- Thin Bed Head Loss Test Test No. 1.
- Fibrous Debris Only Bypass Test (Incremental Fiber Addition) Test No. 2.
- Fibrous Debris Only Bypass Test (Full Fiber Addition) Test No. 3. This test is not required if the retaining basket did not overflow because of thin bed testing.
- Design Basis Debris Loaded Strainer Head Loss Test Test No. 4. This test was not planned if the design basis debris source term was used in Test 1.

The Phase 2 ECCS strainer performance testing was intended to include a total five (5) ECCS strainer performance type tests. However, testing was terminated prior to completion of all testing. To verify the test facility design responded prototypically for the planned testing, the test facility configuration was subsequently modified and the debris generation amounts adjusted. Based on review of the Phase 1 test data, the results for the Debris Transport Test (Test No. 5) were acceptable. The remainder of the four (4) strainer performance type tests were completed in Phase 2 following modification of the test facility configuration. Table E.2-1 lists and describes Phase 1 testing. Table E.2-2 lists and describes Phase 2 testing:

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Table E.2-1	U.S. EPR S	trainer Perform	nance Tests -	Phase 1
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	Phase 1 Test						
Type Test	Test No.	Title	Description				
1	1	Clean Strainer Head Loss Test	Test determines the head loss of the clean strainer for five (5) different flow rates. (performed February, 2010)				
2	2	Design Basis Debris Loaded Strainer Head Loss Test	Test determines the debris bed head loss for the design basis accident for the U.S. EPR design. (performed February, 2010)				
3	3A	Fibrous Debris Only Sample Bypass Test	Tests include fiber only to determine a percent bypass fraction. (performed March, 2010)				
4	4	Debris Loaded Strainer Head Loss Thin Bed Test	Test determines if a higher head loss is possible with a thin bed of fibers, particulate, and chemical debris present, rather than with the design basis quantity of debris. (Performed February, 2010)				
5	5	Debris Transport Test	Test determines the transportability of reflective metallic insulation (RMI), coatings (in the form of paint chips), and miscellaneous debris including other miscellaneous debris (gloves, labels, etc). (performed December, 2009)				

Table E.2-2 U.S. EPR Strainer Performance Tests - Phase 2

	Phase 2 Tests							
Type Test	Test No.	Title	Description					
1	1, 1A, 1B, 1C, 1D, and 1E	Thin Bed Head Loss Tests	Tests to determine strainer head loss and retaining basket rise with various combinations of filtration media. Tests 1B- 1E utilized the design basis debris source term. Testing was performed in January and February 2011.					
2	2A, 2E, and 2F	Fibrous only Bypass Tests (Incremental Fiber Addition)	Tests include fiber only to determine a percent fiber bypass fraction. Testing was performed in January and February 2011.					

E.3 Test Apparatus

The test configuration is prototypical of the U.S. EPR design. The test loop includes a flume, strainer, retaining basket, instrumentation & controls, and associated piping and valves for a flow recirculation loop.

The test apparatus and configuration are based on the following conservative assumptions:

- 100% of all the debris passes through a single heavy floor opening
- 100% of the LOCA return flow passes through a single heavy floor opening.

The test apparatus is designed to simulate plant conditions and includes two simulated plant elevations; the containment level heavy floor and the lower IRWST level that contains the borated water supply used for ECCS operation. The test apparatus contains one retaining basket and one strainer, which is representative of one of four ECCS trains in the U.S. EPR design. In the plant design, fluid from a postulated LOCA flows onto the heavy floor and then falls into the IRWST through one of four heavy floor openings. The test apparatus simulates the free-fall flow of water from the heavy floor by introducing the return flow at an elevation above the flume water surface. As the water enters the test flume, it flows through the retaining basket, towards the strainer and into the strainer sump. From the strainer sump, the water enters a recirculation loop and is pumped back to the top of the retaining basket to simulate the flow of water on the heavy floor through the floor opening.

