

Attachment 10

CHLE-018:

Results of Bench Tests to Assess Corrosion of Aluminum in STP  
Containment Conditions, Revision 3

## PROJECT DOCUMENTATION COVER PAGE

Document No.: CHLE-018	Revision: 3	Page 1 of 45
Title: Results of Bench Tests to Assess Corrosion of Aluminum in STP Containment Conditions		
Project: Corrosion/Head Loss Experiment (CHLE) Program		Date: 2/22/2014
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### Summary/Purpose of Analysis or Calculation:

The Corrosion/Head Loss Experiment (CHLE) program has been designed to obtain realistic material release and product formation results for use in Containment Accident Stochastic Analysis (CASA). Values for the CHLE test parameters were derived from South Texas Project (STP) conditions for a spectrum of Loss of Coolant Accident (LOCA) scenarios.

The objective of this bench test series was to evaluate the corrosion of aluminum under conditions typical of a LOCA at STP, including the effect of pH and temperature in the presence of boric acid and trisodium phosphate (TSP). Tests were also conducted with additional silicon in solution at a concentration similar to that which was observed in earlier 30-day LOCA experiments to evaluate whether small amounts of silicon would contribute to aluminum passivation, and with pH adjustment using sodium hydroxide instead of TSP to evaluate whether phosphate would contribute to aluminum passivation. Tests of leaching of aluminum, silicon, and calcium from fiberglass were also conducted. The results were compared to regression equations from WCAP 16530-NP. The series consisted of six 24-hour bench tests as described in this document.

The rate of corrosion of aluminum increased as temperature and pH increased. TSP inhibited the corrosion of aluminum but a low concentration of silicon did not. Aluminum and calcium leaching from fiberglass in the presence of TSP were lower than predicted by the WCAP 16530-NP regression equation (generated without TSP). Silicon leaching from fiberglass in the presence of TSP showed stronger dependence on pH and temperature than predicted by the WCAP 16530-NP.

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aluminum nitrate

## 1.0 Introduction and Objectives

The Corrosion/Head Loss Experiment (CHLE) program was designed to obtain realistic material release and product formation results for use in Containment Accident Stochastic Analysis (CASA). Values for the CHLE test parameters were derived from South Texas Project (STP) conditions for a spectrum of Loss of Coolant Accident (LOCA) scenarios. These conditions were tested in three ways: 30-day tank tests, bench tests, and short-term tank tests. This report describes the results of bench tests of aluminum corrosion and release of materials from fiberglass.

The objectives of this bench test series were to create conditions that promoted the generation of chemical products from corrosion sources (i.e., aluminum coupons and fiberglass) as a function of temperature and pH. The tests evaluated the corrosion of aluminum in a solution of boric acid and trisodium phosphate (TSP), with or without added dissolved silicon. Another test evaluated the effects of temperature and pH on the corrosion of aluminum in a boric acid and sodium hydroxide (NaOH) mix. The bench test was also used to evaluate chemical release products from fiberglass (Nukon) and the response of fiberglass to the presence of added soluble aluminum concentrations in the form of  $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ . The chemical release products of interest were aluminum, calcium, and silicon. The series consisted of six sets of 24-hour bench tests, as described in this document.

These tests were conducted from November 9, 2012 to February 14, 2013 with the following characteristics:

1. Six sets of benchtop tests in a water batch on a oscillatory table at temperatures of 35, 60, and 85°C, with the table rotation set at 75 rpm to create turbulent fluid conditions.
2. Aluminum coupons, 1" by 1" by 16 gauge, ASTM B-209, were the source of aluminum corrosion material, with 100% of the surface area submerged in a 1-L bottle filled with 500 mL of STP solution.
3. Fiberglass (Nukon) massed at approximately 5.0 grams.
4. Material exposure to baseline chemicals of boric acid and TSP for a pH of 7.2, with additions of hydrochloric acid (HCl) or sodium hydroxide to reach desired pH of 6.0 and 7.7, at time zero.

## 2.0 Methods and Materials

A bench-scale bath (Figure 1) was constructed and insulated to fit atop a shaker table while a thermoregulator provided and maintained heat through the bath via copper pipes and water heat transfer. The shaker bath apparatus provided a non-quiescent condition and maintained the desired test temperature. The results in this report were collected during a series of six benchtop tests (Table 2), each lasting 24 hours at one of the three temperatures (35, 60, and 85°C) and 3 pH values (6.0, 7.2, or 7.7 boric acid/TSP solutions). A single aluminum coupon (Figure 2) or a 5.0 gram sample of fiberglass was suspended by nylon string in a 1-L bottle with 500 mL solution. Aluminum alloy 3003 was used in these tests. The composition table for alloy 3003 is listed below with a weight percentage in Table 1.

Table 1: Aluminum alloy 3003 composition

Alloy	Si	Fe	Cu	Mn	Zn	Al
3003	0.6%	0.7%	0.05-0.20%	1.0-1.5%	0.10%	remainder



Figure 1: Bench test bath on shaker table.



Figure 2: 1-L Nalgene bottle with solution and aluminum coupon.

Table 2: Series of six benchtop tests.

Date of test: November 9, 2012. 24-hour test at 85°C <sup>a</sup>			
Material	Boric acid <sup>b</sup> /TSP <sup>c</sup> solution, pH		
	6.0	7.2	7.7
Aluminum only	3 + blank	3 + blank	3 + blank
Aluminum + 4.5 mg/L Si	3 + blank	3 + blank	3 + blank
Fiberglass	3	3 + blank	3
Fiberglass + 0.3 mg/L Al(NO <sub>3</sub> ) <sub>3</sub> <sup>f</sup>	<sup>e</sup>	3	

Date of test: November 14, 2012. 24-hour test at 60°C <sup>a</sup>			
Material	Boric acid <sup>b</sup> /TSP <sup>c</sup> solution, pH		
	6.0	7.2	7.7
Aluminum only	3 + blank		3 + blank
Aluminum + 4.5 mg/L Si	3 + blank		3 + blank
Fiberglass	3	3 + blank	3
Fiberglass + 0.3 mg/L Al(NO <sub>3</sub> ) <sub>3</sub> <sup>f</sup>		3	

Date of test: December 5, 2012. 24-hour test at 35°C <sup>a</sup>			
Material	Boric acid <sup>b</sup> /TSP <sup>c</sup> solution, pH		
	6.0	7.2	7.7
Aluminum only	3 + blank	3 + blank	3 + blank
Aluminum + 4.5 mg/L Si	3 + blank	3 + blank	3 + blank
Fiberglass		3	
Fiberglass + 0.3 mg/L Al(NO <sub>3</sub> ) <sub>3</sub> <sup>f</sup>		3	

Date of test: January 16, 2013. 24-hour test at 35°C <sup>a</sup>			
Material	Boric acid <sup>b</sup> , pH		
	6.0	7.2	7.7
Al, in NaOH	3 + blank	3 + blank	3 + blank
Fiberglass + 0.3 mg/L Al(NO <sub>3</sub> ) <sub>3</sub> <sup>f</sup> / TSP <sup>c</sup>	3 + blank		3 + blank

Date of test: January 28, 2013. 24-hour test at 60°C <sup>a</sup>			
Material	Boric acid <sup>b</sup> , pH		
	6.0	7.2	7.7
Al, in NaOH	3 + blank	3 + blank	3 + blank
Fiberglass + 0.3 mg/L Al(NO <sub>3</sub> ) <sub>3</sub> <sup>f</sup> / TSP <sup>c</sup>	3 + blank		3 + blank

Date of test: February 14, 2013. 24-hour test at 85°C <sup>a</sup>			
Material	Boric acid <sup>b</sup> , pH		
	6.0	7.2	7.7
Al, in NaOH	3 + blank	3 + blank	3 + blank
Fiberglass + 0.3 mg/L Al(NO <sub>3</sub> ) <sub>3</sub> <sup>f</sup> / TSP <sup>d</sup>	3 + blank		3 + blank

<sup>a</sup> Temperature was maintained  $\pm 3^\circ\text{C}$ .

<sup>b</sup> Boron was added as H<sub>3</sub>BO<sub>3</sub>.

<sup>c</sup> Trisodium phosphate (TSP) = (Na<sub>3</sub>PO<sub>4</sub>·12H<sub>2</sub>O)<sub>4</sub>-NaOH.

<sup>d</sup> Trisodium phosphate (TSP) = Na<sub>3</sub>PO<sub>4</sub>·12H<sub>2</sub>O.

<sup>e</sup> Gray cells indicate conditions that were not part of the test matrix.

<sup>f</sup> Al was added as Al(NO<sub>3</sub>)<sub>3</sub>·9H<sub>2</sub>O.

Prior to testing, the filled bottles were placed inside the preheated bath, capped, and allowed to come to the desired temperature, usually overnight. Pre-heating the solution prior to introducing the aluminum coupon or fiberglass was done so that material exposure to the correct temperature was from time zero. The shaker baths were maintained at 5°C above required temperature prior to testing to accommodate the temperature loss when removing bottles to add coupons or fiberglass. During the test, the temperature setting on the thermoregulators was set at 3°C above the required temperature. Calibration testing done before the start of test showed a -3°C reading between the thermoregulator and bath and sample temperatures. Samples were run in triplicate, and a blank sample for each solution pH condition was tested. The blank was used to measure the pH change that occurred over the test period without materials present.

During testing, bottles were capped to prevent evaporation. After the immersion time was complete, each aluminum coupon and fiberglass was removed for observation and the weight was recorded. Fiberglass was discarded, and aluminum coupons were weighed, cleaned, and weighed again. For aluminum coupons, the difference in mass between the start of test and after cleaning includes the aluminum (both soluble and insoluble) released into solution and assimilated into the scale layer.

When testing analyte release from aluminum coupons, a filtered 125-mL sample was collected from each bottle and aluminum, calcium, and silicon concentrations were measured by inductively coupled plasma optical emission spectrometry (ICP-OES) analysis at Hall Environmental Analysis Laboratory (Hall

Environmental, an independent certified laboratory). The filter used was an Inlet Pall Corporation 0.45- $\mu\text{m}$  Aquaprep filter.

## 2.1 Experimental Apparatus and Equipment

- VWR Advanced Digital Shaker
- TECHNE TU-20D Temp unit thermoregulator
- OHAUS AR1140 Scale, readability: 0.0001 g
- ThermoOrion model 720A+ pH meter
- Nano-pure water
- 1000-mL volumetric flask
- 1000-mL Nalgene polypropylene bottles
- 125-mL bottles, acidified with 0.40 mL of nitric acid
- Inlet Pall Corporation 0.45- $\mu\text{m}$  Aquaprep<sup>TM</sup> filter
- 50-mL syringe
- Graduated cylinder
- Fireline<sup>TM</sup> 0.008" diameter braided nylon thread

## 2.2 Coupon Preparation

The aluminum coupons (ASTM B-209) were 1" x 1" x 0.0787". Each coupon had a 1/16" hole drilled in it for stringing. The following coupon preparation was in accordance with ASTM G31-72.

- The coupons were rinsed with de-ionized (DI) water and then with a suitable solvent such as acetone. Rinsing removed residual boric acid/TSP solution from the surface, which would add to the weight if allowed to dry on the surface. Scrubbing with abrasive powder might have damaged the surface of the specimen.
- The coupon was allowed to air dry. Towel drying might have introduced an error through contamination of the specimens with grease or lint.
- The coupon was weighed, and its dimensions were recorded to determine the initial mass and total surface area.

## 2.3 Temperature

The test was conducted at 85°C (185°F), 60°C (140°F), and 35°C (95°F). These temperatures were selected to span the range of temperatures in the CHLE tests and were not representative of a specific LOCA scenario. The high temperature is close to the CHLE equipment limits. Temperature in the shaker bath was maintained by a TECHNE TU-20D Temp unit thermoregulator and measured with a thermometer.

## 2.4 Solution pH Control

### 2.4.1 pH 7.2 stock solution

A stock solution of boric acid/TSP was made by mixing 250.0 mM boric acid with 2.16 mM ( $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$ )<sub>4</sub>-NaOH (TSP, molecular weight of 1560 g/mol) in the desired amount of DI water and



then allowing it to fully dissolve to produce to the pH 7.2 solution. The masses of boric acid and TSP were calculated independently by the following equation:

$$M = C * (FW) * V \quad (1)$$

M = Mass of the stock chemicals (g)

C = Molar concentration (mol/L) of boric acid or TSP

FW = Formula weight for boric acid (61.83 g/mol) or TSP (1560 g/mol)

V = the volume of solution being prepared (L)

#### 2.4.2 pH 6.0 and pH 7.7 solutions

A stock solution of pH 7.2 can be brought to pH 6.0 by adding a qualitative 1/10 dilution of 12.1 M hydrochloric acid (HCl). In the same manner, a stock solution can be brought to pH 7.7 by adding standardized 12.0 M sodium hydroxide (NaOH). These solutions were actually made by mixing 275.5 mM boric acid with 1.64 mM TSP for pH 6.0, or 231.4 mM boric acid and 2.16 mM TSP for pH 7.7, and fully dissolving in the desired amount of DI water. A precise 1.0-L aliquot was then taken. A general titration setup was constructed with a ring stand to hold a vertical burette, a 1.0-L Erlenmeyer flask with a stir bar in it, and a stir plate. A calibrated pH meter was used.



Figure 3: Titration setup

To prepare the pH 6.0 solution, the titration apparatus (see Figure 3) was assembled and the burette was rinsed (conditioned) with the dilute HCl solution that was used for the titration. The burette was then filled, and the initial volume was read and recorded to two decimal places. The pH probe was placed into the 1.0-L Erlenmeyer flask with the 1-L aliquot of the stock solution, the stir bar was then placed on the stir plate with the ring stand and burette, and an initial pH reading was taken. The titration was conducted at room temperature. Titrant was slowly added to the boric acid/TSP solution until a pH of 6.0 was reached, and the final volume on the burette was recorded. The 1-L aliquot was

returned to the bulk stock solution. The volume of HCl needed to adjust the full volume of the solution to the required pH was calculated by Equation 2.

$$V_{HCl} = (V_{final} - V_{init}) \times \frac{C_{DHCl}}{C_{SHCl}} \times \frac{(V_{Tot} - 1 L)}{1} \quad (2)$$

$V_{HCl}$  = Total volume of stock 12.1 M HCl needed (L)

$V_{final}$  = Volume of solution in burette after titration was complete (L)

$V_{init}$  = Volume of solution in burette before titration started (L)

$C_{DHCl}$  = Concentration of the dilute HCl (M)

$C_{SHCl}$  = Concentration of the stock HCl (M)

$V_{Tot}$  = Volume of solution being created (L)

To prepare the pH 7.7 solution, this same procedure was followed except that NaOH was titrated instead of HCl.

