



APR 28 2010

L-2010-082  
10 CFR 50.90

U.S. Nuclear Regulatory Commission  
Attn: Document Control Desk  
Washington, D. C. 20555-0001

Re: Turkey Point Units 3 and 4  
Docket Nos. 50-250 and 50-251  
Supplement to License Amendment Request 196 (ADAMS Accession No. ML092050112) – Revised Summary of Turkey Point Sump pH Calculation Inputs, Assumptions, Methodology, and Results

By letter L-2009-133 dated June 25, 2009, Florida Power and Light (FPL) requested to amend Facility Operating Licenses DPR-31 and DPR-41 and revise the Turkey Point Units 3 and 4 Technical Specifications. The proposed amendments revise the Technical Specifications to adopt the alternative source term (AST) as allowed in 10 CFR 50.67.

FPL received a Request for Additional Information (RAI) from the U.S. Nuclear Regulatory Commission (NRC) via letter dated July 22, 2009 (ADAMS Accession No. ML092020529) to which it provided a response via letter L-2009-177 on July 30, 2009 (ADAMS Accession No. ML092230254). Subsequent changes to several design inputs necessitates revision of this response which is provided in Attachment 1, Revised Summary of Turkey Point Sump pH Calculation Inputs, Assumptions, Methodology, and Results, and Attachment 2, NAI-1396-046, Rev. 2, Turkey Point Units 3 & 4 Post-LOCA Sump pH Report of this letter.

In accordance with 10 CFR 50.91(b)(1), a copy of this letter is being forwarded to the State Designee of Florida.

This submittal does not alter the significant hazards consideration or the environmental assessment previously submitted by FPL letter L-2009-133 [Reference 1].

This letter contains no new commitments and no revisions to existing commitments.

Should you have any questions regarding this submittal, please contact Mr. Robert J. Tomonto, Licensing Manager, at (305) 246-7327.

I declare under penalty of perjury that the foregoing is true and correct.

Executed on April 27<sup>th</sup>, 2010.

Very truly yours,

Michael Kiley  
Site Vice President  
Turkey Point Nuclear Plant

A001  
NRR

Turkey Point Units 3 and 4  
Docket Nos. 50-250 and 50-251

L-2010-082  
Page 2 of 2

cc: USNRC Regional Administrator, Region II  
USNRC Project Manager, Turkey Point Nuclear Plant  
USNRC Resident Inspector, Turkey Point Nuclear Plant  
Mr. W. A. Passetti, Florida Department of Health

Attachment 1

Revised Summary of Turkey Point Sump pH Calculation  
Inputs, Assumptions, Methodology, and Results

LICENSE AMENDMENT REQUEST 196  
REVISED SUMMARY OF SUMP pH CALCULATION INPUTS,  
ASSUMPTIONS, METHODOLOGY AND RESULTS

Florida Power & Light (FPL) submitted a License Amendment Request (LAR 196) to implement the Alternative Source Term by letter L-2009-133 dated June 25, 2009 (ADAMS Accession No. ML092050112). FPL received a Request for Additional Information (RAI) from the U.S. Nuclear Regulatory Commission (NRC) via letter dated July 22, 2009 (ADAMS Accession No. ML092020529) to which it provided a response via letter L-2009-177 dated July 30, 2009 (ADAMS Accession No. ML092230254).

The following information revises the RAI response provided by FPL to the NRC. The revision was required to reflect changes to several design inputs including the maximum refueling water storage tank (RWST), the reactor coolant system (RCS), and the accumulators/safety injection tanks (SIT) inventory profiles (volumes). In addition to these revised inputs, the boric acid equilibrium equations have been replaced with those of Palmer (Reference 1) which have been recognized by the NRC as an acceptable methodology used in the pH sump analytical calculation (Reference 2). Furthermore, the Palmer methodology has been used by the NRC to calculate sump pH values (Reference 3).

**NRC Questions 1 and 2:**

- 1. Provide time dependant values of strong acid concentrations in the sump for a period of 30 days after a loss of coolant accident (LOCA).***
- 2. Describe the analysis methodology used, including assumptions and inputs, to determine the pH in the sump water during a period of 30 days post-LOCA. Include detailed calculations of time dependant pH values in the sump during a 30-day period post-LOCA to demonstrate that the pH remains greater than 7 throughout this time period.***

**FPL Response:**

Purpose

This revised document provides a summary of the approach, inputs, assumptions and results of NAI-1396-046 Rev. 2, Turkey Point Units 3 and 4 Post-LOCA Sump pH Report, to demonstrate that the sump pH remains sufficiently high to assure that significant iodine re-evolution does not occur over the period of 30 days following a loss of coolant accident (LOCA). This report includes:

- Determining the time-dependant containment sump pH during the period of time from the onset of containment spray recirculation flow (2725 seconds) through the 30-day duration following a LOCA.
- Determining the quantity of sodium tetraborate decahydrate (NaTB) and the number of NaTB baskets required to raise the sump pH to 7.0 at the onset of containment spray recirculation.
- Determining the minimum NaTB mass required to adjust the pH level in containment.
- Assessing the impact of formations of acid from radiolysis of air and water, and radiolysis of chloride bearing electrical cable insulation and jacketing.

### Containment Sump pH Determination Methodology

The hydrogen ion concentration ( $[H^+]$ ) in a solution is measured using the pH scale. The concentration of hydrogen ions is based on the relative concentrations of acids and bases and other ions in the solution. For evaluating the post-LOCA sump pH, the following chemical compounds are considered:

- Boron/Boric acid
- NaTB
- Hydrochloric acid
- Nitric acid

The minor contributions from other acidic and basic species are assumed to offset and are negligible compared to the chemicals above. The boron/boric acid is introduced to the sump due to the borated water from the reactor coolant system (RCS), refueling water storage tank (RWST), and other inventory sources which travel to the sump following a LOCA. In order to offset the effect of the boron, NaTB is added to the sump to act as a buffer and raise the pH to a value greater than or equal to 7.0 at the onset of containment recirculation mode. Hydrochloric acid is generated as a result of the irradiation of the cable insulation in containment and acts to reduce the sump pH. Nitric acid is formed due to the irradiation of water in the sump and also decreases the sump pH. The relative concentration of these chemical species impacts the resulting sump pH.

The Turkey Point (PTN) sump pH report (Attachment 2) provides a comprehensive description of the methods used to determine the pH of the containment sump following a LOCA.

To account for the increase in containment sump volume the method was changed from Mesmer to Palmer (Reference 1). The Palmer equilibrium quotients have shown to fit a wider range of experimental data and temperatures, and properly consider the ionic strength dependence.

### Inputs to the pH Calculation

Inputs to the PTN containment sump pH calculation include the following:

- RCS volume and boron concentration
- Emergency Core Cooling System (ECCS) Accumulator volume and boron concentration
- RWST volume and boron concentration
- Chloride bearing electrical cable insulation and jacketing mass
- Time-Dependent Containment sump level
- Small and Large NaTB Basket Dimensions
- NaTB bulk density
- NaTB surface dissolution rate

The following table summarizes the inputs used in the enclosed PTN sump pH report:

Parameter	Minimum Sump pH	Maximum Sump pH
RCS Mass (lbm)	381,126	0
RCS Boron Concentration (ppm)	1950	0
ECCS Accumulator Mass (lbm)	169,614	107,405
ECCS Accumulator Boron Concentration (ppm)	2600	2300
RWST Mass (lbm)	2,394,672	2,152,498
RWST Boron Concentration (ppm)	2600	2400
Chloride Bearing Electrical Cable Insulation and Jacketing Mass (lbm)	41,742	0
Small NaTB Basket Dimensions (ft)	Length = 3.0 Width = 3.0 Height = 2.5	Length = 3.0 Width = 3.0 Height = 2.5
Small NATB Basket Bottom Elevation (ft)	14.54	14.54
Large NaTB Basket Dimensions (ft)	Length = 4.5 Width = 4.5 Height = 2.77	Length = 4.5 Width = 4.5 Height = 2.77
Large NaTB Basket Bottom Elevation (ft)	14.29	14.29
NaTB Bulk Density (lbm/ft <sup>3</sup> )	48.82	54.13
Sump temperature assumed for dissolution of NaTB (F)	100	100
30-day integrated containment sump water dose (Rad)	4.64E6	0
30-day integrated containment air dose (Rad)	3.05E8	0
NaTB Surface Dissolution Rate (lbm/ft <sup>2</sup> -sec)	0.00895 (at 100F)	10 (assumed)