The test apparatus contains two flow paths. The primary flow path circulates approximately 91 percent of the water from the strainer to above the retaining basket for re-introduction into the test flume. The secondary flow path simulates the ECCS miniflow lines that circulate approximately 9 percent of the water from the strainer suction to the IRWST pool. The secondary flow path bypasses the retaining basket. This flow split is based on plant design requirements and scaled for the test facility. During the fiber-only bypass testing, two filter housing units were used to capture bypassed fiber debris. The filter housing units were not used during head loss testing.

E.3.1 Test Configuration and Scaling

The test apparatus conservatively represents the U.S. EPR plant conditions for developing strainer head loss. Testing involved two different test configurations and scaling combinations for Phase 1 and Phase 2 testing. Sections 3.8 and 3.9 describe the scaling methodology used.

E.3.2 Test Configuration Selection

The large compartment of the double compartment basket was selected for the test configuration to represent the most limiting condition under full debris loading. This is based on the fibrous debris distribution in containment. The U.S. EPR design source term for fiber is from latent debris.

The limited amount of latent debris is distributed throughout containment. The heavy floor area and the annular floor area both receive latent debris and comprise the total area for the latent debris assumed to enter the IRWST. There are no other sources of fibrous material within the zone of influence (ZOI) that will enter the IRWST.

The large compartment testing bounds the small compartment testing as follows. The only source of fiber within the zones of influence is from latent fiber. Latent fiber is uniformly distributed within containment. Based on a uniform distribution, 66 percent of the available containment surface area feeds the service area annular space. The remainder of the surface area feeds the heavy floor and the retention volumes. Therefore, the annular space will receive 6.7 pounds of latent fiber (66 percent of 10.2 pounds total latent fiber).

To address compartment loading and fiber retention performance, the available screen surface area needs to be identified. The small compartment has a minimum requirement of 269 ft² of total surface area. The wetted surface area at the minimum

level for safety injection pump NPSH is approximately 135 ft². The large compartment has a total surface area of 642 ft² and approximately 450 ft² of wetted surface area at the same IRWST level. The wetted surface areas above do not include the common screen between the two compartments.

Fiber in the annular space transports to each of the four baskets via openings in the IRWST wall. The debris is routed into the basket through gutters that discharge below the IRWST water level. Latent fiber in the annular space migrates uniformly to each basket. Therefore, each basket receives 1.7 pounds of latent fiber. This yields a loading of 0.013 lb/ft² for the wetted surface of the small compartment. By comparison, the wetted surface of the large compartment (as tested) is loaded with 22.5 pounds of latent fiber for a loading of 0.035 lb/ft².

Testing of the large compartment, discussed later in this appendix, introduced fiber in small batch sizes. No basket level increase was observed after complete loading with the design basis latent fiber. The level increased only after addition of the paint chips. The small compartment receives fiber arrival in small increments, similar to the large compartment. The small compartment does not directly receive paint chips as they are introduced via the heavy floor. Some chips may be introduced by overflow from a single compartment basket, but the chips will be spread out among the other three baskets. A small amount of paint chips will not adversely affect the other baskets as a large amount of chips is required to create an overflow condition in one basket. The overall fiber loading is less than that of the large compartment.

Therefore, the level in the small compartment is not expected to rise and result in any overflow condition. Testing performed on two other basket and strainer configurations showed that the fiber bypass rate was relatively insensitive to basket/screen modifications to hole size and material type (Table E.7-1). Fiber bypass ratios observed were between 65 and 70 percent (Table E.6-10). The small compartment is expected to perform similarly to the large basket with a consistent bypass fraction. A surge strainer

will see a higher loading from the basket bypass for the as-tested basket compared to an evenly distributed debris load over four strainers.