After the added HCl or NaOH had been mixed thoroughly into the solution, a pH reading was taken. If the pH was not correct, a second titration was performed by following the same procedure outlined above.

The DI water was measured with a graduated cylinder, so the absolute error of the volume measurement had to be taken into account in determining the potential error of the solution concentration. If the graduated cylinder was used more than once (e.g., a 2,000-mL graduated cylinder used 10 times to make 20.0 L of solution), the accuracy must be accounted for. The new error for the total measurement can be calculated as follows:

$$Total\ error = \sqrt{[n \cdot (\pm Instrument\ error)^2]} \quad (3)$$

$n$  = number of times instrument is used.

*Instrument error* = error value indicated on the graduated cylinder.

## 2.5 Step-by-Step Procedure for Bench Testing

1. Measure and record:
  - a) For coupons, measure the initial mass and dimensions of aluminum coupons. A surface area of 13 cm<sup>2</sup> is targeted.
  - b) For fiberglass, measure and record the mass of fiberglass. A repeated mass of 5.0 g of rectangular piece of cut fiberglass is sought.
2. Prepare bulk solutions of boric acid/TSP of pH 6.0, 7.2, and 7.7.
3. Measure and record the actual pH of the solutions.
4. Heat 500 mL of prepared test solution in 1-L Nalgene bottles to desired temperature of 35, 60, or 85°C, and maintain the temperature for the remainder of the test.
5. Insert a coupon or fiberglass by hanging with nylon string so that coupon or fiberglass is suspended at the midpoint of the solution depth and is completely submerged.
6. Set shaker bath to a speed of 75 oscillations per minute. This speed allows flow across the coupon and fiberglass without its bumping the inside of the bottle.

7. After 24 hours:
  - a) For coupons, remove, rinse with DI, and allow to air dry and cool to room temperature. Note formation of precipitate in the bottle or on the surface of the coupon.
  - b) For fiberglass, note any formation of precipitate on fiberglass or in the bottle, and discard fiberglass.
8. Measure and record the final pH of the solution. Shake the bottle of solution, and pour 125-mL samples for testing of metal precipitates by ICP-OES. Metals of interest are aluminum, calcium, and silicon. Filter all solutions having fiberglass. Use Inlet Pall Corporation Aquaprep™, 0.45-μm filters.

## 2.6 Post Test

### 2.6.1 Post-Corrosion Cleaning

After a test was completed, coupons were removed from solution and set aside to air dry. Dry coupons were weighed and recorded, and then cleaned one-by-one in the proper cleaning solution. The ASTM G1-03 "Aluminum and Aluminum Alloys" cleaning procedure was followed to determine corrosion of aluminum coupons. The cleaning solution used is given in Table 3, and the cleaning procedure follows.

Table 3: Cleaning solution for aluminum.

Cleaning solution	Time and temperature	Note
50 mL of phosphoric acid ( $\text{H}_3\text{PO}_4$ ) 20 g of chromium trioxide ( $\text{CrO}_3$ ) Reagent water to make 1,000 mL	5 to 10 min    90°C to Boiling	If corrosion product film remains, rinse and then follow with nitric acid procedure.
Nitric acid ( $\text{HNO}_3$ )	1 to 5 min    20 to 25°C	Remove any visibly remaining deposits.

In hood vent:

- Place the cleaning solution on a hot plate and allow it to reach at least 90°C but not more than 100°C.
- Place the coupon in the hot solution for 5 to 10 minutes (suspend coupon with a string for ease).
- Rinse with DI and allow to air dry. Clip off any string.
- Weigh and record.
- If corrosion product film remains, place the coupon in nitric acid for 1 to 5 minutes.
- Rinse with DI water, allow to air dry, weigh, and record.

### 2.6.2 Calculation of Corrosion and Release Rates

When aluminum metal corrodes, the aluminum can be released into solution or it can form a scale layer on the material itself. Once in solution, the corroded aluminum can remain in solution, precipitate and be separated from solution by sedimentation or filtration, or adhere on other surfaces in the system. The concentration of material remaining in solution, whether in soluble or precipitate form, was obtained by ICP-OES measurements. The corroded mass is the sum of the aluminum released into



solution and the mass assimilated into the scale layer on the corroded material itself, as shown in Figure 4 and defined by Equation 4.

$$Al_{corroded} = Al_{released} + Al_{scale} \quad (4)$$

$Al_{corroded}$  = mass difference of aluminum coupon before test and after cleaning:  $A - C$ .

$Al_{released}$  = mass of aluminum that leaves the coupon and enters the solution during the test, measured by ICP-OES.

$Al_{scale}$  = mass of aluminum that adheres to the coupon as a scale layer.

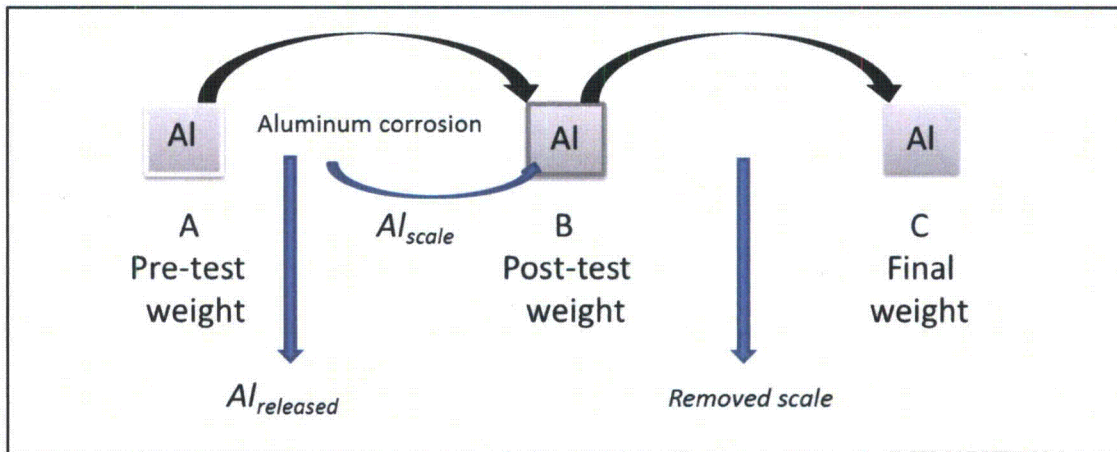


Figure 4: Using measured weight of aluminum coupon to determine corrosion.

The mass of the coupons were measured three times. First, the initial mass of the coupon was measured and recorded. After immersion in the solution for the test period, the coupons were removed, rinsed, and allowed to air dry, and the new mass was recorded. A decrease in mass represented a release of aluminum and/or original scale (aluminum hydroxide layer formed from being in normal environmental air) into solution. The release may contain soluble and insoluble aluminum (precipitate), which cannot be differentiated by ICP-OES, and new scale. New scale may also form on the surface of the aluminum and add weight to the coupon. To include the mass of corroded aluminum that was incorporated into the scale layer on the material itself required measuring the mass of the aluminum coupon at the end of testing after cleaning.

Corrosion rates were calculated using the initial and final (post-cleaning) mass of the aluminum coupons. This result can be compared to ICP-OES results. The dimensions of the coupons and the time of experiment were also in this calculation.

$$CR = \frac{M}{A_s * t} \quad (5)$$

$CR$  = corrosion rate (g/(m<sup>2</sup>·min))

$M$  = total mass lost (g)

$A_s$  = surface area (m<sup>2</sup>)

$t$  = time of immersion in test solution (min)

If there is some loss of mass due to corrosion, then this value,  $M$ , may be positive. If a significant scale layer forms, then  $M$  may be negative. The surface area was calculated using the dimensions of the aluminum coupons.

### 3.0 Results

#### 3.1 Effect of pH and Temperature on the Corrosion of Aluminum in Boric Acid/TSP Solution

As described in Section 2.6.2, corrosion processes were evaluated by determining the corrosion rate using weight loss measurements and by determining the release rate by measuring the concentration of metals in solution. The target temperature and pH were verified during testing. The temperature was measured in the blank sample at start of the test, at a random time in the middle of the test, and at the end of test and was consistently found to be within  $\pm 1^\circ\text{C}$  of the target temperature. The pH was measured in the blank sample and in one of the triplicate samples at the beginning and end of the test. At the beginning of the test, the pH was consistently found to be within  $\pm 0.05$  of the target pH. The pH values measured at the end of the test are reported in Table 4. In general, the pH increased during the corrosion immersion period. The pH was typically 0 to 0.2 higher than the target value at the end of the immersion period.

Table 4: Initial and final pH values during aluminum-only corrosion tests.

Temperature	Boric acid/TSP solution			
	pH			
	Target	Actual initial	Final	Change
35°C	6.0	6.0	6.13	+0.13
	7.2	7.2	7.38	+0.18
	7.7	7.7	7.81	+0.11
60°C	6.0	5.99	6.03	+0.04
	7.2	b	b	b
	7.7	7.7	7.69-7.73	-0.01 to +0.03
85°C	6.0	6.0	-- <sup>a</sup>	--
	7.2	7.2	--	--
	7.7	7.7	--	--

--<sup>a</sup> Final pH was not measured.

b A test at pH 7.2 and 60°C was not completed.

After immersion time was complete, the aluminum coupons were removed to air dry and then be weighed and photographed. Each coupon was visually examined for any change and for formation of scale on its surface. The solution was examined for any precipitate formation therein or on the bottom of the bottle. No visible precipitates were seen in the bottles. The degree of corrosion and scale formation was rated on a scale of 1 to 4, where 1 indicated no change and 4 indicated a blackened surface with no shine, as shown in Figure 5 through Figure 8 and described in Table 5. For tests at 35°C,

aluminum coupons seemed unchanged (score of 1); at 60°C and pH of 6.0, the coupons were still unchanged except for a few pit marks on one of three coupons tested at that pH and temperature; at pH 7.7, the coupons were darker at edges (score of 3) and no longer shiny. At 85°C and pH 7.2, the coupons were black and no longer shiny (score of 4).

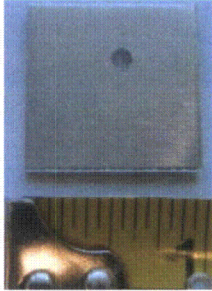


Figure 5: Example of corrosion score of 1 of aluminum.

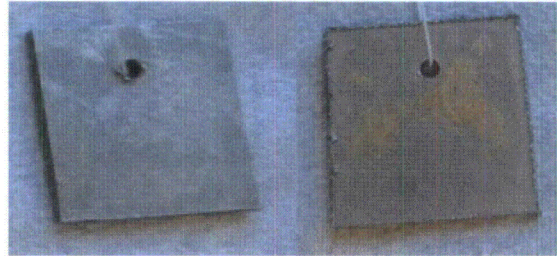


Figure 6: Examples of corrosion score of 2 of aluminum.

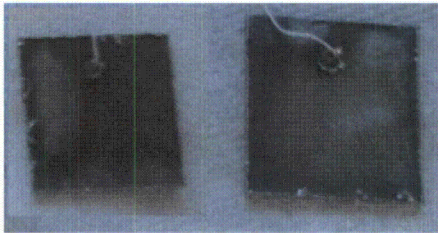


Figure 7: Examples of corrosion score of 3 of aluminum.

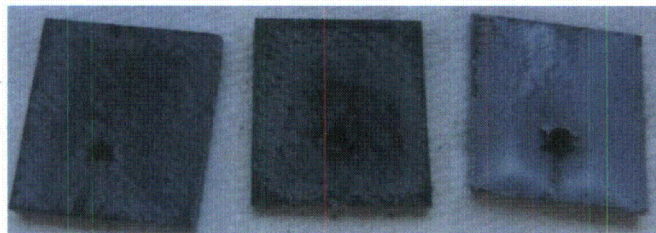


Figure 8: Examples of corrosion score of 4 of aluminum.

Table 5 describes for corrosion score, the appearance of the metal coupons upon completion of testing. The duration for soaking in the acid solution for cleaning of the coupons varied from 0 to 10 minutes, depending on the visual appearance of the coupons at the end of the immersion time and on observation of removal of the scale layer during the cleaning operation. General times for the duration of soaking in the acid solution for each of the degrees of corrosion are listed in Table 5. Coupons were removed as soon as they appeared clean, to prevent further reaction. Time for cleaning was determined by visual inspection and never to exceed a total of 10 minutes. The coupons were immediately rinsed with DI water to stop acid solution from reacting with the aluminum.

Table 5: Corrosion scores of aluminum coupons.

Corrosion score	General corrosion appearance	Color	Luster	Cleaning time
1	No apparent corrosion	light grey	metallic	0-2 minutes
2	Low corrosion	grey	mostly metallic / some dullness	2-5 minutes
3	Moderate corrosion	dark grey	loss of metallic / very dull	5-8 minutes
4	High corrosion	black	very dull / ash-like	8-10 minutes

Weight loss measurements for corrosion at 35 and 60°C are shown in Table 6. Results from the tests at 85°C are not shown because of coupon handling errors during the final weight measurements. As



expected from previous corrosion studies, the corrosion rate increased as the pH increased and as the temperature increased, as shown in Figure 9. At 35°C, the corrosion rate increased by a factor of 2.6 as the pH increased from 6.0 to pH 7.7, whereas at 60°C, the corrosion rate increased by a factor of 7.3 for the same pH increase.

Table 6: Average aluminum mass lost post-test and post-cleaning.

35°C	Aluminum in boric acid/TSP solution		
	pH = 6.0	pH = 7.2	pH = 7.7
A, Avg. starting mass of coupon (g)	2.4175	2.4941	2.3997
B, Avg. post-test mass of coupon (g)	2.4172	2.4939	2.3990
C, Avg. post-cleaning mass of coupon (g)	2.4170	2.4934	2.3984
$Al_{released}(g) = A - B (g)$	0.0003	0.0002	0.0007
$Al_{scale}(g) = B - C (g)$	0.0002	0.0005	0.0006
$Al_{corrosion}(g) = A - C (g)$	0.0005	0.0007	0.0013

60°C	Aluminum in boric acid/TSP solution		
	pH = 6.0	pH = 7.2	pH = 7.7
A, Avg. starting mass of coupon (g)	2.4663	-- <sup>a</sup>	2.4393
B, Avg. post-test mass of coupon (g)	2.4662	--	2.4356
C, Avg. post-cleaning mass of coupon (g)	2.4656	--	2.4342
$Al_{released}(g) = A - B (g)$	0.0001	--	0.0037
$Al_{scale}(g) = B - C (g)$	0.0006	--	0.0014
$Al_{corrosion}(g) = A - C (g)$	0.0007	--	0.0051

--<sup>a</sup> A test for pH 7.2 at 60°C was not completed.