A minimum amount of NATB is required to be placed in the containment sump to ensure that the pH will reach 7.0 by the time operators initiate recirculation following a LOCA. A critical factor in this determination is the maximum amount of boric acid that can be deposited into the containment sump from the RWSTs, the accumulators/SITs, and the RCS. The boric acid content and water volume from these sources is used to determine the initial sump pH. Turkey Point's unique design feature allows a portion of the unaffected unit's RWST to be pumped to the affected unit's sump. When assessing this maximum volume, the previous submittal did not take into account the unaffected unit's RWST that also contributes to the sump volume. This revised submittal includes the RWST additional volume amount, as well as refinements of density values on the RCS and accumulator/SIT volumes. In the case of the maximum sump pH inputs, the entire inventory of two accumulators/SITs is conservatively assumed to be deposited into the sump.

A time dependent sump level profile was developed based upon minimum ECCS injection rates and conservative assumptions regarding fluid holdup in containment. The sump level profile has the following critical points where specified levels are reached and/or ECCS flow rates change.

### Critical Sump Fill Level Points

Description	Time (min)	Level * (ft)
14' elevation reached	12.69	14.0000
RHR Injection Ends	31.66	15.6349
RWST drain down terminated	75.14	17.2432

\* Relative to containment elevation.

The sump level profile shows that the RWST drain down terminates at a minimum sump level of 17.2432 feet, which occurs at 75.14 minutes. Switchover does not occur until there is enough available net positive suction head for recirculation; therefore, the baskets will always be covered at the onset of sump recirculation flow, regardless of when switchover occurs. A faster fill rate is conservative for this assessment because there is less time for the surface area of the NaTB to be in contact with the sump water prior to the baskets becoming fully submerged. Therefore, a fill rate that covers the baskets in the minimum switchover time of 2725 seconds (45.43 minutes) will result in a conservatively low pH. The minimum time before containment spray will take suction from the containment sump is 2725 seconds. This faster fill rate is achieved by adjusting the below fill level profile such that the minimum sump level is reached at 45.43 minutes.

The temperature profile used to develop LOCA containment pressure and temperature analysis is based on a methodology that biases the temperature high. Since lower temperatures are conservative for surface dissolution rates and for pH determination, lower temperatures were used for the PTN pH analyses. The minimum post-LOCA sump temperature prior to containment spray recirculation was determined to be greater than 110°F. The minimum long term containment sump temperature of 77°F was conservatively based on Component Cooling Water parameters. It should also be noted that the minimum post-LOCA containment sump temperature remains above 100°F for at least 4 hours. Enough NaTB is dissolved within the first 45.43 minutes to adjust the pH to 7.0 ensuring that iodine does not re-evolve from the sump water, and post-LOCA sump pH stays above 7.0 as acids are generated.

When assessing the maximum pH, the maximum post-LOCA containment sump temperature is conservatively assumed to be 300°F.

#### Assumptions used in the pH analyses

- All ionic species in the solution are assumed to be in equilibrium. Thus, pH results at any given time are based on a steady-state analysis.
- The individual activity coefficients are based on the Debye-Hückel theory which utilizes the effective ionic radius. The ionic radii utilized are provided at 25°C and the impact of temperature on the approximate ionic radii is assumed to be negligible.
- The density of borated water is assumed equal to that of water due to the low boron concentrations utilized.
- The density of water in the sump is assumed equal to that of water due to the low boron and borax concentrations in the sump.
- The hydrochloric acid and nitric acid are assumed to fully dissociate in the sump. It is conservatively assumed that these acids act to neutralize the NaTB.

- The acidic RCS, Accumulators/Safety Injection Tank (SIT), and RWST inventories are conservatively considered to be in the sump at the beginning of the event for purposes of determining concentrations for calculating the pH. This assumption does not affect the dissolution of the NaTB. The dissolution rate of the NaTB is dependent on the water level in the sump which is applied separately.
- No credit is taken for enhanced dissolution due to flow through the NaTB baskets.

#### Radiolysis of Sump Water

The nitric acid produced during irradiation of the sump water is determined based on Section 2.2.4 of NUREG/CR-5950, "Iodine Evolution and pH Control." For the minimum sump pH case,  $4.77E-01$  g-mol of nitric acid are produced at the onset of containment spray recirculation (2725 seconds) and  $4.54E+01$  g-mol of nitric acid are produced at 30 days.

#### Radiolysis of Electrical Cables

The amount of cable insulation in containment subject to radiolysis is determined based on a review of data from the PTN Fire Protection Program Report. Specifically, the entire mass of cable insulation located in the containment building is assumed to be chloride-bearing cable insulation that is subject to radiolysis. The estimate for the quantity of cable material is based on plant walkdowns.

The following inherent conservatisms exist in this approach:

- Many cables have non-chlorinated insulation and jacketing material, however, the entire mass of cable insulation located in the containment building is assumed to be chloride-bearing cable insulation that is subject to radiolysis.
- Many cables have chlorinated cable jackets and non-chlorinated conductor insulation.
- For conservatism, cable trays are considered to be 40% full or the actual fill if more than 40% full.

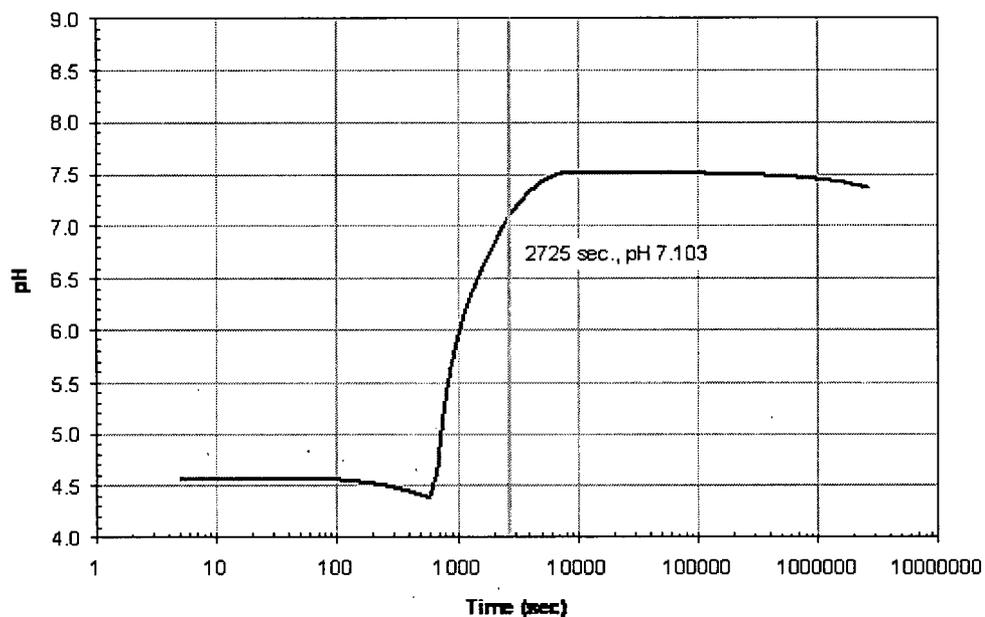
The hydrochloric acid produced during irradiation of electrical cable is determined based on Section 2.2.5.2 of NUREG/CR-5950, "Iodine Evolution and pH Control." For the minimum sump pH case,  $1.08E+02$  g-mol of hydrochloric acid are produced at the onset of containment spray recirculation and  $5.86E+03$  g-mol of hydrochloric acid are produced at 30 days.