The selection of the large compartment of the double compartment basket also bounds the single compartment basket. The total surface area at overflow for the large compartment without the divider plate is 642 ft² compared to 600 ft² for the single basket at the point where it spills into the annular space. Using the approach discussed above, the single compartment basket sees one quarter of the total latent fiber (2.55 lbs of 10.2 lbs) based on a uniform distribution. This yields a loading per square foot of 0.004 lbs/ft². The large compartment as tested received 22.5 lbs yielding a loading per square foot of 0.035 lbs/ft². The loading for the single compartment basket is not expected to result in a level increase, based on testing results, and is expected to perform similarly to the large basket with a consistent bypass fraction. Again, the strainer will see a higher loading from the basket bypass for the as-tested basket compared to an evenly distributed debris load.

There is a potential for a small amount (20 percent using linear feet and the perimeter of the trash rack) of debris to directly impinge upon the sloped, screened surface of the double compartment basket. From the standpoint of bypass, it is unknown whether direct impingement may increase or decrease the amount of bypass. However, any bypass from the large compartment would enter the small compartment basket which contains the same filtering media.

Evaluating the loading per square foot as a result of this potential additional loading of the small compartment yields 0.008 lbs/ft². Assuming that there is a uniform distribution of latent debris, the small compartment sees 1.7 lbs of latent fiber from the annular space. The large compartment sees 0.85 lbs of latent debris from the heavy floor. If 20 percent of that fiber is passed to the small compartment, the small compartment sees an additional 0.17 lbs of latent fiber. At the minimum IRWST level for ECCS pump NPSH, the wetted surface of the small compartment is 135 ft². This yields a loading per square foot of 0.008 lbs /ft². This is bounded by the as-tested configuration.

Testing did not mimic basket design because the actual design is open on three sides to the IRWST and flow and debris will enter all four baskets. The tested basket used a scaled surface area of the large compartment of the double compartment basket. Testing with only one side open to the test strainer conservatively directed debris towards the strainer, which was observed after drain down with debris on the strainer during head loss and bypass testing. Testing a prototype basket would allow debris settling, which is not conservative. In addition, strainer testing created non-prototypical turbulence and directed pump mini-flow return towards the floor in front of the strainer to prevent settling. Adding a sloped face to the test configuration with a secondary basket prototypical to plant design would yield more prototypical and less conservative results.

Phase 1 Test Configuration and Scaling

Figure E.3-1 and Figure E.3-2 illustrate the test configuration for Phase 1 testing. Table E.3-1 provides the test scaling summary for Phase 1 testing.



Figure E.3-1 Test Configuration for Phase 1 Testing (Side View, - inches)



Figure E.3-2 Test Configuration for Phase 1 Testing (Top View, - inches)

Description	Value	Unit
Flume / Strainer Width	5.0	ft
Water depth in flume	9.25	ft
Strainer length in flume	6.6	ft
Overhang length in flume	2.6	ft
Strainer height	7.1	ft
Strainer screened slant height	7.5	ft
Test strainer area	70.6	ft ²
Total active strainer area	753.5	ft ²
Scale factor ¹	9.37	%
Total active strainer flow rate	3,284.0	gpm
Heavy floor flow rate	2,997.0	gpm
Total test flume flow rate	307.8	gpm
Test flume heavy floor flow rate	280.9	gpm
Double retaining basket total surface area	642.0	ft ²
Test flume retaining basket area	60.17	ft ²
Test flume retaining basket width	3.1	ft
Double retaining basket volume in plant	2024.0	ft ³
Retaining basket volume in flume	189.7	ft ³
Basket length (depth)	3.7	ft
Test flume volume (without piping)	3,885	gal
Test flume piping	236.4	gal
Total flume volume	4122	gal
Flume Turnover Time	14	min
Mini-flow	26.9	gpm

Table E.3-1 Scaling Summary for Phase 1 Testing

Note 1: A scaling factor is applied to total flow rate, heavy floor flow rate, mini-flow flow rate, strainer surface area, and retaining basket surface area/volume.

Phase 2 Test Configuration and Scaling

The test flume scaling is consistent with the plant design. The retaining basket height is full height. The bottom of the retaining basket is supported off the flume floor by foot pedestals and contains a perforated screen filtering area. In addition, the water management system is used to prototypically control flume water levels consistent with design basis conditions.