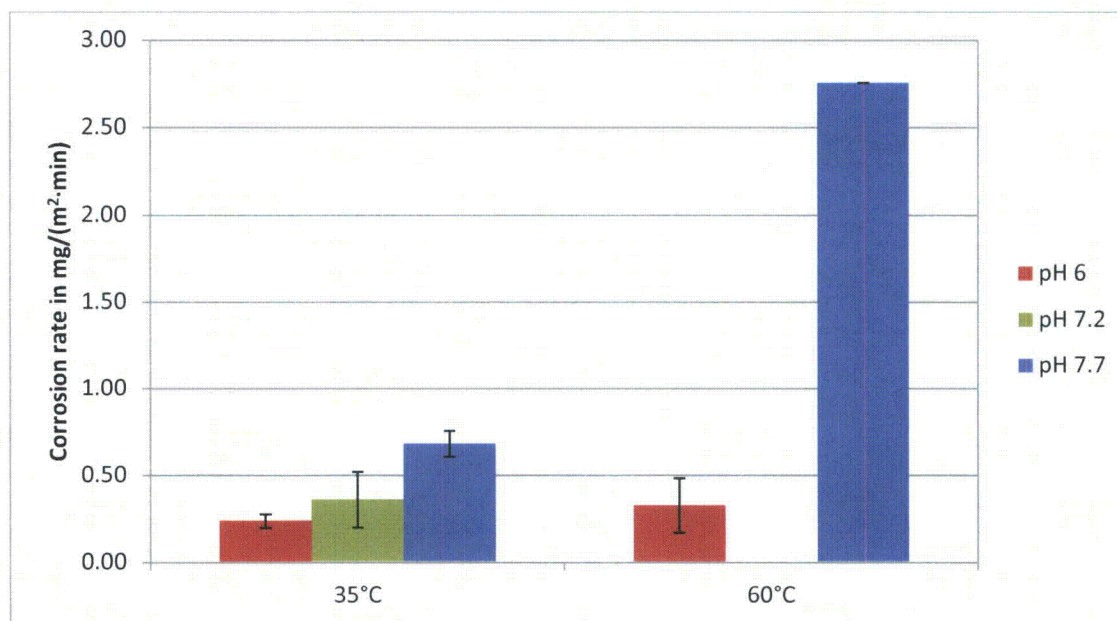


Figure 9: Effect of pH and temperature on corrosion rate of aluminum in solution.

The increase in aluminum concentration in solution resulting from release into solution followed the same trend as did the weight loss, with respect to pH and temperature. The concentration of aluminum in solution in each test is shown in Table 7 and Figure 10. The lowest concentrations of aluminum occurred for the tests at pH 6.0 and were below the reporting limit of 0.2 mg/L for the tests at all three temperatures. The highest concentration of aluminum (29.33 mg/L) was measured for the highest temperature and pH tested. The reported concentrations are the average of three replicate tests. The relative standard deviation (RSD) of the three measurements was generally 10% or less.

Table 7: Release of aluminum concentration in boric acid/TSP solution.

35°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.11	0.55	1.63
Standard deviation	0.010	0.012	0.058
% RSD	9.09	2.09	3.53
60°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.10	-- <sup>a</sup>	8.47
Standard deviation	0.020	--	1.153
% RSD	20.90	--	1.80
85°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.17	14.12	29.33
Standard deviation	0.006	0.168	0.577

% RSD	3.33	1.19	1.97
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--<sup>a</sup> A test at pH 7.2 and 60°C was not completed.

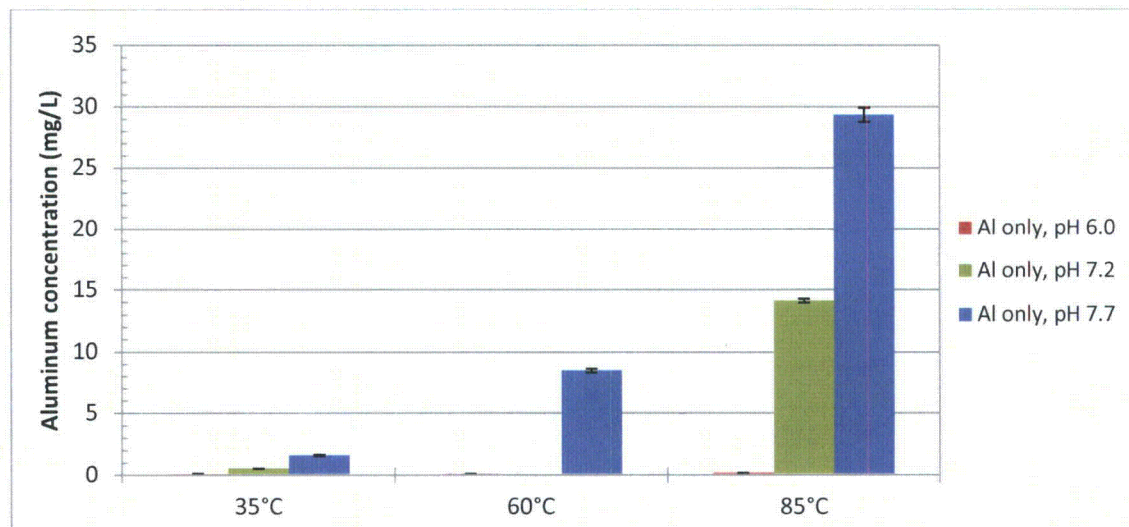


Figure 10: Effect of pH and temperature on release of aluminum in solution.

To evaluate whether the aluminum concentration had reached the saturation concentration, the measured concentrations in solution were compared to the saturation concentration of aluminum in equilibrium with amorphous aluminum hydroxide. The solubility curves shown in Figure 11 were calculated as a function of temperature and pH using Visual MINTEQ for aluminum hydroxide (identified as an expected precipitation product in previous testing [1]). The solubility calculations demonstrate that aluminum in solution will reach minimum solubility in a pH range of 5.7 to 6.8 for temperatures from 85°C to 35°C. The corrosion of aluminum increases as pH and temperature increase due to increased kinetics, but Figure 11 demonstrates that the solubility of amorphous aluminum hydroxide follows the same trend when the pH is above 7. For each test, the aluminum concentration measured in solution was less than the saturation concentration of aluminum at that pH and temperature, indicating that the measured concentration was not limited by the formation of a precipitate in the solution.



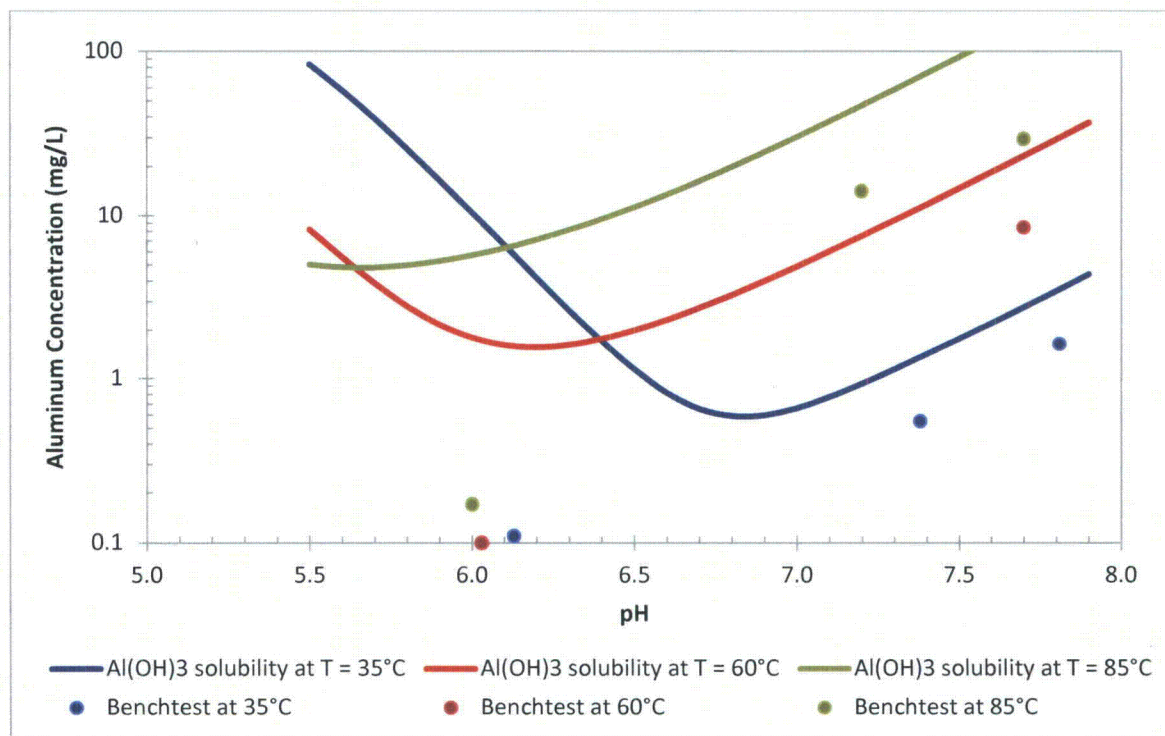


Figure 11: Aluminum concentration vs. pH and temperature on the  $\text{Al}(\text{OH})_3$  solubility curve.

The corrosion rate determined by weight loss measurements can be compared to the release rate determined by solution concentrations and to the rate of release calculated from WCAP 16530-NP Equation 6.2. These comparisons are shown in Table 8. For all tests that can be compared, the rate of release into solution was less than the measured corrosion rate. This result is expected because corrosion brings about release of ions into solution and formation of a scale layer. Since only a portion of the corroded aluminum is released into solution, the release rate is expected to be less than the corrosion rate. The ratio of release to corrosion appears to increase as the pH increases. At pH 6.0, the aluminum release rate is at most 10% of the corrosion rate. At pH = 7.2, the release rate is 40% of the corrosion rate; and at pH = 7.7, the release rate ranged from 60% to over 80% of the corrosion rate.

In these tests, the measured release rates were generally less than the corresponding release rate determined from Equation 6.2 in WCAP-16530-NP. At the lowest pH, the measured release rate was dramatically lower than the calculated rate, ranging from 4 to 140 times lower than the calculated rate. At pH = 7.2, the measured and calculated rates were closer to each other, with the measured rates between 1.5 and 2.5 times lower than the calculated rates. At the highest pH, the measured rates ranged from slightly above to slightly below the calculated rates. The results may indicate that the WCAP-16530-NP equation is less accurate at low pH values or with TSP in solution. At this pH, the release rate is very low (close to the detection limit) so relative differences between calculated and measured rates may appear more significant, but both the WCAP-16530-NP equation and the measurements indicate low release rates. Some variability is common in corrosion studies because of the difficulties in measuring small changes in weight and the impact that scale formation and cleaning can have on weight loss measurements.

Table 8: Corrosion rate results for aluminum.

Aluminum in boric acid/TSP solution		Corrosion by weight loss		Release rate by solution measurement (ICP-OES)		Calculated <sup>a</sup> release rate mg/(m <sup>2</sup> ·min)
Temp.	Final pH	Mass lost (g)	Corrosion rate mg/(m <sup>2</sup> ·min)	Aluminum conc. (mg/L)	Release rate mg/(m <sup>2</sup> ·min)	
35°C	6.13	0.0005	0.248	0.11	0.027	0.105
	7.38	0.0007	0.347	0.55	0.136	0.204
	7.81	0.0013	0.645	1.63	0.404	0.277
60°C	6.03	0.0007	0.347	0.10	0.025	0.898
	7.20	-- <sup>b</sup>	--	--	--	1.50
	7.70	0.0051	2.53	8.47	2.10	2.03
85°C	6.00	N/A <sup>c</sup>	N/A	0.17	0.042	5.53
	7.20	N/A	N/A	14.12	3.50	8.55
	7.70	N/A	N/A	29.33	7.27	11.2

<sup>a</sup> Calculated using WCAP-16530-NP Equation 6-2.<sup>b</sup> -- A test at pH 7.2 and 60°C was not completed.<sup>c</sup> N/A Weight loss measurements are not available because of errors in coupon handling during the final weight measurements.

### 3.2 Corrosion of Aluminum in the Presence of Silicon in Boric Acid/TSP Solution

The corrosion processes for aluminum in the presence of silicon were also evaluated, by determining the corrosion rate using weight loss measurements and by determining the release rate by measuring the concentration of metals in solution. The target temperatures and pH were verified during testing in the same way as aluminum in boric and TSP solution (Section 3.1) with no added silicon. The temperature at start of test, mid-test, and end of test were consistently found to be within  $\pm 1^\circ\text{C}$ . At the beginning of the test, pH was found to be within  $\pm 0.05$  of the target pH. The pH values measured at end of test are reported in Table 9. The pH was typically 0.2 to 0.5 pH units higher than the target value at the end of the immersion period.

Table 9: Target and final pH values during tests of aluminum in boric acid/TSP solution with 4.5 mg/L of added silicon.

Temperature	pH		
	Target	Final	Difference
35°C	6.0	6.47	+0.47
	7.2	7.47	+0.27
	7.7	7.87	+0.17
60°C	6.0	6.49	+0.49
	7.2	-- <sup>a</sup>	--
	7.7	7.81	+0.11



85°C	6.0	--	--
	7.2	--	--
	7.7	--	--

--<sup>a</sup> A test at pH 7.2 and 60°C was not completed.

After immersion time was complete, the aluminum coupons were removed to air dry, to then be weighed and photographed. Each coupon was visually examined for any change and for formation of scale on its surface. The solution was examined for any precipitate formation within or on the bottom of the bottle. However, no visible precipitates were seen in the bottles. The degree of corrosion and scale formation was rated on the same scale of 1 to 4 as was used in the tests without added silicon. For tests at 35°C, aluminum coupons again seemed unchanged (score of 1); at 60°C and pH of 6.0, the coupons were less shiny, slightly darkened especially at edges, and coupons had some pitting (score of 3); at pH 7.7, the coupons were darker (score of 3 to 4); and at 85°C and pH 7.7, the coupons were black and no longer shiny (score of 4).