#### Summary of PTN pH Report Results

The table below presents the minimum and maximum pH results.

Purpose (Min/Max pH)	Initial Borax Mass (lbm)	Dissolved Mass Prior to Recirc. (lbm)	pH at Recirc.	Min./Max. Long-term pH
Min	11061	4637	7.103	7.366 (Min.)
Max	17034	17034	8.079	8.079 (Max.)

The figure below presents the pH as a function of time for the minimum pH case:



Therefore, FPL concludes that this revised summary of the approach, inputs, assumptions and results of NAI-1396-046 Rev. 2, Turkey Point Units 3 and 4 Post-LOCA Sump pH Report, which demonstrates that the sump pH remains sufficiently high to provide assurance that significant iodine re-evolution does not occur over the period of 30 days following a loss of coolant accident (LOCA).

#### References

1. D. A. Palmer, P. Benezeth, and D. J. Wesolowski, "Boric Acid Hydrolysis: A New Look at the Available Data", Power Plant Chemistry, Volume 2, Number 5, pp. 261-264, 2000.
2. NUREG-0800, Standard Review Plan, Chapter 6, Section 6.5.2, Containment Spray as a Fission Product Cleanup System, Rev. 4, March 2007.
3. Y. Ogata (MHI) To U.S. Nuclear Regulatory Commission (UAP-HF-09519), "MHI's Response to US-APWR DCD RAI No. 460-3484 Rev.0," Accession No. ML093210469, November 13, 2009.

Attachment 2

NAI-1396-046, Rev. 2, Turkey Point Units 3 & 4 Post-LOCA Sump pH Report



## Report Release

Report Number: NAI-1396-046

Revision Number: 2

Title: Turkey Point Units 3 & 4 Post-LOCA Sump pH Report

Description:

Revision 0 presents the time dependent pH of the post-LOCA containment sump. The pH is controlled using baskets of sodium tetraborate (borax) placed on the 14' elevation of containment. This report presents the number of baskets, and the minimum and maximum borax levels in the baskets, required to raise the sump pH to 7.0 by the onset of containment spray recirculation mode. The maximum sump pH is also presented to assist in evaluating sump strainer head loss and other phenomena.

Revision 1 clarifies the conservative basis for some of the inputs.

The purpose of Revision 2 is to incorporate several revised inputs including the maximum RWST, RCS and SIT inventory profiles. Moreover, the boric acid equilibrium equations have been replaced with those of Palmer et. al. (Reference [6.2]).

Sharon K. Thorne 4/20/10  
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NAI Management Date  
Tom George



Check items in the following lists to verify that project documentation and engineering calculations that relate to this report are complete. It is the responsibility of the Report Author and Reviewer to confirm that the required Project documentation is complete to the extent necessary to cover the release of this Report. The Report Author is responsible for archiving the report and the supporting documents.

Mark any items that are not applicable with N/A notation.

**Project Documentation Checklist:**

- Project QA Requirements Form.
- Project QA Plan.
- Project Organization.
- Project Work Scope and Design Plan.
- Project Calculation and Document Index including a listing for this report.
- Project Engineer Training and Qualification Forms for engineers involved with this report.
- Project QA Training Certification Forms for engineers involved with this report.
- Supporting documents reviewed and signed.\*\*
- Report complies with relevant Purchase Order QA requirements.
- Report and supporting documents to be archived by \_\_\_\_\_ (not more than 1 month from the final date on this Report).

\*\* Inputs for this report are provided in the FPL Summary RAI Response.



## Table of Contents

1. Purpose	5
2. Results	5
3. Methodology	10
3.1 pH Calculations	10
3.2 Sump pH/Dissolution	16
3.3 Basket Configurations	21
4. Assumptions	22
5. Inputs	22
5.1 Common Inputs	22
5.2 Minimum Sump pH	33
5.3 Maximum Sump pH	38
6. References	40

## List of Tables

Table 1: Borax level inputs and minimum pH results for parametric level cases (2 large baskets, 8 small baskets).....	7
Table 2: Minimum and maximum sump pH results .....	7
Table 3: The parameters for equilibrium equations regarding the polymeric boric acid species..	14
Table 4: Gamma radiation signature and integrated energy releases.....	24
Table 5: Beta radiation signature and integrated energy releases.....	26
Table 6: Integrated containment air dose .....	27
Table 7: Integrated containment sump dose .....	29
Table 8: Water specific volume .....	30
Table 9: Water ion products .....	31
Table 10: Debye-Hückel constants .....	32
Table 11: Time domains.....	34
Table 12: Minimum sump temperature profile.....	34
Table 13: Maximum RCS inventory profile.....	35
Table 14: Maximum RWST inventory profile .....	35
Table 15: Maximum SIT inventory profile .....	35
Table 16: Critical sump fill level points.....	36
Table 17: Critical sump fill level points - adjusted.....	36



Table 18: Sump fill level.....	37
Table 19: Time domains.....	38
Table 20: Minimum RCS inventory profile .....	39
Table 21: Minimum RWST inventory profile .....	39
Table 22: Minimum SIT inventory profile.....	40
Table 23: Sump fill level.....	40

### List of Figures

Figure 1: Dissolved borax mass at 2725 seconds vs. initial borax level.....	8
Figure 2: Sump pH at 2725 seconds vs. initial borax level.....	8
Figure 3: Case 1 sump pH profile .....	9
Figure 4: Case 2 sump pH profile .....	9
Figure 5: General Borax Basket Dimensions .....	18

## 1. Purpose

The purpose of this report is to determine the time-dependent post-Loss of Coolant Accident (LOCA) pH of the containment sump. A post-LOCA pH of 7.0 prevents radioactive iodine evolution. The pH is controlled with baskets of borax (sodium tetraborate) in the containment sump which dissolve as the post-LOCA water level increases. The quantity of borax and the number of baskets required to raise the sump pH to 7.0 at the onset of containment spray recirculation mode are determined. Minimum and maximum borax levels in the baskets are also determined. The maximum sump pH is also determined based on the number of baskets required.

## 2. Results

Multiple cases were evaluated to determine acceptable basket configurations for obtaining a minimum sump pH of 7.0 at the onset of containment spray recirculation which occurs 2725 seconds into the event. This time represents the minimum time before containment spray will take suction from the containment sump. The configuration that resulted in the minimum number of baskets required was determined to be comprised of two (2) large baskets and eight (8) small baskets. Using this basket configuration a parametric study was performed to determine the acceptable borax levels in these baskets that provide a sump pH of 7.0 or greater at the onset of containment spray recirculation. Case 1 provides the results for the baskets being completely filled. Case 2 provides the sump pH response for the minimum borax level that is the basis for the proposed Technical Specification minimum NaTB value of 11,061 lbs. Each of these cases uses the inputs for determining minimum sump pH which are presented in Sections 5.1 and 5.2.

For the range of borax levels evaluated, the pH at the onset of containment spray recirculation ranges from 7.103 to 7.111. Table 1 gives a summary of the inputs for this parametric study. The third column of this table provides the height of the borax relative to the bottom of the basket. The fourth and fifth columns of this table provide the mass of borax dissolved by 2725 seconds and the resulting sump pH, respectively. These results are presented graphically in Figure 1 and Figure 2. As is expected, the competing effects described in Section 3.3 cause an inverted parabolic shape to the curves and provide the bounding borax levels.

The time-dependent pH profile for Cases 1 and 2 are shown in Figure 3 and Figure 4, respectively. The corresponding minimum long-term pH varies between 7.366 and 7.522 for these cases. Each of these figures shows the sump pH initially decreasing due to hydrochloric and nitric acid generation. The pH increases quickly once the water level reaches the bottom of the baskets and begins dissolving the borax. The peak sump pH is reached once all of the borax is dissolved and then begins declining due to continued acid generation. Table 2 summarizes the inputs and results for these cases.