Figure E.3-3 and Figure E.3-4 illustrate the test configuration for Phase 2 testing. Table E.3-2 provides the test scaling summary for Phase 2 testing. Figure E.3-5 and Figure E.3-6 depict the strainer, retaining basket, and components within the Phase 2 test flume.

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Figure E.3-3 Test Configuration for Phase 2 Testing

Figure E.3-4 Test Configuration for Phase 2 Testing (Recirculation Loop and Make-up Water Tank)



Description	Value	Unit
Flume / Strainer Width	5.0	ft
Water depth in flume	9.25	ft
Strainer length in flume	6.6	ft
Overhang length in flume	2.6	ft
Strainer height	7.1	ft
Strainer screened slant height	7.5	ft
Test strainer area	70.6	ft ²
Total active strainer area	753.5	ft ²
Scale factor ¹	9.37	%
Total active strainer flow rate ²	3447/3284	gpm
Heavy floor flow rate ²	3160/2997	gpm
Total test flume flow rate ²	323.0/307.8	gpm
Test flume heavy floor flow rate ²	296.1/280.9	gpm
Double retaining basket total surface area	642.0	ft ²
Test flume retaining basket area	60.17	ft ²
Test flume retaining basket width	3.1	ft
Double retaining basket volume in plant	2024.0	ft ³
Retaining basket volume in flume	189.7	ft ³
Basket length (depth)	3.7	ft
Test flume volume (without piping)	3,885	gal
Test flume piping	236.4	gal
Total flume volume	4,122	gal
Flume Turnover Time	14	min
Mini-flow	26.9	gpm

Table E.3-2 Scaling Summary for Phase 2 Testing

- Note 1: A scaling factor is applied to total flow rate, heavy floor flow rate, mini-flow flow rate, strainer surface area, and retaining basket surface area/volume.
- Note 2: Tests 1D, 1E, 2E, 2F were performed at the higher flow rates listed.

retaining basket (downstream) Side) miniflow piping top of strainer

Figure E.3-5 Strainer, Retaining Basket, and Miniflow Lines Within the Phase 2 Test Flume



Figure E.3-6 Strainer, Retaining Basket, and Components Within the Phase 2 Test Flume

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E.3.3 Flume Recirculation Loop

The flume recirculation loop is constructed mostly from four and six inch diameter pipe. Flow is provided by a centrifugal pump controlled by a variable frequency drive. The main flow from the strainer suction is routed above the retaining basket to simulate plant flow conditions from the heavy floor into the retaining basket. This flow is measured through a calibrated orifice meter and discharges through a common header. A secondary flow loop circulates a small portion of the total flow from the sump suction directly into the flume water pool between the retaining basket and strainer to simulate the ECCS miniflow. The miniflow is also measured by a calibrated orifice meter. The miniflow is split into two pipes (each 2 inches in diameter) that route water to the bottom of the flume's pool between the retaining basket and the strainer. At the bottom of the pool the miniflow is discharged via perforations in the piping along the flume floor. The perforations are oriented such that the discharge flow conservatively creates turbulence to prevent debris settling. The tests are conducted with city domestic water. For testing, the flume water is heated and maintained at approximately 120°F via a heat exchanger connected to the recirculation loop.

E.3.4 Test Instrumentation

The flume test instrumentation consists of flow meters, level indication, differential pressure cells, and temperature instruments. A debris scale is used for weighing debris.

Flow instrumentation is provided for the flume recirculation loop. Differential pressure cells measure the flow differential pressure across the retaining basket and strainer. Level instrumentation is provided to monitor and control the flume water levels. Temperature instrumentation monitors the flume water temperature. A debris scale is used to weigh the debris in a dry state. The test instrumentation is calibrated using methods traceable to National Institute of Standards and Technology (NIST) or other reputable standards or procedures.