Weight loss measurements for corrosion at 35 and 60°C are shown in Table 10. Results from the tests at 85°C are not shown because of coupon handling errors during the final weight measurements. As expected from previous corrosion studies, the corrosion rate increased as the pH increased and as the temperature increased, as shown in Figure 12. At 35°C, the corrosion rate increased by 2.4 times as the pH increased from 6.0 to pH 7.7 (similar to the corrosion rate increase of 2.6 times for aluminum in solution without added silicon), whereas at 60°C, the corrosion rate increased 9.5 times (for aluminum in solution without added silicon, the increase was 7.3 times) for the same pH increase.

Table 10: Average aluminum mass lost in boric acid/TSP solution with 4.5 mg/L of added silicon.

35°C	pH=6.0	pH=7.2	pH=7.7
A, Avg. starting mass of coupon (g)	2.4018	2.4062	2.4415
B, Avg. post-test mass of coupon (g)	2.4017	2.4060	2.4406
C, Avg. post-cleaning mass of coupon (g)	2.4013	2.4057	2.4403
$Al_{released}(g) = A - B (g)$	0.0001	0.0002	0.0009
$Al_{scale}(g) = B - C (g)$	0.0004	0.0003	0.0003
$Al_{corrosion}(g) = A - C (g)$	0.0005	0.0005	0.0012

60°C	pH=6.0	pH=7.2	pH=7.7
A, Avg. starting mass of coupon (g)	2.5048	-- <sup>a</sup>	2.4940
B, Avg. post-test mass of coupon (g)	2.5054	--	2.4908
C, Avg. post-cleaning mass of coupon (g)	2.5042	--	2.4883
$Al_{released}(g) = A - B (g)$	-0.0006	--	0.0032
$Al_{scale}(g) = B - C (g)$	0.0012	--	0.0025
$Al_{corrosion}(g) = A - C (g)$	0.0006	--	0.0057

--<sup>a</sup> A test at pH 7.2 and 60°C was not completed.

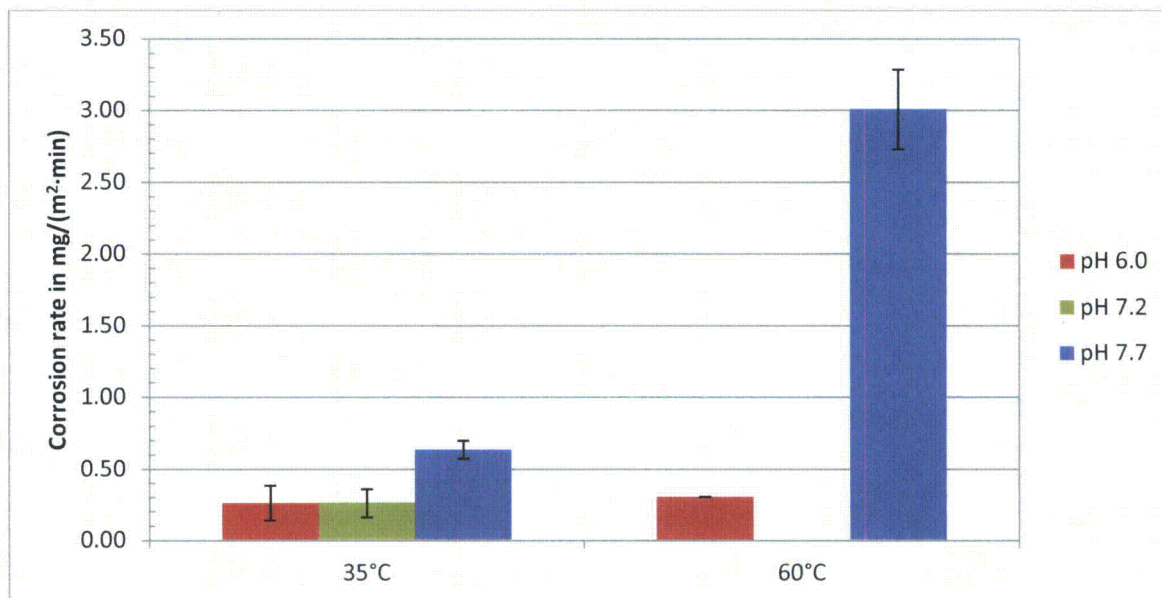


Figure 12: Effect of pH and temperature on corrosion rate of aluminum in solution with added silicon.

The increase in aluminum concentration in solution resulting from release into solution followed the same trends with respect to pH and temperature as did weight loss. The concentration of aluminum in solution in each test is shown in Table 11 and Figure 13. The lowest concentrations of aluminum occurred for the tests at pH 6.0 and were below the reporting limit of 0.2 mg/L at 35°C. The highest concentration of aluminum (33.33 mg/L) was measured at the highest temperature and pH tested. The reported concentrations are the average of three replicate tests. The relative standard deviation (RSD) of the three measurements was 7% or less, except for the 60°C test at pH 6.0, which had a relatively high RSD (19%).

Table 11: Test results for aluminum measurements in the presence of 4.5 mg/L of added silicon in boric acid/TSP solution.

35°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.15	0.76	2.07
Standard deviation	0.012	0.012	0.058
% RSD	7.53	1.53	2.79
60°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.32	-- <sup>a</sup>	8.27
Standard deviation	0.060	--	0.115
% RSD	18.64	--	1.40
85°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.62	18.12	33.33
Standard deviation	0.021	0.487	2.082
% RSD	3.34	2.69	6.24

--<sup>a</sup> A test for pH 7.2 at 60°C was not completed.

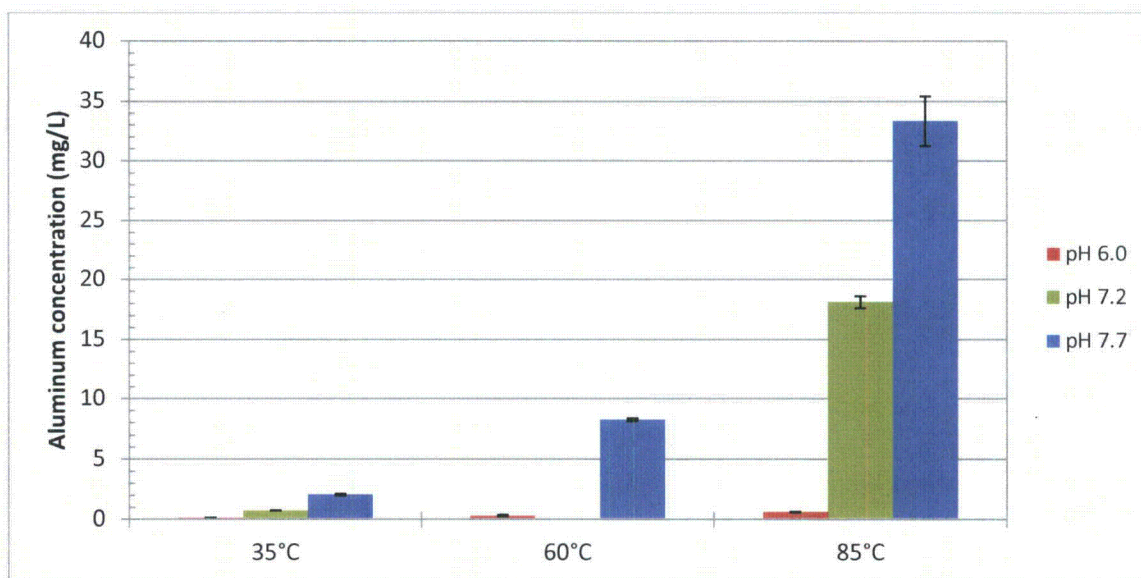


Figure 13: Effect of pH and temperature on release of aluminum in boric acid/TSP solution with added silicon.

When comparing aluminum release in solution with and without added silicon, as shown in Figure 14, the concentration resulting from release from the corrosion with added silicon was higher in 7 of the 8 comparable experiments. However, at pH 7.7 at 60°C, the measurements are almost equal (within 3%), due to silicon's not being added to solution as intended. When comparing concentration differences (among concentrations above reporting limits of 0.20 mg/L), aluminum release in solutions with added silicon were slightly higher, ranging from 12 to 27% additional aluminum. Based on weight loss measurements, however, the rates of aluminum corrosion were similar with and without silicon in



solution (Tables 5 and 9). The WCAP 16785 report reflects passivation with the addition of 50 mg/L of silicon [2].

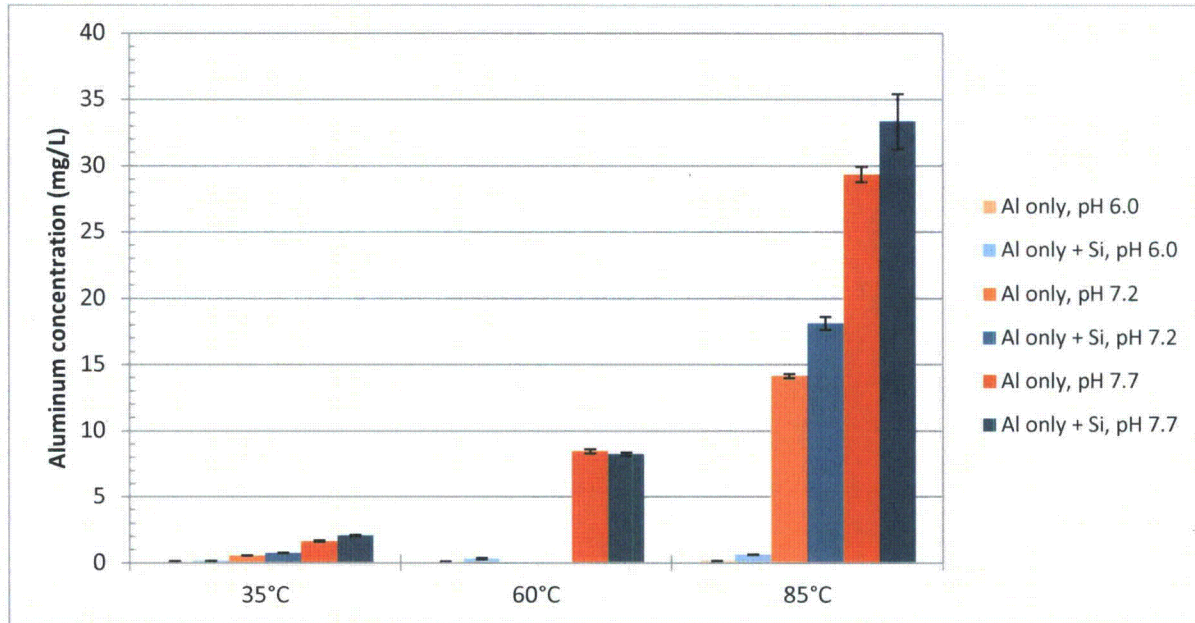


Figure 14: Aluminum concentration in STP solution with or without added silicon.

As a check, measured concentrations of silicon were compared to the amount of dissolved silicon (4.50 mg/L) added to solution at the start of the test. The measured concentrations of silicon are listed in Table 12. At 60°C and pH 7.7, the check confirmed that silicon had not been added to solution. Otherwise, the concentration of silicon was  $\pm 0.34$  mg/L of the intended 4.50 mg/L of silicon.

Table 12: Silicon concentration verification.

Temperature	pH	Avg. concentration of Si, mg/L	Difference, mg/L
35°C	6.0	4.60	+0.10
	7.2	4.53	+0.03
	7.7	4.50	+0.00
60°C	6.0	4.20	-0.30
	7.2	-- <sup>a</sup>	--
	7.7	0.00 <sup>b</sup>	-4.50
85°C	6.0	4.50	+0.00
	7.2	4.16	-0.34
	7.7	4.47	-0.03

--<sup>a</sup> A test for pH 7.2 at 60°C was not completed.

<sup>b</sup> Indicates silicon was not added to solution.

The corrosion rate determined by weight loss measurements were compared to the release rate determined by solution concentrations and to the rate of release calculated from WCAP 16530-NP Equation 6.2. These comparisons are shown in Table 13. For all tests that can be compared, the rate of release into solution was again less than the measured corrosion rate. Again, this result is expected because corrosion brought about both release of ions into solution and formation of a scale layer (see Section 2.6). The ratio of release to corrosion appears to increase as the pH increases. At pH 6.0, the aluminum release rate ranged from 15% to 27% of the corrosion rate; at pH 7.2, the release rate was 76% of the corrosion rate; and at pH 7.7, the release rate ranged from 72% to over 85% of the corrosion rate.

In these tests, the measured release rates were also generally less than the corresponding release rate determined from Equation 6.2 in WCAP-16530-NP. This time, the measured release rate ranged from 3 to almost 40 times lower than the calculated rate at the lowest pH. Otherwise, measured release rates were 1 to 2 times lower than the calculated rate. The differences in measured release rate and calculated release rates are less dramatic in solution with added silicon but still indicate that the WCAP equation overestimates release.

Table 13: Corrosion rate results for aluminum in the presence of added silicon.

Temp.	Final pH	Corrosion by weight loss		Release rate by solution measurement (ICP-OES)		Calculated <sup>a</sup> release rate mg/(m <sup>2</sup> ·min)
		Mass lost (g)	Corrosion rate mg/(m <sup>2</sup> ·min)	Aluminum conc. (mg/L)	Release rate mg/(m <sup>2</sup> ·min)	
35°C	6.47	0.0005	0.248	0.150	0.037	0.122
	7.47	0.0005	0.248	0.760	0.188	0.217
	7.87	0.0012	0.595	2.070	0.513	0.289
60°C	6.49	0.0006	0.298	0.320	0.079	1.06
	7.20	-- <sup>b</sup>	--	--	--	1.50
	7.81 <sup>d</sup>	0.0057	2.83	8.27	2.05	2.18
85°C	6.00	N/A <sup>c</sup>	N/A	0.620	0.154	5.53
	7.20	N/A	N/A	18.120	4.49	8.55
	7.70	N/A	N/A	33.330	8.27	11.2

<sup>a</sup> Calculated using WCAP-16530-NP Equation 6-2.

<sup>b</sup> -- A test at pH 7.2 and 60°C was not completed.

<sup>c</sup> N/A Weight loss measurements are not available because of errors in coupon handling during the final weight measurements.

<sup>d</sup> Silicon was inadvertently not added to solution for this experimental condition.