Starting with the Case 1 basket configuration, the maximum sump pH was also evaluated using Case 3 and Case 4. In Case 3 an additional small basket was conservatively added to the configuration to provide Turkey Point the ability to increase the quantity of borax in



containment. This basket configuration, 9 small baskets and 2 large baskets filled completely, results in a maximum initial borax mass of 17,034 lbm which provides a maximum post-recirculation sump pH of 8.079. This is conservative since it includes an additional small basket. Case 4 was run with only 8 small baskets and 2 large baskets resulting in a maximum initial borax mass and post-recirculation sump pH of 15,816 lbm and 8.048, respectively. These cases were run using the inputs for determining maximum sump pH as documented in Sections 5.1 and 5.3. A summary of the inputs and results for Case 3 and Case 4 is given in Table 2.



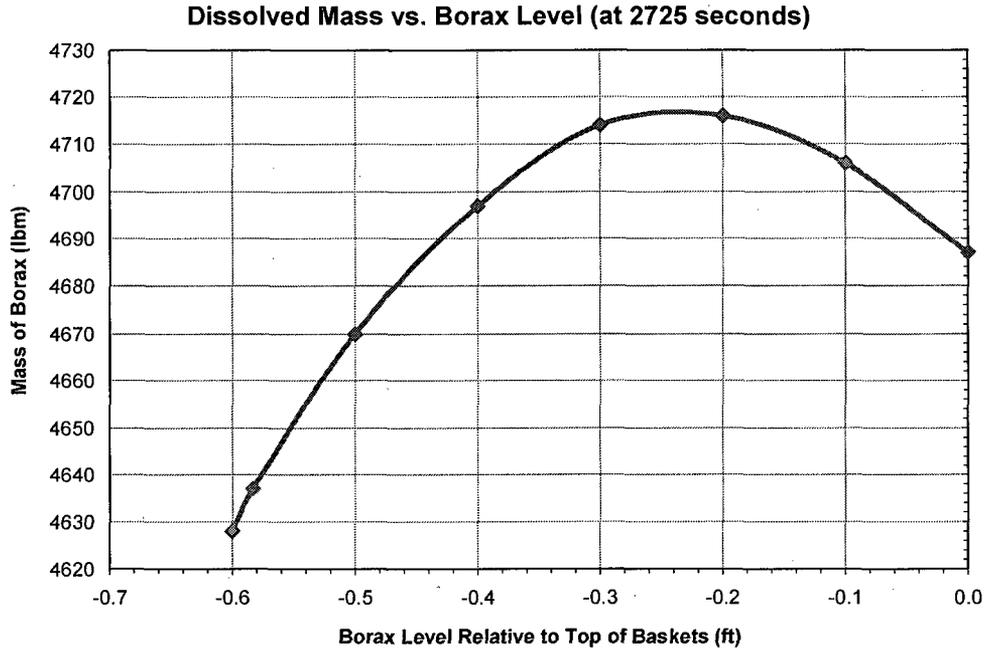
**Table 1: Borax level inputs and minimum pH results for parametric level cases (2 large baskets, 8 small baskets)**

Small Basket Borax Height (ft)	Large Basket Borax Height (ft)	Borax Level Relative to Top of Basket (ft)	Dissolved Mass at CS Recirculation (lbm)	pH
2.5	2.77	0.0000	4687	7.108
2.4	2.67	-0.1000	4706	7.110
2.3	2.57	-0.2000	4716	7.111
2.2	2.47	-0.3000	4714	7.110
2.1	2.37	-0.4000	4697	7.109
2	2.27	-0.5000	4670	7.106
1.9167	2.1867	-0.5833 (-7 in)	4637	7.103
1.9	2.17	-0.6000	4628	7.102

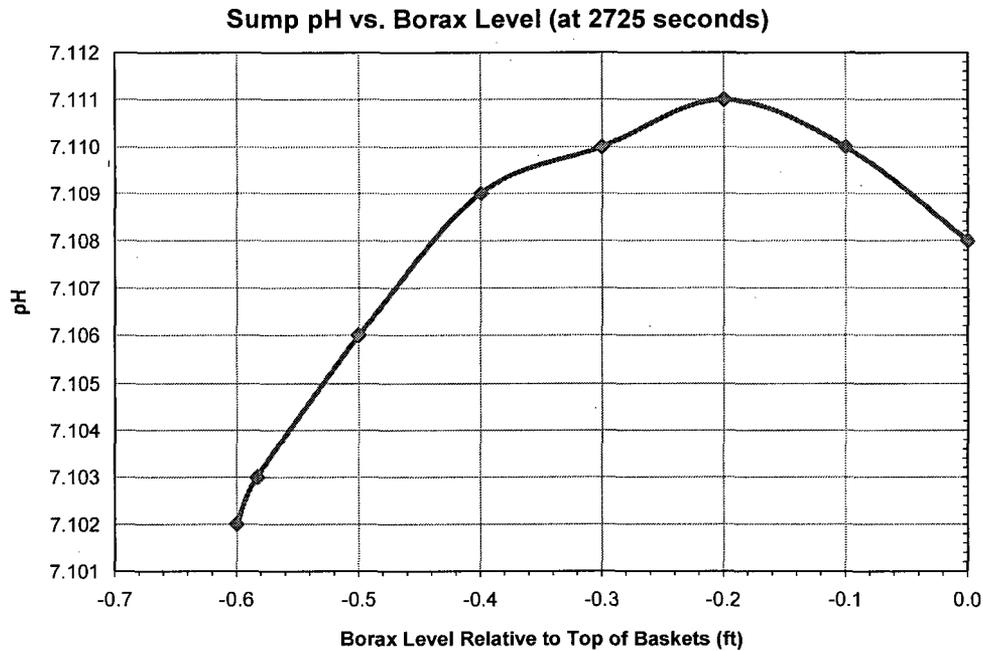
**Table 2: Minimum and maximum sump pH results**

Case No.	Purpose (Min/Max pH)	Small Basket Borax Height (ft)	Large Basket Borax Height (ft)	Initial Borax Mass (lbm)	Dissolved Mass at CS Recirc. (lbm)	pH at Recirc.	Min./Max. Long-term pH
1	Min	2.5	2.77	14264	4687	7.108	7.522(Min.)
2	Min	1.9167	2.1867	11061	4637	7.103	7.366 (Min.)
3	Max	2.5	2.77	17034*	17034	8.079	8.079 (Max.)
4	Max	2.5	2.77	15816	15816	8.048	8.048 (Max)

\* An additional small basket was added to the sump for calculation of the maximum pH