### 3.3 Corrosion of Aluminum in a Solution of Boric Acid and NaOH

In this series of tests, the solution contained sodium hydroxide (NaOH) instead of TSP. The test procedures were otherwise the same. The corrosion processes were evaluated by determining the corrosion rate using weight loss measurements and by determining the release rate by measuring the concentration of metals in solution. The target temperature and pH were verified during testing. The

temperature was measured in the blank sample at start of test, a random time in the middle of the test, and at the end of a test and was consistently found to be within  $\pm 1^{\circ}\text{C}$  of the target temperature. The pH was measured in the blank sample and one of the triplicate samples at the beginning and end of the test. At the beginning of the test, the pH was consistently found to be within  $\pm 0.05$  of the target pH, except for the test series at  $85^{\circ}\text{C}$ . The pH values measured at the end of the test are reported in Table 14. The pH remained mostly unchanged during the corrosion immersion period. An increase of 0.5 in pH was measured at the lowest temperature and lowest pH, and a decrease of 0.2 in pH was measured at the highest temperature and highest pH tested.

**Table 14: Initial and final pH values during aluminum in boric acid/NaOH corrosion tests.**

Temp.	pH			
	Target	Actual Initial	Final	Difference
35°C	6.0	6.0	6.47	+0.47
	7.2	7.2	7.47	+0.27
	7.7	7.7	7.87	+0.17
60°C	6.0	5.99-6.0	6.03	0+0.03
	7.2	7.25	7.2	0.00
	7.7	7.7	7.69	-0.01
85°C	6.0	5.75	5.98	-0.02
	7.2	6.96	7.02	-0.18
	7.7	7.44	7.5	-0.2

After immersion time was complete, the aluminum coupons were removed to air dry to be weighed and photographed. Each coupon was visually examined for any change and for formation of scale on its surface. The solution was examined for any precipitate formation within or on the bottom of the bottle. No precipitates were visible in the bottles. At  $85^{\circ}\text{C}$  and pH 6.0, the aluminum coupons appeared gray and lacked luster (corrosion/scale score of 2); at pH 7.2 and 7.7 the coupons were black and had no luster (corrosion/scale score of 4). For all other temperatures and pH ranges tested, the coupons showed no visible change (corrosion/scale score of 1).

Weight loss measurements for corrosion at 35, 60, and  $85^{\circ}\text{C}$  are shown in Table 15. Again, the corrosion rate increased as the pH increased and as the temperature increased, as shown in Figure 15. When the pH was 7.7, At  $35^{\circ}\text{C}$ , the corrosion rate increased by a factor of 6.4 as the pH increased from 6.0 to pH 7.7; at  $60^{\circ}\text{C}$ , the corrosion rate increased by a factor of 7.6 for the same pH increase; and at  $85^{\circ}\text{C}$  the corrosion rate further increased by a factor of 11.4 for the same pH increase.

**Table 15: Average aluminum mass lost post-test and post-cleaning in boric acid/NaOH solution.**

35°C	pH = 6.0	pH = 7.2	pH = 7.7
A, Avg. starting mass of coupon (g)	2.6610	2.6917	2.7191
B, Avg. post-test mass of coupon (g)	2.6610	2.6903	2.7158
C, Avg. post-cleaning mass of coupon (g)	2.6603	2.6894	2.7146

$Al_{\text{released}}(g) = A - B (g)$	0.0001	0.0014	0.0033
$Al_{\text{scale}}(g) = B - C (g)$	0.0006	0.0009	0.0012
$Al_{\text{corrosion}}(g) = A - C (g)$	0.0007	0.0023	0.0045

<b>60°C</b>	pH = 6.0	pH = 7.2	pH = 7.7
A, Avg. starting mass of coupon (g)	2.7597	2.8300	2.6807
B, Avg. post-test mass of coupon (g)	2.7576	2.8252	2.6671
C, Avg. post-cleaning mass of coupon (g)	2.7574	2.8209	2.6632
$Al_{\text{released}}(g) = A - B (g)$	0.0021	0.0048	0.0136
$Al_{\text{scale}}(g) = B - C (g)$	0.0002	0.0043	0.0039
$Al_{\text{corrosion}}(g) = A - C (g)$	0.0023	0.0091	0.0175

<b>85°C</b>	pH = 6.0	pH = 7.2	pH = 7.7
A, Avg. starting mass of coupon (g)	2.7124	2.7950	2.8245
B, Avg. post-test mass of coupon (g)	2.7109	2.7810	2.7865
C, Avg. post-cleaning mass of coupon (g)	2.7076	2.7716	2.7696
$Al_{\text{released}}(g) = A - B (g)$	0.0014	0.0140	0.0380
$Al_{\text{scale}}(g) = B - C (g)$	0.0033	0.0094	0.0170
$Al_{\text{corrosion}}(g) = A - C (g)$	0.0048	0.0234	0.0549

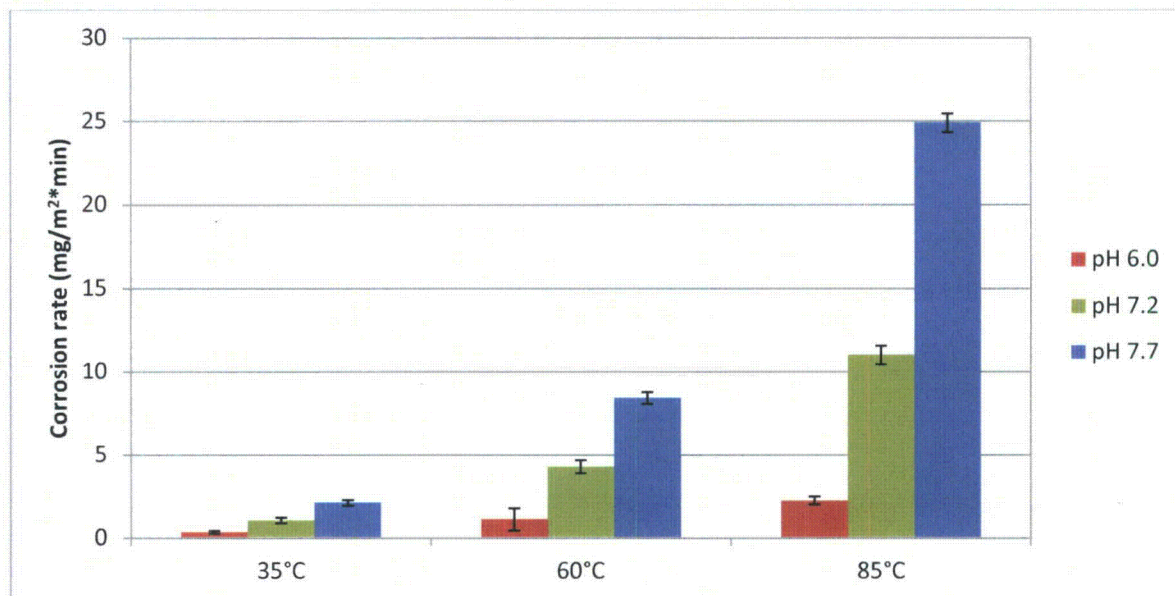


Figure 15: Effect of pH and temperature on corrosion rate of aluminum in boric acid/NaOH solution.

The increase in aluminum concentration in solution resulting from release from the corrosion followed the same trends with respect to pH and temperature as the weight loss. The concentration of aluminum

in solution in each test is shown in Table 16 and Figure 16. The lowest concentrations of aluminum (0.21 mg/L) occurred for the tests at the lowest temperature and pH, and were at the reporting limit of 0.2 mg/L. The highest concentration of aluminum (65.33 mg/L) was measured for the highest temperature and pH tested. The solution was examined for any precipitate formation within or on the bottom of the bottle; no precipitates were visible in the bottle. The reported concentrations are the average of three replicate tests. The relative standard deviation (RSD) of the three measurements was generally 5% or less.

**Table 16: Aluminum concentration in boric acid/NaOH solution.**

<b>35°C</b>			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.21	3.00	7.00
Standard deviation	0.01	0.361	0.265
% RSD	4.76	12.02	3.78

<b>60°C</b>			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.74	14.33	33.33
Standard deviation	0.025	0.577	1.155
% RSD	3.42	4.03	3.46

<b>85°C</b>			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	2.80	30.67	65.33
Standard deviation	0.100	1.155	8.386
% RSD	3.57	3.77	12.84



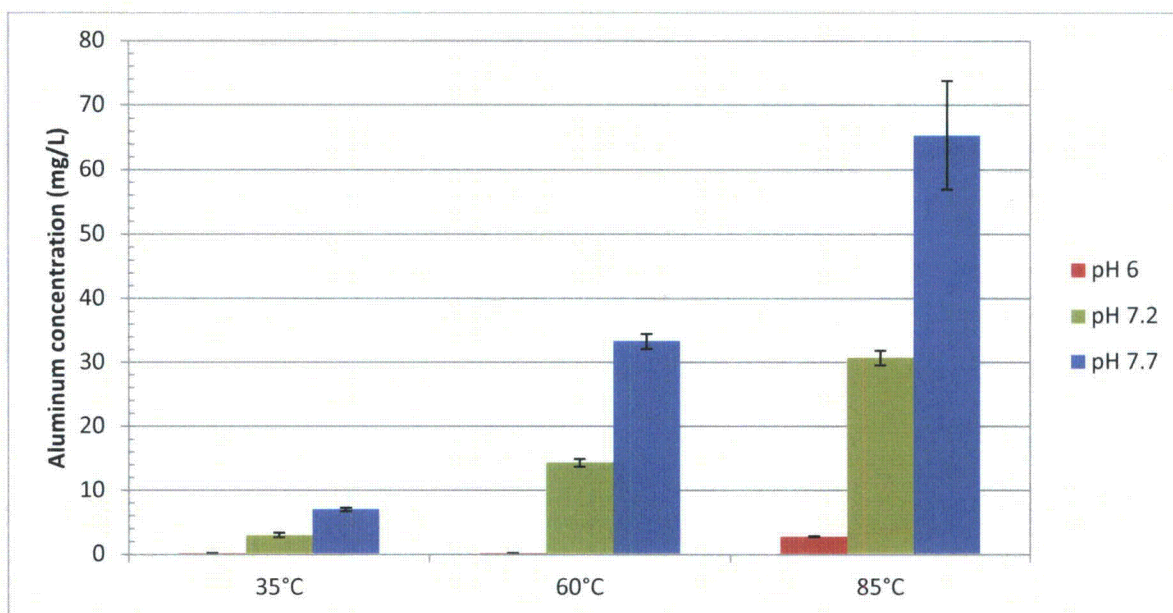


Figure 16: Effect of pH and temperature on release of aluminum in boric acid/NaOH solution.

The corrosion rate determined by weight loss measurements can be compared to the release rate determined by solution concentrations and to the rate of release calculated from WCAP 16530-NP Equation 6.2. These comparisons are shown in Table 17. As in previous test series, the rate of release into solution was less than the measured corrosion rate for all tests (except at 60°C and pH = 7.7, when the release rate was slightly higher than the measured corrosion rate).

In these nine tests, five of the measured release rates were higher than the corresponding release rate determined from Equation 6.2 in WCAP-16530-NP, and four were lower. The measured release rates ranged from 1.6 to 7 times higher than the calculated release rate. At low pH, measured release rates were lower than the calculated release rate and ranged from one-tenth to one-half the calculated release rate.

Table 17: Corrosion rate results for aluminum in boric acid/NaOH solution.

Temp.	Final pH	Corrosion by weight loss		Release rate by solution measurement (ICP-OES)		Calculated <sup>a</sup> release rate mg/(m <sup>2</sup> ·min)
		Mass lost (g)	Corrosion rate mg/(m <sup>2</sup> ·min)	Aluminum conc. (mg/L)	Release rate: mg/(m <sup>2</sup> ·min)	
35°C	6.00	0.0007	0.332	0.21	0.052	0.100
	7.17	0.0023	1.06	3.00	0.744	0.178
	7.68	0.0045	2.07	7.00	1.74	0.251
60°C	6.03	0.0023	1.06	0.74	0.184	0.898
	7.20	0.0091	4.21	14.33	3.55	1.50
	7.69	0.0175	8.10	33.33	8.27	2.01
85°C	5.98	0.0048	2.22	2.80	0.694	5.50

	7.02	0.0234	10.8	30.67	7.61	7.86
	7.50	0.0549	25.4	65.33	16.2	9.98

<sup>a</sup> Calculated using WCAP-16530-NP Equation 6-2.

Measured corrosion rates in solution of boric acid and NaOH were generally three times those in solution of boric acid and TSP buffer (Table 18). The corrosion rate difference was lower at 35°C and pH 6.0, 1.3 times lower. Release rates were also higher in solution of boric acid and NaOH compared to solution of boric acid and TSP buffer (Figure 17 and Table 19). The release rates ranged from 2 to above 16 times higher than in solution with TSP buffer. The release rate difference was also lower at 35°C and pH 6.0, with measured concentrations near or below minimum reporting limits.

**Table 18: Corrosion rates for aluminum in boric acid/TSP and boric acid/NaOH solutions.**

Temp.	pH	Corrosion rate mg/(m <sup>2</sup> ·min)		Ratio of corrosion rates (NaOH/TSP)
		TSP	NaOH	
35°C	6.00	0.248	0.332	1.34
	7.20	0.347	1.06	3.07
	7.70	0.645	2.07	3.21
60°C	6.00	0.347	1.06	3.07
	7.20	--	4.21	--
	7.70	2.53	8.10	3.20
85°C	6.00	--	2.22	--
	7.20	--	10.8	--
	7.70	--	25.4	--

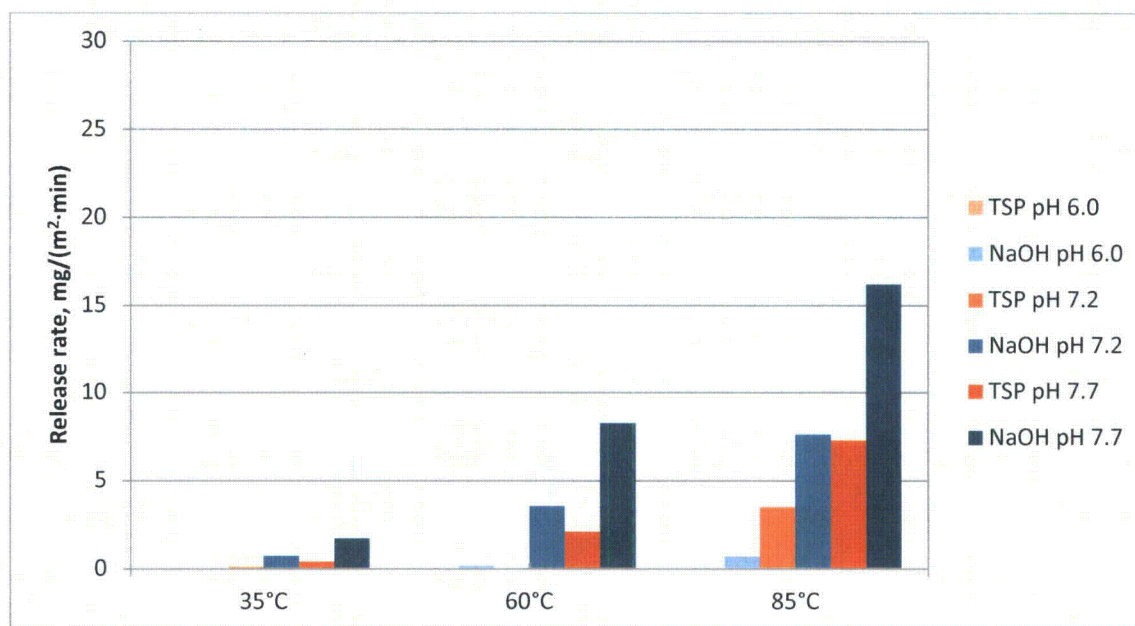


Figure 17: Release rates of aluminum in boric acid/TSP and boric acid/NaOH solutions.

Table 19: Release rates for aluminum in boric acid/TSP and boric acid/NaOH solutions.

Temp.	Target pH	Release rate mg/(m <sup>2</sup> ·min)		Ratio of release rates (NaOH/TSP)
		TSP	NaOH	
35°C	6.00	0.027	0.052	1.91
	7.20	0.136	0.744	5.45
	7.70	0.404	1.74	4.29
60°C	6.00	0.025	0.184	7.40
	7.20	--	3.55	--
	7.70	2.10	8.27	3.94
85°C	6.00	0.042	0.694	16.47
	7.20	3.502	7.61	2.17
	7.70	7.274	16.2	2.23

### 3.4 Effect of pH and Temperature on the Leaching of Fiberglass

Release rates for aluminum, calcium, and silicon from fiberglass (Nukon) were determined by measuring the concentration of metals in solution by ICP-OES. The target temperature and pH were verified during testing by measuring temperature in the blank sample at start of test, a random time in the middle of the test, and at the end of the test and was consistently found to be within  $\pm 1^\circ\text{C}$ . The pH was measured in the blank sample and in one of the triplicate samples at the beginning and end of the test. At the beginning of the test, the pH was consistently found to be within  $\pm 0.02$  of the target pH. The pH values

measured at the end of the test are reported in Table 20. During the corrosion immersion period, the increase in pH beyond the target value ranged from 0.14 to almost 0.40.

**Table 20: Temperature and pH test conditions for leaching from fiberglass in boric acid/TSP solution.**

Temperature	pH			
	Target	Actual initial	Final	Difference
35°C	6.0	± 0.02	6.14	0.14
	7.2	± 0.02	7.41	0.21
	7.7	± 0.02	7.84	0.14
60°C	6.0	± 0.02	6.26	0.26
	7.2	± 0.02	7.57	0.37
	7.7	± 0.02	7.89	0.19
85°C	6.0	± 0.02	--*	--
	7.2	± 0.02	--*	--
	7.7	± 0.02	--*	--

--\* Failed to measure ending pH.

After immersion time was complete, the fiberglass was removed and was visually examined for any change and for precipitate formation on the fibers. The solution was also examined for any precipitate formation within or on the bottom of the bottle. No precipitates were visible in the bottles, but the fiberglass lost some of its yellow color and the solution took on a yellow color. Fibers were also seen to be floating or settling on the bottom of the bottle, prompting the collection of all samples by filtering solution through 0.45-µm Aquaprep™ filters into a 125-mL sample bottle.

### 3.4.1 Aluminum

At temperatures of 35 and 60°C, aluminum concentration in solution increased as pH and temperature increased, with the highest concentration of aluminum (0.07 mg/L) at pH 7.2 or 7.8 in combination with temperature 60°C (Figure 18, Table 21). The lowest concentrations of aluminum occurred for tests at 85°C, but the measured concentrations of aluminum for all three temperatures and across the pH range tested were below the reporting limit of 0.2 mg/L (concentrations that a commercial laboratory would normally report as being below the detection limit (BDL) because they would not meet the laboratory's QA standards). The reported concentrations are the average of three replicate tests. The RSD was high because of the concentrations' being below the reporting limit.



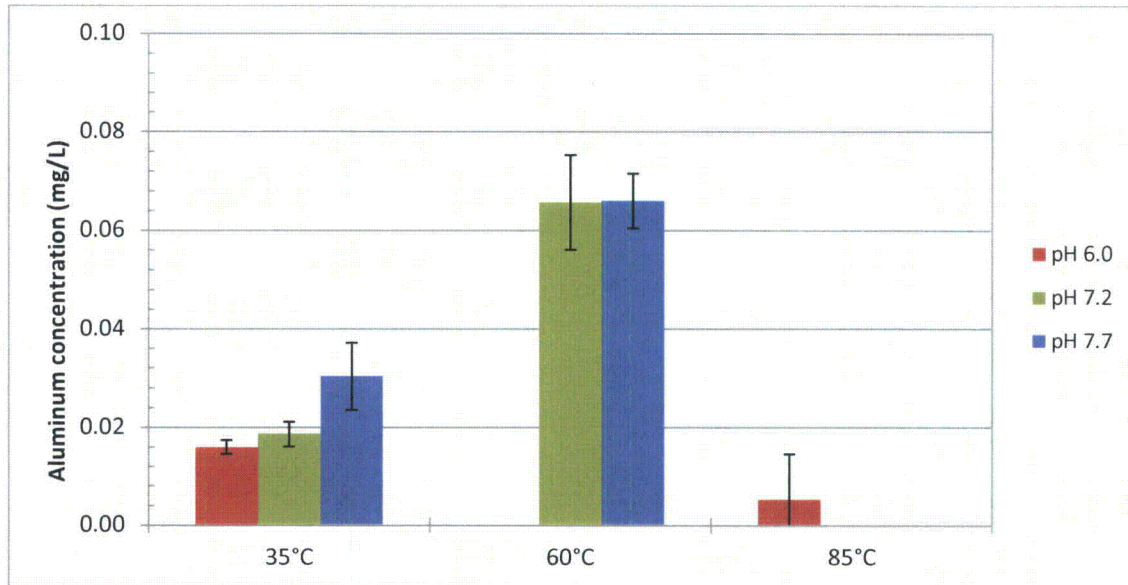


Figure 18: Aluminum concentration in boric acid/TSP solution with fiberglass.

Table 21: Resulting concentrations of aluminum in boric acid/TSP solution with fiberglass.

35°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.02	0.02	0.03
Standard deviation	0.001	0.003	0.007
% RSD	8.84	13.48	22.44
60°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.00*	0.07	0.07
Standard deviation	0	0.010	0.006
% RSD	0	14.63	8.44
85°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.005	0.00*	0.00*
Standard deviation	0.009	0	0
% RSD	173.21	0	0

\* Less than minimum detection limit of 0.0109 mg/L

The release rate can be determined by solution concentrations and can be compared to the release rate and concentrations calculated from WCAP 16530-NP Equation 6-4. These comparisons are shown in Table 22.. The concentration of aluminum in solution was consistently lower than the predicted WCAP concentration. In these tests, the measured concentration was below reporting limits (0.2 mg/L) and shows there is virtually no release of aluminum in solution. The results of these tests demonstrate that the WCAP equation is a conservative prediction of the amount of aluminum that may be released into

solution under STP conditions, and that fiberglass dissolution will not be a significant source of aluminum under these conditions. The lower release of aluminum may be related to passivation by the phosphate in solution.

Table 22: Release rate results for aluminum from fiberglass

Temp (°C)	pH	Time (min)	Fiberglass (kg)	Measured Al conc. (mg/L)	Calculated <sup>a</sup> conc. (mg/L)
35	6.14	1440	0.005	0.02	0.07
35	7.41	1440	0.005	0.02	0.11
35	7.84	1440	0.005	0.03	0.13
60	6.26	1440	0.005	0.00	0.32
60	7.57	1440	0.005	0.07	0.49
60	7.89	1440	0.005	0.07	0.55
85	6.0	1440	0.005	0.01	0.68
85	7.2	1440	0.005	0.00	1.01
85	7.7	1440	0.005	0.00	1.18

<sup>a</sup> WCAP 16530 NP, Equation 6-4 using rate constants for E-glass from Table 6.2-3 using 1-hour increments.

### 3.4.2 Calcium

Another analyte of interest from leaching of fiberglass was calcium. Calcium release increased as pH increased at 35 and 60°C as shown in Figure 19 and Table 22. At those temperatures, concentrations were below 7 mg/L. The highest concentration of calcium (15 mg/L) was measured at the highest temperature and lowest pH tested. At higher pH, the concentration of calcium in solution was again below 7 mg/L.

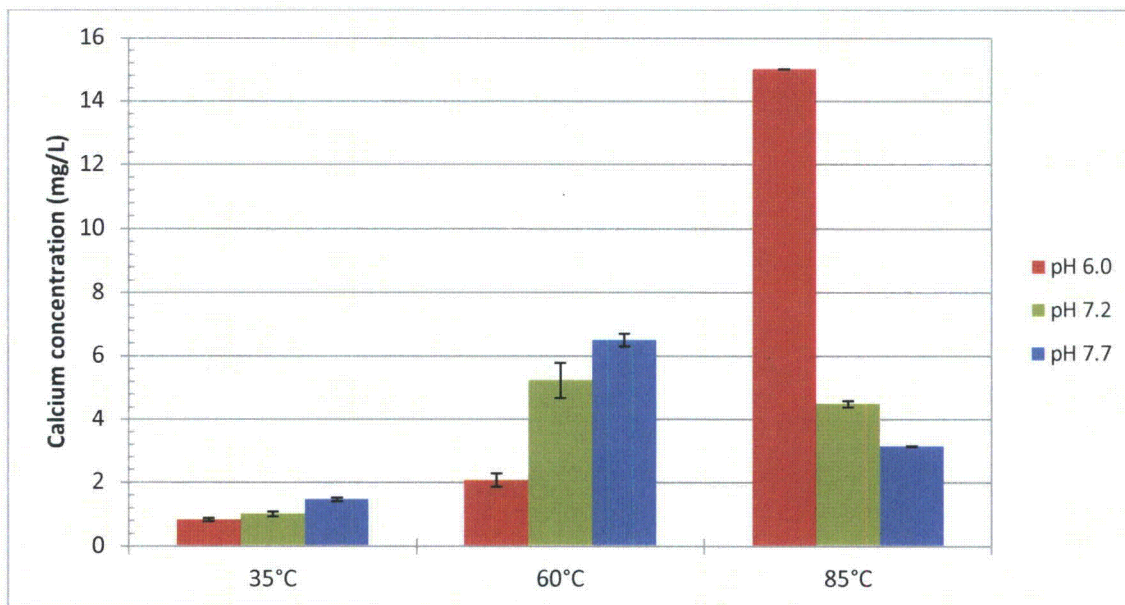


Figure 19: Concentration of calcium in solution with fiberglass.

**Table 23: Concentration results of calcium in solution containing fiberglass.**

<b>35°C</b>			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.84	1.02	1.47
Standard deviation	0.050	0.076	0.058
% RSD	6.02	7.51	3.94
<b>60°C</b>			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	2.07	5.23	6.50
Standard deviation	0.208	0.551	0.200
% RSD	10.07	10.52	3.08
<b>85°C</b>			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	15.00	4.50	3.13
Standard deviation	0.000	0.100	0.208
% RSD	0.00	2.22	6.64

The measured concentrations in solution were compared to the WCAP predicted concentrations; these comparisons are shown in Table 24. With one exception (pH = 6, T = 85°C), the measured concentrations of calcium in solution were lower than the corresponding WCAP concentrations. The calculated concentrations ranged from 1.4 to 6.3 times greater than the measured concentrations. The lower measured concentrations may have been due to interactions with phosphate that reduced the release of calcium in these tests compared to the WCAP experiments, which were conducted without TSP present. The results indicate that the WCAP equation is a conservative prediction of the amount of calcium that would be present due to the dissolution of fiberglass following a LOCA. The results are consistent with the 30-day LBLOCA test, but the MBLOCA test resulted in a calcium concentration that was somewhat higher than the predicted concentration.

**Table 24: Release rate results for calcium from fiberglass.**

Temp (°C)	pH	Time (min)	Fiberglass (kg)	Measured Ca conc. (mg/L)	Calculated <sup>a</sup> conc. (mg/L)
35	6.14	1440	0.005	0.84	5.24
35	7.41	1440	0.005	1.02	6.40
35	7.84	1440	0.005	1.47	6.85
60	6.26	1440	0.005	2.07	6.96
60	7.57	1440	0.005	5.23	8.55
60	7.89	1440	0.005	6.50	8.99
85	6.0	1440	0.005	15.0	8.38



85	7.2	1440	0.005	4.50	10.1
85	7.7	1440	0.005	3.13	10.9

<sup>a</sup> WCAP 16530 NP, Equation 6-4 using rate constants for E-glass from Table 6.2-3, using 1-hour increments.

### 3.4.3 Silicon

Silicon release as concentrations in solution were also measured in these tests. Silicon has been observed to passivate the corrosion of aluminum when in solution at concentrations over 50 mg/L [2]. Silicon release increased as temperature and pH increased (Figure 20 and Table 25). The lowest concentration (0.98 mg/L) was measured at the lowest temperature and pH tested. The highest concentration of silicon (170 mg/L) was measured at the highest temperature and pH tested. The reported concentrations are the average of three replicate tests. The RSD of the three measurements was generally 6% or less.