**Figure 1: Dissolved borax mass at 2725 seconds vs. initial borax level**



**Figure 2: Sump pH at 2725 seconds vs. initial borax level**

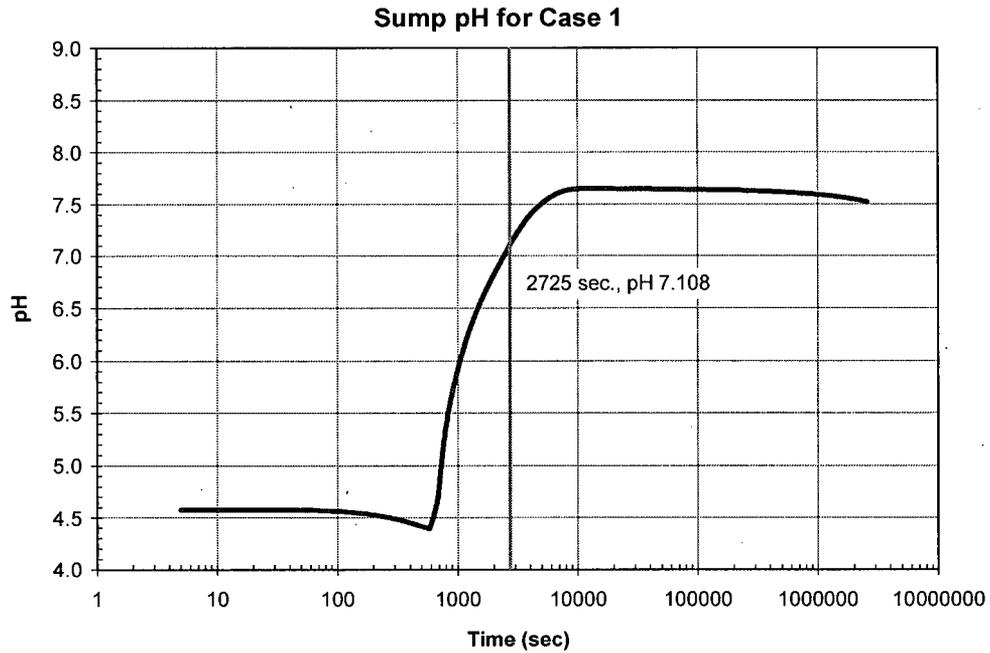


Figure 3: Case 1 sump pH profile

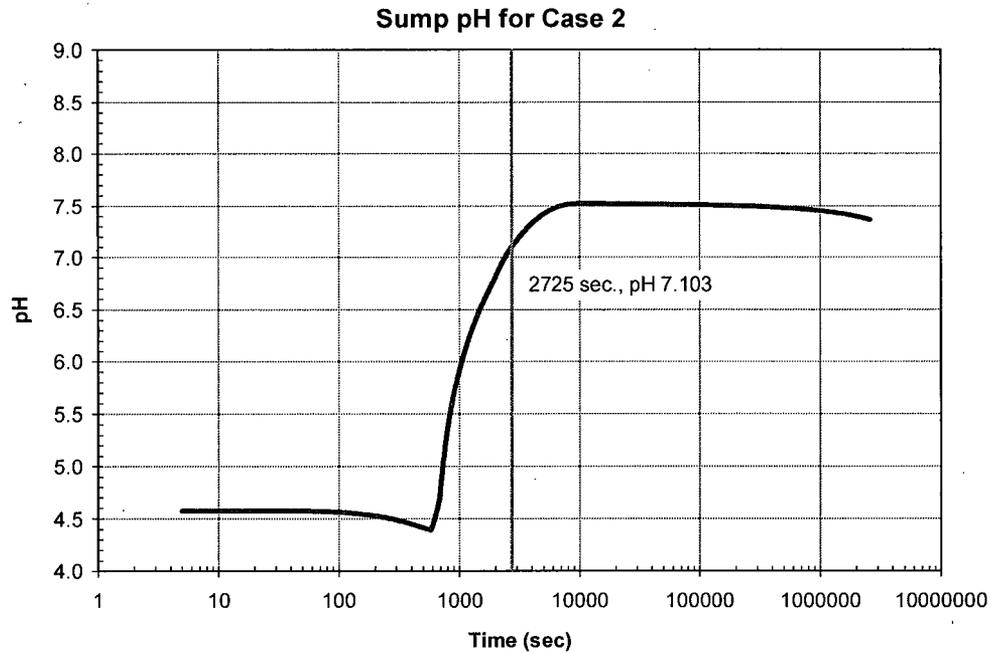


Figure 4: Case 2 sump pH profile

### 3. Methodology

#### 3.1 pH Calculations

The hydrogen ion concentration ( $[H^+]$ ) in a solution is measured using the pH scale where:

$$pH = -\log([H^+]) \quad (1)$$

The concentration of hydrogen ions is based on the relative concentrations of acids and bases and other ions in the solution. For evaluating the post-LOCA sump pH the following chemical compounds are considered:

- Boron/Boric acid
- Borax (sodium tetraborate)
- Hydrochloric acid
- Nitric acid

The minor contributions from other acidic and basic species are assumed to offset and are negligible compared to the chemicals above. The boron is introduced to the sump due to the borated water from the RCS, RWST, and other inventory sources which travel to the sump following a LOCA. In order to offset the effect of the boron, borax is added to the sump to act as a buffer and raise the pH to 7.0. Hydrochloric acid is generated as a result of the irradiation of the cable insulation in containment and tends to reduce the sump pH. Nitric acid is formed due to the irradiation of water in the sump and also decreases the pH. The relative concentration of these chemical species impacts the resulting sump pH.

The following sections provide the method for determining the pH of a solution with the chemical species identified above.

##### 3.1.1 Conservation laws

In order to determine the equilibrium conditions for a solution two general relationships are utilized. The law of conservation of charge and law(s) of conservation of mass can be combined into a single proton balance equation. This equation can be solved to determine  $[H^+]$  and the resulting pH of the solution.

In general, a solution is macroscopically electro-neutral (law of conservation of charge). Thus, the sum of all cations and anions in the solution is zero. This relationship can be described mathematically for species  $A^-$ ,  $B^{2-}$ ,  $C^+$ , and  $D^{2+}$  as:

$$(-1)[A^-] + (-2)[B^{2-}] + (+1)[C^+] + (+2)[D^{2+}] = 0 \quad (2)$$

In a given solution, the mass of a single atomic species must also be conserved. For an example acid,  $HA$ , with a known stoichiometric concentration,  $C$ , the mass conservative law is written as:

$$[HA] + [A^-] = C \quad (3)$$

This equation conserves the quantity of  $[A^-]$  ions in the solution.

### 3.1.2 Equilibrium constants

Many chemical species reach an equilibrium which takes the following form:



For such chemical species, the mass action law specifies that a fixed relationship exists between the concentrations of the chemicals and their stoichiometric coefficients. This law can be written in equation form as:

$$K = \frac{[A]^a [B]^b [C]^c}{[X]^x [Y]^y [Z]^z} \quad (5)$$

where  $K$  is defined as the equilibrium constant. For the example acid,  $HA$ , the equilibrium equation and mass action law can be written as:



$$K_a = \frac{[H^+][A^-]}{[HA]} \quad (7)$$

### 3.1.3 Activity coefficients

Direct use of the mass action law omits the impact of the interaction of solute particles on the equilibrium of the solution. To account for this interaction, an activity coefficient,  $\gamma$ , is introduced which accounts for these effects on the equilibrium constant. The individual activity coefficients are based on the ionic strength of the solution,  $I$ , which is defined as:

$$I = \frac{1}{2} \sum_i z_i^2 C_i \quad (8)$$

where  $z_i$  is the ionic charge and  $C_i$  is the concentration of the ion.

The Debye-Hückel equation (p. 1.300 of Reference [6.7]) provides the activity for an ion of a specific valency (charge),  $z_i$ , ionic radius,  $a_i$ , and solution ionic strength,  $I$ , as:

$$\log(\gamma) = \frac{-Az_i^2 \sqrt{I}}{1 + Ba_i \sqrt{I}} \quad (9)$$

These activity coefficients are included in the equilibrium equations which define the dissociation constants. For the example acid,  $HA$ , the dissociation constant from equation (7) is rewritten in the following manner:

$$K_a = \frac{\gamma_{H^+} [H^+] \gamma_{A^-} [A^-]}{\gamma_{HA} [HA]} \quad (10)$$

### 3.1.4 Water speciation

The equilibrium constant for water,  $K_w$ , is typically defined assuming the concentration of water is constant. Thus, the equilibrium equation and equilibrium constant can be defined as:



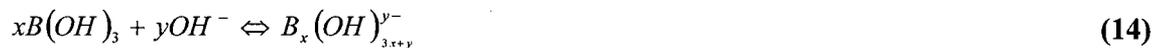
$$K_w = [H^+] [OH^-] \quad (12)$$

As with other equilibrium constants, the value is dependent on temperature and ionic strength based on the activity coefficient. Thus, the equilibrium constant is rewritten as:

$$K_w = \gamma_{H^+} [H^+] \gamma_{OH^-} [OH^-] \quad (13)$$

### 3.1.5 Boron/boric acid speciation

Using simple dissociation constants for boric acid from literature does not account for polyborate species that typically form in borated water buffers. In order to determine the equilibrium concentrations of the boron species, equilibrium quotients from experimental data are utilized for this analysis. Reference [6.2] considers the formation of the following polymeric boric acid species:  $B(OH)_3$ ,  $B(OH)_4^-$ ,  $B_2(OH)_7^-$ ,  $B_3(OH)_{10}^-$ ,  $B_4(OH)_{14}^{2-}$ . The general form of the equilibrium equation for the polymeric species formed by the boric acid is given below from this reference:



The molal equilibrium constant,  $Q_{x,y}$ , is defined for the above equation as:

$$Q_{x,y} = \frac{[B_x(OH)_{3x+y}^{y-}]}{[B(OH)_3]^x [OH^-]^y} \quad (15)$$

The equilibrium equation and molal equilibrium quotients from Reference [6.2] are given below for each of the species considered. The parameter values for these equations are listed in Reference [6.2].