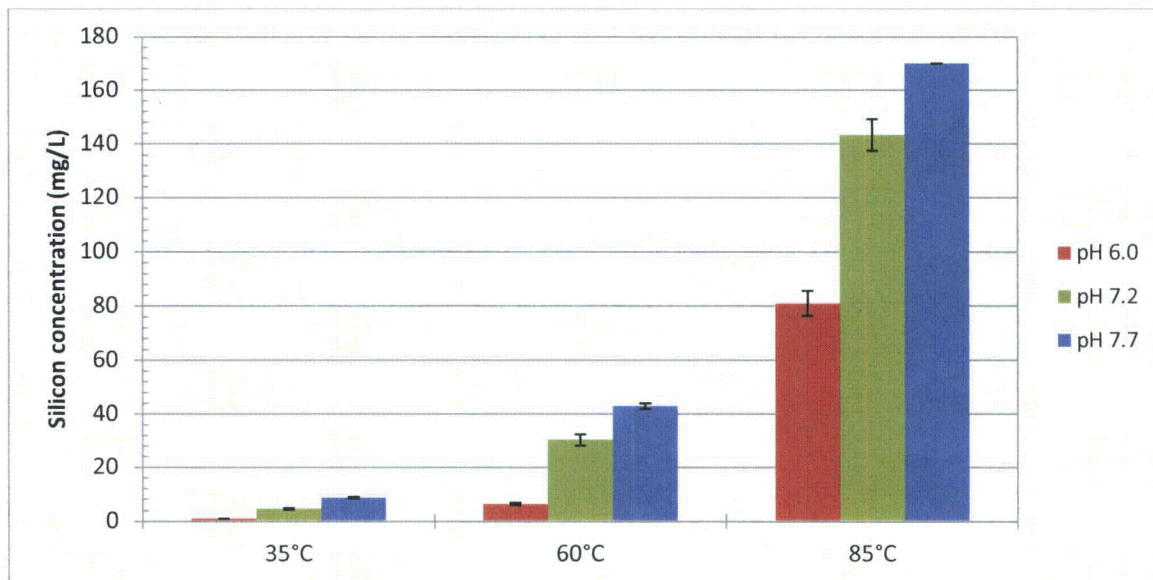


Figure 20: Concentration of silicon in solution with fiberglass.

Table 25: Concentration results of silicon in solution containing fiberglass.

35°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.98	4.60	8.63
Standard deviation	0.015	0.265	0.289
% RSD	1.55	5.75	3.34
60°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	6.40	30.33	43.00
Standard deviation	0.400	2.082	1.000
% RSD	6.25	6.86	2.33
85°C			



pH	6.0	7.2	7.7
Avg. concentration, mg/L	81.00	143.33	170.00
Standard deviation	4.583	5.774	0.000
% RSD	5.66	4.03	0.00

The measured concentrations in solution were compared to the WCAP predicted concentrations, as shown in Table 26. In these tests, the measured concentrations of silicon in solution were sometimes lower and sometimes higher than the corresponding WCAP concentrations. At lower temperature (35°C) and at 60°C and pH = 6, the measured concentration was lower. At higher temperature and pH conditions, the measured concentration was higher than the predictions.

Table 26: Release rate results for silicon from fiberglass.

Temp (°C)	pH	Time (min)	Fiberglass (kg)	Measured Si conc. (mg/L)	Calculated <sup>a</sup> conc. (mg/L)
35	6.14	1440	0.005	0.98	8.16
35	7.41	1440	0.005	4.60	11.5
35	7.84	1440	0.005	8.63	12.8
60	6.26	1440	0.005	6.40	21.3
60	7.57	1440	0.005	30.33	29.3
60	7.89	1440	0.005	43.00	31.6
85	6.0	1440	0.005	81.00	41.7
85	7.2	1440	0.005	143.33	55.8
85	7.7	1440	0.005	170.00	62.5

<sup>a</sup> WCAP 16530 NP, Equation 6-4 using rate constants for E-glass from Table 6.2-3, using 1-hour time increments.

### 3.4.4 Conclusion

Aluminum release from fiberglass appeared to be zero, in contrast to other analytes tested. Even at 85°C, aluminum release was undetectable. Across all temperatures and pH tested, aluminum was found in only trace amounts. Calcium concentration peaked at pH 6.0 at high temperature (85°C); calcium otherwise measured below 7 mg/L. Silicon made up the highest concentration of analyte release in fiberglass.

### 3.5 Leaching of Fiberglass in the Presence of Soluble Aluminum

The purpose of this test was to determine the effects of soluble aluminum on the dissolution of fiberglass. It utilized 0.3 mg/L aluminum nitrate for the soluble aluminum (an aluminum concentration of 0.038 mg/L). Release rate for aluminum, calcium, and silicon from fiberglass (Nukon) was determined by measuring the concentration of metals in solution by ICP-OES. The target temperature and pH were verified during testing by measuring temperature in the blank sample at start of test, a random time in the middle of the test, and at the end of the test and was consistently found to be within  $\pm 1^\circ\text{C}$ . The pH was measured in the blank sample and one of the triplicate samples at the beginning and end of the test. At the beginning of the test, the pH was found to be within  $\pm 0.02$  of the target pH except at 85°C. The pH values measured at the end of the test are reported in Table 27. During the immersion period, the pH increased in the range of -0.02 to almost 0.56 pH units from the target value. Analyte release

from fiberglass was compared with analyte release from fiberglass with added aluminum nitrate at the same conditions.

**Table 27: Temperature and pH conditions for leaching of fiberglass with added aluminum.**

Fiberglass in boric acid/TSP solution + 0.3 mg/L Al				
Temperature	pH			
	Target	Actual	Ending	Difference
35°C	6.0	6.0	6.13	0.13
	7.2	7.2	7.56-7.68	0.36 to 0.48
	7.7	7.7	7.68	-0.02
60°C	6.0	6.0	6.10	0.10
	7.2	7.2	7.28	0.08
	7.7	7.7	7.67	-0.03
85°C	6.0	5.78*	6.34	0.56
	7.2	-- <sup>a</sup>	--	--
	7.7	7.48*	7.69	0.21

\* Actual pH levels were lower than the intended pH for 24-hour tests done at 85°C. A different TSP was used ( $\text{Na}_3\text{PO}_4 \cdot 12\text{H}_2\text{O}$ ) and had a molecular weight of 380.

--<sup>a</sup> Final pH was not measured.

When immersion time was complete, the fiberglass was removed and was visually examined as in Section 4.4. No precipitates were visible in the bottles, the solution took on a yellow color, and the fiberglass lost some of its yellow color. Fibers were also seen to be floating in or settling on the bottom of the bottle, prompting the collection of all samples by filtering solution through 0.45- $\mu\text{m}$  Aquaprep™ filters into a 125-mL sample bottle.

### 3.5.1 Aluminum

Most of the measured concentrations of aluminum for all three temperatures and pH values tested were below the reporting limit of 0.2 mg/L. A high concentration (2.33 mg/L) was measured at pH 6.0 and 60°C and is outside the general trend (Figure 21 and Table 28). Lab notes do not reveal anything unusual, but an excess amount of aluminum nitrate might have been added to solution, or the laboratory reported the results incorrectly. The reported concentrations are the average of three replicate tests. The RSD was generally below 12%.

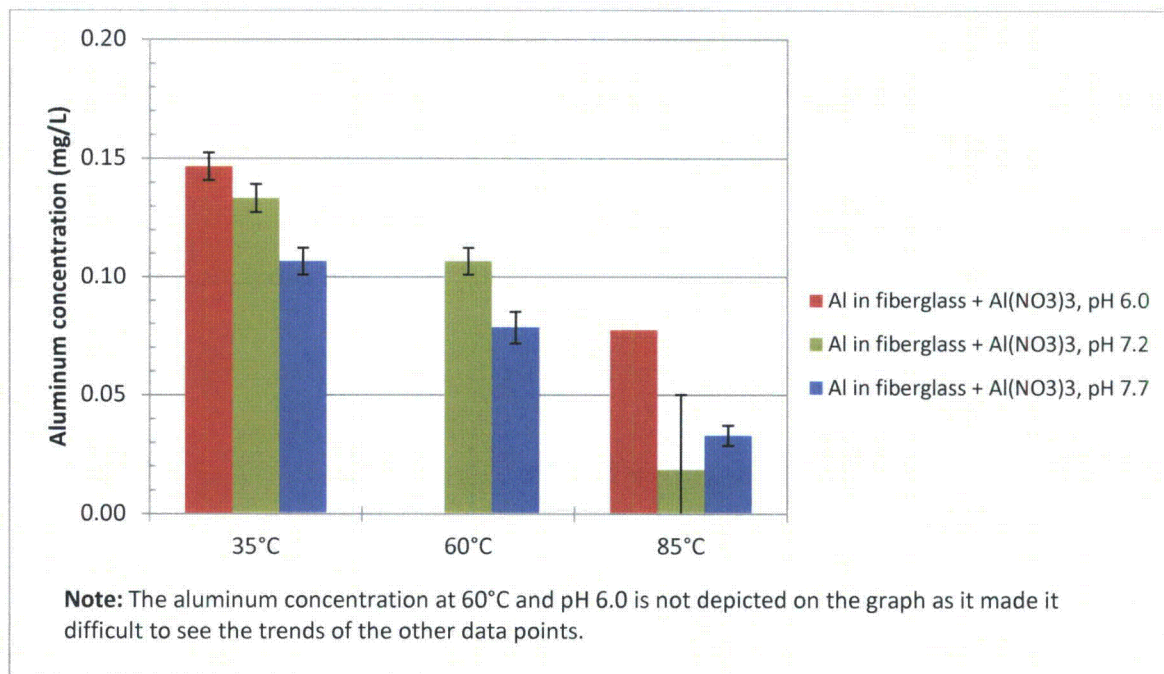


Figure 21: Concentration of aluminum in solution with fiberglass and Al(NO<sub>3</sub>)<sub>3</sub>.

Table 28: Concentration of aluminum in solution with fiberglass and Aluminum nitrate.

35°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.15	0.13	0.11
Standard deviation	0.006	0.006	0.08
% RSD	3.94	4.33	5.41
60°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	2.33	0.11	0.08
Standard deviation	0.321	0.006	0.007
% RSD	13.78	5.41	8.50
85°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.08	0.02	0.03
Standard deviation	0.002	0.032	0.004
% RSD	1.98	173.21	12.86

The resulting concentrations were corrected by subtracting 0.038 mg/L aluminum concentration (Table 29). Concentrations of aluminum in solution measure higher than those measured in solution without added aluminum at temperatures of 35 and 60°C and across the pH values tested. However, the measured concentrations remained below reporting limits (except at pH = 6.0 at 60°C). Due to possible errors in reporting and in test method, these concentrations are considered equal to those measured in solution without added aluminum.

Table 29: Aluminum concentration corrected for added aluminum.

35°C			
pH	6.0	7.2	7.7
Corrected Al concentration, mg/L	0.11	0.10	0.07
60°C			
pH	6.0	7.2	7.7
Corrected Al concentration, mg/L	2.30	0.07	0.04
85°C			
pH	6.0	7.2	7.7
Corrected Al concentration, mg/L	0.04	0.00	0.00

The release rate was again determined by solution concentrations and compared to the release rate and concentrations calculated from WCAP 16530-NP Equation 6-4. The concentration of aluminum in solution was higher than the predicted WCAP concentration at 35°C. However, the measured concentrations are below reporting limits (0.2 mg/L) and show there is virtually no release of aluminum in solution. While the WCAP prediction overstates concentration, the calculated WCAP concentrations also indicated low concentrations.

### 3.5.2 Calcium

Calcium release increased as pH increased at 35 and 60°C as shown in Figure 22 and Table 29. The combination of 85°C and pH 6.0 yielded the highest concentration of calcium (13 mg/L), but all other combinations of temperature and pH yielded a concentration of calcium below 5 mg/L. This follows the same behavior as calcium release from fiberglass without added aluminum, except that concentrations are lower (1 to 2 times) in solution with added aluminum, as seen in Figure 23. Aluminum in solution reduced the concentration of calcium leached from fiberglass. Although the measured concentrations in solution are lower, they are still higher than the corresponding WCAP concentrations, ranging from 4 to over 32 times greater than predicted.

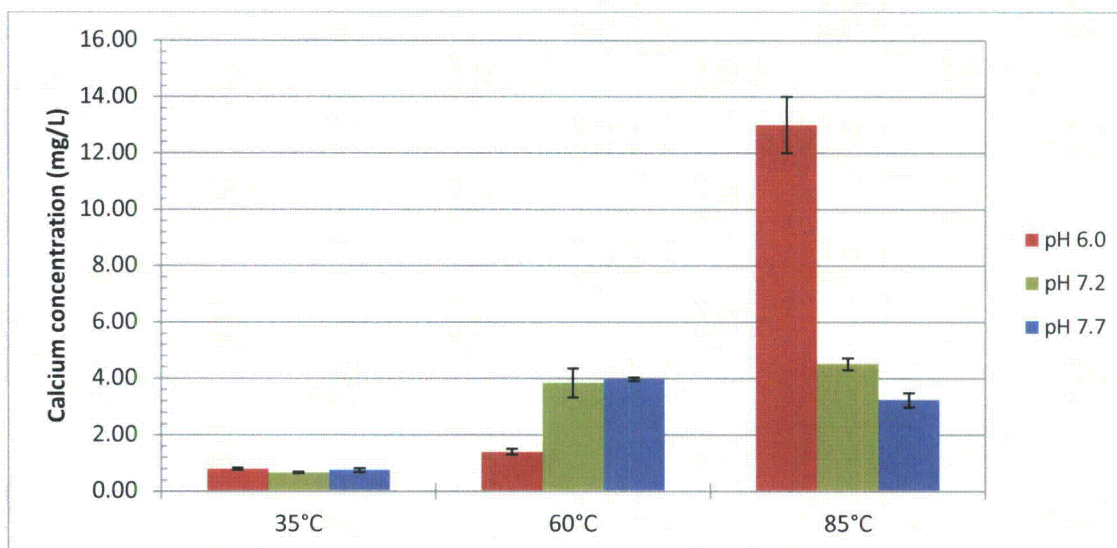


Figure 22: Concentration of calcium in solution with fiberglass and Aluminum nitrate.

Table 30: Concentration of calcium in solution with fiberglass and Aluminum nitrate.