Species (1,1)



$$Q_{1,1} = \frac{[B(OH)_4^-]}{[B(OH)_3][OH^-]} \quad (17)$$

$$\log(Q_{1,1}) = p_1 + \frac{p_2}{T} + p_3 \log(T) + (p_4 + p_5 T) \log(\rho_w) - p_6 I - \frac{p_7 I(f_i)}{T} - p_8 I^2 \log(\rho_w) \quad (18)$$

Species (2,1)



$$Q_{2,1} = \frac{[B_2(OH)_7^-]}{[B(OH)_3]^2 [OH^-]} \quad (20)$$

$$\log(Q_{2,1}) = -3.935 + \frac{1780.5}{T} + 0.95183 \log(T) + p_6 I + \frac{p_7 I(f_i)}{T} + p_8 I^2 \log(\rho_w) \quad (21)$$

Species (3,1)



$$Q_{3,1} = \frac{[B_3(OH)_{10}^-]}{[B(OH)_3]^3 [OH^-]} \quad (23)$$

$$\log(Q_{3,1}) = -6.495 + \frac{3219.1}{T} + 0.95186 \log(T) + p_6 I + \frac{p_7 I(f_i)}{T} + p_8 I^2 \log(\rho_w) \quad (24)$$

Species (4,2)



$$Q_{4,2} = \frac{[B_4(OH)_{14}^{2-}]}{[B(OH)_3]^4 [OH^-]^2} \quad (26)$$

$$\log(Q_{4,2}) = -5.031 + \frac{6001.3}{T} - 1.3572 \log(T) + u_1 I + u_2 IT + u_3 \sqrt{I} + u_4 T \sqrt{I} \quad (27)$$

where  $T$  is the temperature in Kelvin and  $I$  is the solution ionic strength (see Section 3.1.3) and  $\rho_w$  is the density of water.

**Table 3: The parameters for equilibrium equations regarding the polymeric boric acid species.**

Parameters	Equations	Values
p <sub>1</sub>	18	-36.2605
p <sub>2</sub>	18	3645.18
p <sub>3</sub>	18	11.6402
p <sub>4</sub>	18	16.4914
p <sub>5</sub>	18	-0.023917
p <sub>6</sub>	18, 21, 24	0.11902
p <sub>7</sub>	18, 21, 24	36.3613
p <sub>8</sub>	18, 21, 24	0.72132
f <sub>i</sub>	18, 21, 24	$\frac{1 - (1 + 2\sqrt{I}) \exp(-2\sqrt{I})}{2I}$
u <sub>1</sub>	27	0.11830
u <sub>2</sub>	27	-0.0013078
u <sub>3</sub>	27	0.23298
u <sub>4</sub>	27	0.0021211

The mass balance for the boron is defined by the following equation:

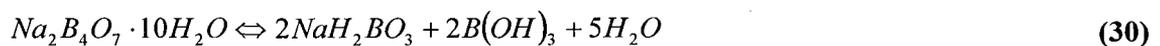
$$C_B = [B(OH)_3] + \sum x Q_{x,y} [B(OH)_3]^x [OH^-]^y \quad (28)$$

where  $C_B$  is the stoichiometric boron concentration in the solution. This equation can be rewritten for the boron species considered here as follows:

$$C_B = [B(OH)_3] + Q_{1,1} [B(OH)_3] [OH^-] + 2Q_{2,1} [B(OH)_3]^2 [OH^-] + 3Q_{3,1} [B(OH)_3]^3 [OH^-] + 4Q_{4,2} [B(OH)_3]^4 [OH^-]^2 \quad (29)$$

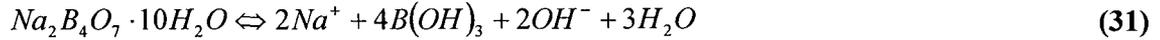
### 3.1.6 Borax speciation

Borax, also known as sodium tetraborate ( $Na_2B_4O_7 \cdot 10H_2O$ ) is used to control the sump pH. When borax is dissolved in water it creates a buffer of boric acid ( $B(OH)_3$ ) and its monosodium salt ( $NaH_2BO_3$ ). The equilibrium equation for the borax solution is:



Although borax occurs naturally, the monosodium salt portion of the crystal can be created using a solution of boric acid and sodium hydroxide ( $NaOH$ ). Since the salt of a

strong base and weak acid completely dissociates, we can write the equilibrium equation for the borax solution as:



The borax solution can now be treated as sodium salt ions, which are completely dissociated, and boric acid, which dissociates based on the mechanisms described in Section 3.1.5. Thus, the mass balance equations for the sodium ion and boric acid are calculated as follows:

$$[Na^+] = 2C_{borax} \quad (32)$$

$$[B(OH)_3]_{borax} = 4C_{borax} \quad (33)$$

Where  $C_{borax}$  is the stoichiometric concentration of borax in the sump.

### 3.1.7 Hydrochloric and nitric acid speciation

The impact of hydrochloric and nitric acid is also considered in this evaluation. For conservatism, these species are assumed to dissociate completely in the sump. This is equivalent to having a very small dissociation constant. Thus, the hydrochloric and nitric acid dissociate as follows:



Thus, the mass balance equations for these acids are:

$$[Cl^-] = C_{HCl} \quad (36)$$

$$[NO_3^-] = C_{HNO_3} \quad (37)$$

Where  $C_{HCl}$  and  $C_{HNO_3}$  are the stoichiometric concentrations of hydrochloric and nitric acid, respectively.

### 3.1.8 Equilibrium pH determination

Post-LOCA the containment sump contains a solution of the boric acid, borax, hydrochloric acid, and nitric acid. The pH of the sump is determined by balancing the charges of the individual species in the solution. By utilizing the equations developed above,  $[H^+]$  (and pH) can be determined. Generalizing equation (2) to consider the four chemical compounds in the sump, in addition to the hydrolization of water, gives the following equation:

$$\begin{aligned} & [H^+] - [OH^-] - [B(OH)_4^-] - [B_2(OH)_7^-] - [B_3(OH)_{10}^-] - 2[B_4(OH)_{14}^{2-}] - [Cl^-] - [NO_3^-] \\ & - [B(OH)_4^-]_{borax} - [B_2(OH)_7^-]_{borax} - [B_3(OH)_{10}^-]_{borax} - 2[B_4(OH)_{14}^{2-}]_{borax} + [Na^+] = 0 \end{aligned} \quad (38)$$

The mass balance equations and equilibrium constants (with activity coefficients) calculated above can be substituted into equation (38) to solve for  $[H^+]$ . Due to the non-linearity of the boric acid speciation scheme and solution ionic strength, this equation must be solved iteratively.

### 3.2 Sump pH/Dissolution

As described in Section 3.1, the sump pH is calculated based on the relative concentrations of borax, boric acid, and other species contained in the sump. Note that the methods for determining minimum and maximum sump pH are identical; the inputs are simply biased in the appropriate direction to obtain the bounding results. The inputs for the minimum and maximum sump pH cases are given in Section 5. The following describes the methodology for determining the pH for the Turkey Point configuration.