35°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.80	0.66	0.75
Standard deviation	0.046	0.026	0.071
% RSD	5.73	4.01	9.50
60°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	1.40	3.83	3.97
Standard deviation	0.100	0.513	0.058
% RSD	7.14	13.39	1.46
85°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	13.00	4.50	3.23
Standard deviation	1.000	0.200	0.252
% RSD	7.69	4.44	7.78



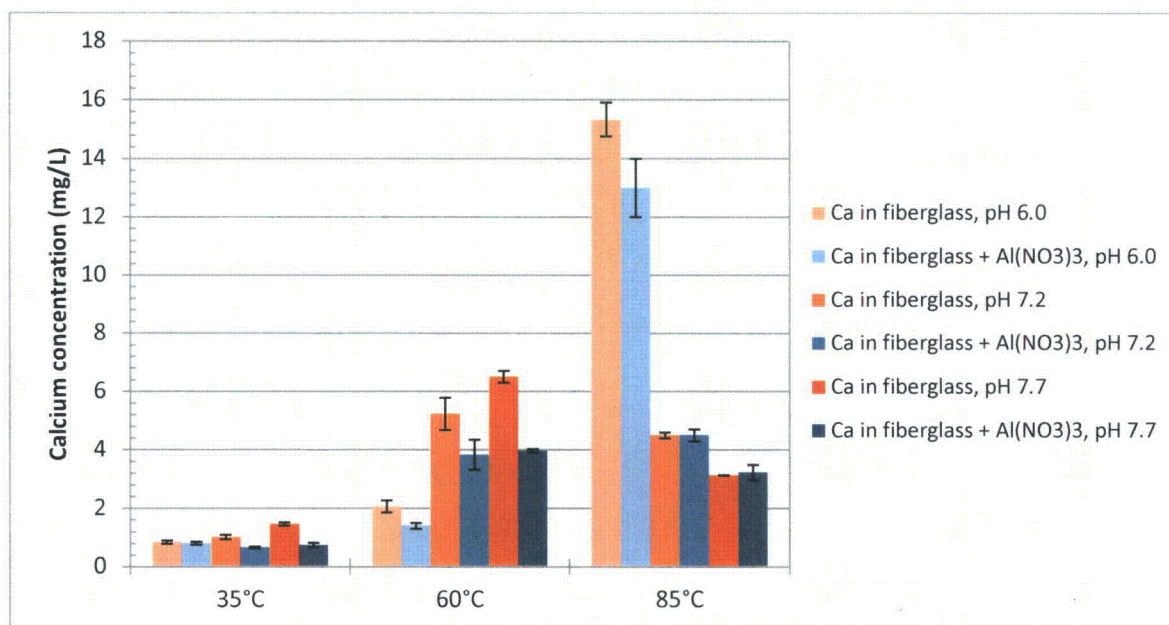


Figure 23: Calcium release from fiberglass vs. fiberglass with Aluminum nitrate.

The measured concentrations of calcium in solution were compared to the WCAP predicted concentrations, as shown in Table 31. With one exception, the measured concentrations of calcium in solution were lower than the corresponding WCAP concentrations. The comparison to the WCAP calculations were generally similar to the comparison without added aluminum.

Table 31: Release rate results for calcium from fiberglass with Aluminum nitrate.

Temp (°C)	pH	Time (min)	Fiberglass (kg)	Measured Ca conc. (mg/L)	Calculated conc. <sup>a</sup> (mg/L)
35	6.00	1440	0.005	0.80	5.14
35	7.20	1440	0.005	0.66	6.20
35	7.70	1440	0.005	0.75	6.71
60	6.00	1440	0.005	1.40	6.69
60	7.20	1440	0.005	3.83	8.08
60	7.70	1440	0.005	3.97	8.74
85	5.78	1440	0.005	13.0	8.11
85	7.20	1440	0.005	4.50	10.1
85	7.48	1440	0.005	3.23	10.6

<sup>a</sup> WCAP 16530 NP, Equation 6-4 using rate constants for E-glass from Table 6.2-3, using 1-hour time increments.

### 3.5.3 Silicon

Silicon release increased as temperature and pH increased (Figure 24 and Table 32). The lowest concentration (0.49 mg/L) was measured at the lowest temperature and pH tested. The highest



concentration (150 mg/L) was measured at the highest temperature and pH tested. The reported concentrations are the average of three replicate tests. The RSD of the three measurements was generally 7% or less.

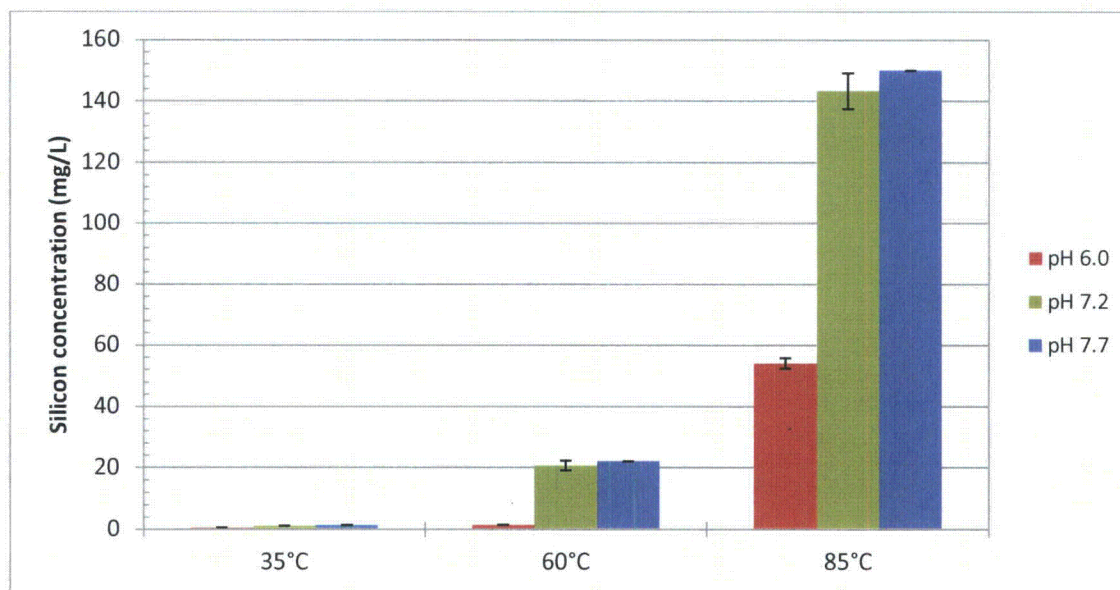


Figure 24: Concentration of silicon in solution with fiberglass and Aluminum nitrate.

Table 32: Concentration of silicon in solution with fiberglass and Aluminum nitrate.

35°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	0.49	1.23	1.47
Standard deviation	0.087	0.058	0.058
% RSD	17.71	4.68	3.94
60°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	1.57	20.67	22.00
Standard deviation	0.058	1.528	0.000
% RSD	3.69	7.39	0.00
85°C			
pH	6.0	7.2	7.7
Avg. concentration, mg/L	54.00	143.33	150.00
Standard deviation	1.732	5.774	0.000
% RSD	3.21	4.03	0.00

As mentioned previously, silicates are major release products of fiberglass. Silicon release increases as temperature and pH increase. Silicon release decreases at lower pH and temperatures when Aluminum nitrate was added; although at 85°C, releases were more similar to that of fiberglass without added aluminum, as shown in Figure 25.

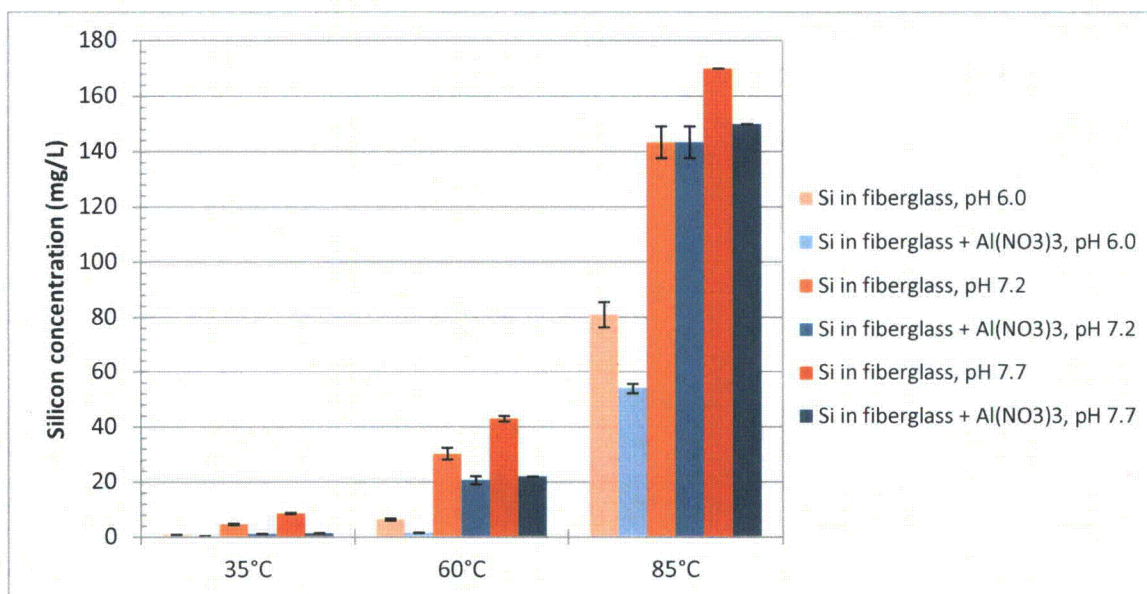


Figure 25: Silicon release from fiberglass vs. fiberglass with Aluminum nitrate.

The measured concentrations of silicon in solution were compared to the WCAP predicted concentrations, as shown in Table 33. In these tests, the comparison between the measured concentrations of silicon and the corresponding WCAP concentrations was similar to the results without added aluminum.

Table 33: Release rate results for silicon from fiberglass with Aluminum nitrate.

Temp (°C)	pH	Time (min)	Fiberglass (kg)	Measured Si conc. (mg/L)	Calculated conc <sup>a</sup> (mg/L)
35	6.00	1440	0.005	0.49	7.86
35	7.20	1440	0.005	1.23	10.9
35	7.70	1440	0.005	1.47	12.4
60	6.00	1440	0.005	1.57	20.0
60	7.20	1440	0.005	20.67	26.8
60	7.70	1440	0.005	22.00	30.3
85	5.78	1440	0.005	54.00	39.7
85	7.20	1440	0.005	143.33	55.8
85	7.48	1440	0.005	150.00	59.7

<sup>a</sup> WCAP 16530 NP, Equation 6-4 using rate constants for E-glass from Table 6.2-3, using 1-hour time increments.

### 3.5.4 Conclusion

For all three analytes (aluminum, calcium, and silicon) tested, leaching of fiberglass with added Aluminum nitrate follows the same trend as leaching from fiberglass without that added compound. For aluminum, concentration remains below the reporting limit of 0.20 mg/L. The measured calcium and

silicon concentrations decreased when soluble aluminum is added at all temperature and pH values tested.

## 4.0 Summary and Conclusions

The following summary and conclusions can be drawn from these bench scale tests.

1. The rate of corrosion of aluminum increased as temperature and pH increased. These trends are consistent with the trends that have been observed in previous literature.
2. The experimental results show that the measured concentrations in solution were lower than the saturation concentration, indicating that the measured release results were not limited by saturation considerations.
3. The corrosion rates of aluminum coupons measured by weight loss measurements (which include a procedure to remove scale from the coupon surface after the immersion time was complete) were consistently greater than the release rates measured using the concentrations of aluminum in solution. A corrosion rate higher than the release rate is consistent with the concept that a portion of the corrosion products remains on the surface as a scale layer instead of being released into solution.
4. When TSP was present, the aluminum release rate was generally lower than predicted by WCAP-16530-NP Equation 6.2. This result was particularly notable at pH = 6, where measured release rates in this study were very low compared to the WCAP predictions.
5. When pH was controlled by NaOH instead of TSP, the corrosion rate was substantially higher (typically 3 to 4 time higher) than when TSP was present. Release rates were also consistently higher when TSP was not present, often more than 3 times higher. Although natural variability exists in data from corrosion studies, the release rates when NaOH was used for pH control were on average comparable to the rates predicted by WCAP-16530-NP Equation 6.2. These results are evidence that a component in TSP (most likely phosphate) effectively reduces the rate of corrosion of aluminum, and that the WCAP-16530-NP Equation 6.2 are conservative for predicting the rate of aluminum corrosion when TSP is present.
6. When 4.5 mg/L of silicon was present, the release rate in a boric acid/TSP solution was slightly higher than when silicon was not present. The corrosion rates were similar with and without added silicon. This result is not consistent with previous testing indicated that silicon may have an inhibitory effect on aluminum corrosion. However, these tests were conducted under different conditions than previous testing. In WCAP 16785, added silicon was in the form of sodium silicate with pH of 8.0 in high concentrations ( $\geq 50$  mg/L) compared to 4.5 mg/L in these tests, and used sodium hydroxide (NaOH) to achieve desired pH compared to TSP in these tests. It is possible that the concentration of silicon was too low to have an inhibitory effect in these tests or that the effect of silicon on aluminum corrosion is not the same when TSP is present as when it is not present.
7. At 35 °C, there was very little change in the visual appearance of the coupons at the end of the test. As the pH and temperature increased, the surface became darker and less shiny. At 85 °C, the coupons were dull and grey at pH = 6 and dull and black at pH = 7.2 and 7.7.

8. The pH generally increased during the corrosion tests with aluminum coupons. The end of test pH was often 0 to 0.2 pH units higher than the initial pH, although in a few cases it was as much as 0.5 pH units higher. The variability in pH at the end of the test may have led to variability in making comparisons to the WCAP release rates.
9. The aluminum concentration was very low (below the reporting limit) in tests for leaching from Nukon fiberglass. The results are consistent with the predictions of the WCAP release equations that Nukon is not a major contributor to the Al in solution during a LOCA. This result was true regardless of whether additional Al was added to solution at the beginning of the test.
10. The calcium concentration in tests for leaching from Nukon fiberglass was generally lower in this study than predicted by WCAP-16530-NP Equation 6.4. The presence of TSP in solution may have contributed to a reduction of the leaching from fiberglass, since the WCAP equation was developed from experiments that did not include TSP.
11. The silicon concentration in tests for leaching from Nukon fiberglass in this study was lower than predicted by WCAP-16530-NP Equation 6.4 at low temperature and pH and higher than predicted at high temperature and pH. Silicon release ranged from just below 1.5 mg/L at 35°C to over 140 mg/L at 85°C. In general, the results predict a stronger dependence on temperature and pH in the presence of TSP than predicted by the WCAP equation, which was developed without the presence of TSP.

## 5.0 References

1. Lane, A.E. et al., *Evaluation of Post-Accident Chemical Effects in Containment Sump Fluids to Support GSI-191*, 2006, Westinghouse Electric Company: Pittsburgh, PA.
2. Reid, R.D., K.R. Crytzer, and A.E. Lane, *Evaluation of Additional Inputs to the WCAP-16530-NP Chemical Model (WCAP-16785-NP)*, 2007, Westinghouse Electric Company: Pittsburgh, PA.