#### 3.2.1 Boron & water inventory

In general, the methodology utilized allows for the use of time-dependent RCS, RWST, and SIT inventories in the sump. These inventories are time dependent based on assumptions regarding the vessel blowdown, number of ECCS pumps operating, etc. Boron concentrations for these sources are generally given in concentrations of parts-per-million (ppm). The quantity of boron added to the sump from these sources is calculated based on the definition of concentration:

$$C_{Boron} = \frac{m_{Boron}}{m_{Boron} + m_{Water}} \quad (39)$$

Rearranging equation (39) gives:

$$m_{Boron} = \left( \frac{C_{Boron}}{1 - C_{Boron}} \right) \times m_{Water} \quad (40)$$

The total boron and water inventory in the sump is determined and is used to determine boron concentrations for the pH and dissolution analyses.

#### 3.2.2 Sump properties

Sump properties including the water level, boron concentration, temperature, volume, etc. impact the borax dissolution and pH calculations. The sump boron concentration is calculated using equation (40) from above. A time-dependent sump temperature is utilized and is converted from °F to K for use in evaluating other chemical properties. This temperature conversion is given by:

$$T[K] = \frac{T[^\circ F] - 32}{1.8} + 273.15 \quad (41)$$

The sump density is determined based on the sump temperature. The volume is calculated based on this density:

$$V = \frac{m}{\rho} \quad (42)$$

### 3.2.3 Acid generation

There are two additional sources beyond boric acid that can decrease the pH of the sump. The dosing of cable insulation can generate hydrochloric acid which will affect the sump pH. In addition, dosing of the sump water itself generates nitric acid which also decreases the pH. To properly evaluate the pH of the sump, these sources must be considered in the pH analysis.

The amount of hydrochloric acid (HCl) produced by irradiation of electrical cable insulation is given in Section 2.2.5.2 of Reference [6.10] as 4.6E-4 g-mol HCl / lbm<sub>insulation</sub>-Mrad. The quantity of HCl produced at any given time is given by the following equation:

$$M_{HCl} = 4.6E-4 \frac{\text{g-mol HCl}}{\text{lbm}_{insulation} - \text{Mrad}} \times M_{insulation} \times \gamma_{containment} \quad (43)$$

For the Case 2, 1.08E+02 g-mol of hydrochloric acid are produced at the time of recirculation (2725 seconds) and 5.86E+03 g-mol of hydrochloric acid are produced at 30 days.

Similarly, the nitric acid produced by irradiation of the sump water is given in Section 2.2.4 of Reference [6.10] as 7.3E-6 g-mol HNO<sub>3</sub> / L - Mrad. The quantity of nitric acid produced is given by the following equation:

$$M_{HNO_3} = 7.3E-6 \frac{\text{g-mol HNO}_3}{\text{L} - \text{Mrad}} \times V_{sump} \times \gamma_{sump} \quad (44)$$

For Case 2, 4.77E-01 g-mol of nitric acid are produced at the time of recirculation (2725 seconds) and 4.54E+01 g-mol of nitric acid are produced at 30 days.

### 3.2.4 Basket dissolution

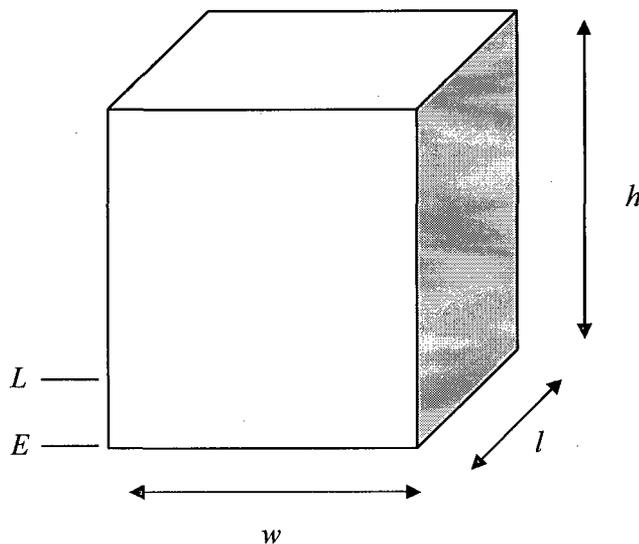
In order for the pH of the sump to be controlled, the borax placed in baskets at the 14' elevation must dissolve into the water. The dissolution process takes a finite amount of time and is dependent on parameters such as the exposed surface area, water temperature, boron concentration in the sump, etc. Basket dimensions, elevations, and porosity along with a time dependent sump level are used to determine the borax surface area exposed to the sump water. The empirically determined surface dissolution rate (SDR) of the borax

(from Section 5.2.10) is used to calculate the mass of borax dissolved at each time step based on the surface area exposed to the water. The following documents the methodology used to determine the exposed surface area for a basket for each time step.

The exposed surface area of a basket as dissolution occurs can be calculated two ways with a simplified methodology. Depending on the sump fill rate, either of the methods may be conservative. For this analysis, the dissolution will be calculated both ways for each time step and the one that results in the conservative sump pH will be utilized. These methods are described in the sections below.

#### 3.2.4.1 *Dissolution method 1*

A basket containing borax is located in containment such that the bottom surface of the borax is located at an elevation,  $E$ . The length, width, and height of the basket is given by  $l$ ,  $w$ , and  $h$ . The sump water level is located at an elevation,  $L$ . These parameters are shown in the figure below.



**Figure 5: General Borax Basket Dimensions**

Depending on the elevation of the sump water level, the surface area of the borax which is dissolved changes. When the water level is below the bottom of the basket the borax surface area in contact with the water is zero. When the water level is between the bottom and top of the basket, the total exposed surface area is the area of the bottom of the basket plus the surface of the sides that are under water. Finally, when the water level covers the top of the borax in the basket, the surface area of the top of the borax is also included. These surface areas are described in additional detail and written in equation form below.

The surface area of the sides is taken as the exposed height of the water multiplied by the perimeter of the basket. The wire mesh and structural supports which hold the basket together reduce the exposed surface area. The calculated surface area is multiplied by an effective porosity to obtain the exposed surface area utilized in the dissolution

calculation. The term  $(L - E)$  in the equation below is limited to a maximum value of the height of borax in the basket,  $h$ , and a minimum value of zero.

$$S.A._{side} = (L - E) \times 2 \times (l + w) \times \alpha_{side} \quad (45)$$

The surface area of the bottom of the basket is the length multiplied by the width and is only used when the water level is above the bottom of the basket. As with the sides of the basket, porosity is multiplied by this area to get an effective surface area.

$$S.A._{bottom} = l \times w \times \alpha_{bottom} \quad (46)$$

The surface area of the top of the basket is the length multiplied by the width and is only used when the water level is above the top of the borax. As with the sides of the basket, porosity is multiplied by this area to get an effective surface area.

$$S.A._{top} = l \times w \times \alpha_{top} \quad (47)$$

The surface areas can be combined into a single equation which is given below.

$$A_{borax} = \begin{cases} L < E & 0 \\ E \leq L < E + h & S.A._{bottom} + S.A._{sides} \\ E \geq E + h & S.A._{bottom} + S.A._{sides} + S.A._{top} \end{cases} \quad (48)$$

This surface area is used to calculate the mass of borax dissolved during a given time step according to equation (49).

$$m_{dissolved} = A_{borax} \times SDR \times t \quad (49)$$

The mass of borax remaining after this time step is calculated from:

$$m_{new} = m_{previous} - m_{dissolved} \quad (50)$$

The ratio of the new mass to the original mass,  $R$ , is determined.

$$R = \frac{m_{new}}{m} \quad (51)$$

Assuming the density of the borax remains constant, this ratio is also equivalent to the volume ratio.

$$R = \frac{V_{new}}{V} \Rightarrow V_{new} = RV \quad (52)$$

$$L_{new} \times w_{new} \times h_{new} = R(L \times w \times h) \quad (53)$$

The length of each side is assumed to be reduced proportional to the total mass dissolved (i.e., the relative dimensions of the borax in the basket do not change). This is written in mathematical form as:

$$L_{new} \times w_{new} \times h_{new} = \left( R^{1/3} \times L \right) \times \left( R^{1/3} \times w \right) \times \left( R^{1/3} \times h \right) \quad (54)$$

Thus, the new dimensions to be substituted into the surface area calculations above (equations (45), (46), and (47)) are:

$$l_{new} = R^{1/3} \times l \quad (55)$$

$$w_{new} = R^{1/3} \times w \quad (56)$$

$$h_{new} = R^{1/3} \times h \quad (57)$$

This process is repeated for each time step until all of the borax is dissolved into solution.

#### 3.2.4.2 *Dissolution method 2*

A potential shortcoming of dissolution method 1 is that it reduces the length of all borax dimensions proportional to the mass dissolved. Depending on the rate at which the water level rises, this may not be conservative. If the water level rises slowly, dissolution method 1 will result in too large of a surface area being considered since some of the surface area is being removed from the top surface of the borax.

The potential non-conservatism identified above is remedied by not reducing the height of the borax for the surface area calculation. Instead of each side being reduced proportional to the total mass dissolved, only the length and width dimensions are reduced. Thus, the new dimensions for the sides of the basket for dissolution method 2 are:

$$l_{new} = R^{1/2} \times l \quad (58)$$

$$w_{new} = R^{1/2} \times w \quad (59)$$

$$h_{new} = h \quad (60)$$

The remaining methodology utilized for dissolution method 1 is used for dissolution methodology 2.

It should be noted that more detailed modeling of the baskets could be performed to provide a more refined result. However, past experience has shown that these more complex methods have a negligible impact on the effective dissolution rate. Both the methods described above include an added measure of conservatism by not crediting the surface area of the top of the borax until the water level is greater than the original level of the top of the borax. In reality, as the borax dissolves from the bottom of the basket the height of the borax will decrease. This effectively moves the top surface of the borax lower in the containment which would result in it being covered more quickly than is assumed in the methods above. Additionally, the surface area is likely to be much greater

than assumed due to the collapsing of the borax. Thus, the methods described above are conservative for determining the time-dependent quantity of borax dissolved in the sump.

### 3.2.5 Species concentrations

Using the water inventory calculated in Section 3.2.1, the concentrations of each of the chemical species in the sump is calculated according to the following equation:

$$[A] = \frac{\frac{m_A}{MW_A}}{V_{sump}} \quad (61)$$

Where

$m_A$  is the mass of species  $A$

$MW_A$  is the molecular mass of species  $A$

$V_{sump}$  is the volume of the sump water

These concentrations are used to calculate the pH of the sump.

### 3.2.6 Activity coefficients

Individual activity coefficients for the hydrogen ion and hydroxide ion are calculated using equation (9) from Section 3.1.3. Since this equation includes a term for ionic strength, an assumed value is used for this parameter which is verified at the end of the pH calculation. Activity coefficients for the remaining species are either included in their respective solution methods (e.g., boric acid) or conservatively are assumed to be unity (e.g., sodium ion and nitric acid ion).

### 3.2.7 Equilibrium pH determination

The post-LOCA containment sump contains a solution of the boric acid, borax, hydrochloric acid, and nitric acid. The pH of the sump is calculated by balancing the charges on the individual ions as described in Section 3.1.8.

## 3.3 Basket Configurations

In order to determine an acceptable basket configuration (i.e., number of large and small baskets required), a parametric study is performed to minimize the number of baskets utilized. Once the minimum number of baskets is identified, a range of acceptable borax levels in the baskets is determined to provide Technical Specification minimum borax levels. Due to the dissolution methodologies utilized, increasing the level of borax in the baskets does not necessarily increase the sump pH at the time containment spray begins to take suction from the containment sump. Lowering the borax level in the basket decreases the quantity available for dissolution but also accelerates the time at which the top surface area is exposed to water, potentially increasing the amount of borax dissolved

at containment spray recirculation. Conversely, raising the borax level increases the mass of borax available for dissolution but also reduces the time when the top of the borax is exposed to sump water. Thus, the acceptable range of borax levels in the sump must be evaluated parametrically.

#### **4. Assumptions**

The following section documents assumptions for the analysis.

- 4.1 All ionic species in the solution are assumed to be in equilibrium. Thus, the pH results at any given time are based on a steady-state analysis.
- 4.2 The individual activity coefficients are based on the Debye- Hückel theory which utilizes the effective ionic radius. The ionic radii utilized are provided at 25°C and the impact of temperature on the approximate ionic radii is assumed to be negligible.
- 4.3 The density of borated water is assumed equal to that of water due to the low boron concentrations utilized.
- 4.4 The density of water in the sump is assumed equal to that of water due to the low boron and borax concentrations in the sump.
- 4.5 The hydrochloric acid and nitric acid are assumed to fully dissociate in the sump. It is conservatively assumed that these acids act to neutralize the borax.
- 4.6 The acidic RCS, SIT, and RWST inventories are conservatively considered to be in the sump at the beginning of the event for purposes of determining concentrations for calculating the pH. This assumption does not affect the dissolution of the borax. The dissolution rate of the borax is dependent on the water level in the sump which is applied separately.
- 4.7 No credit is taken for enhanced dissolution due to flow through the baskets.

#### **5. Inputs**

The following sections provide the development of inputs for determining the minimum and maximum sump pH.

##### **5.1 Common Inputs**

The following section provides inputs that are common to both the minimum and maximum sump pH cases.

### 5.1.1 Large Basket Parameters

The large baskets, hereafter referred to as “basket type 1”, have the following dimensions and elevation:

$$\text{Length} = 54 \text{ in} = \mathbf{4.5 \text{ ft}}$$

$$\text{Width} = 54 \text{ in} = \mathbf{4.5 \text{ ft}}$$

$$\text{Height} = 33.25 \text{ in} = \mathbf{2.77 \text{ ft}}$$

**(Note: the borax height is varied parametrically for this analysis.)**

$$\text{Bottom elevation} = 14' + 3.5 \text{ in legs} = \mathbf{14.29 \text{ ft}}$$

A nominal porosity of 1.0 is utilized for the top and sides of the basket which is consistent with the method utilized by and approved for other licensees as described in Appendix C of Attachment 3 of Reference [6.12]. Use of a porosity of 1.0 for the top of the borax is appropriate since the dissolution of the borax from the bottom of the basket would reduce the height of the borax. Once the sump water level reaches the top of the basket enough material would be dissolved that the top of the borax would no longer be in contact with the basket's lid. Thus, water would be in contact with the entire surface area of the top of the borax. For the sides of the basket, a porosity of 1.0 is appropriate since the borax will no longer be in contact with the basket support structure immediately following the initial dissolution of borax.

$$\alpha_{top} = 1.0$$

$$\alpha_{sides} = 1.0$$

The porosity of the bottom of the basket is calculated by reducing the surface area available for dissolution by the projected area of the basket support structure. This method is appropriate since gravity will tend to keep the borax in contact with the bottom of the basket.

The porosity of the bottom of the basket is calculated as:

$$\alpha_{bottom} = \frac{A_{bottom,open}}{A_{bottom}} = 0.524$$

### 5.1.2 Small Basket Parameters

The small baskets, hereafter referred to as “basket type 2”, have the following dimensions and elevation:

$$\text{Length} = 3'-0'' = \mathbf{3 \text{ ft}}$$

$$\text{Width} = 3'-0'' = \mathbf{3 \text{ ft}}$$

$$\text{Height} = 2'-6'' = \mathbf{2.5 \text{ ft}}$$

**(Note: the borax height is varied parametrically for this analysis.)**

$$\text{Bottom elevation} = 14' + 6.5 \text{ in casters} = \mathbf{14.54 \text{ ft}}$$

The porosities for the bottom, sides, and top of the small baskets are developed in Section 5.1.1 and are repeated here for clarity.

$$\alpha_{top} = 1.0$$

$$\alpha_{sides} = 1.0$$

$$\alpha_{bottom} = 0.524$$

### 5.1.3 Containment Air and Sump Water Dose

In order to calculate the production of HCl and HNO<sub>3</sub> in containment, the integrated doses must be calculated. Typical radiation release signatures for both gamma and beta radiation are given in Figures 1 and 2 of Reference [6.13], respectively. By integrating the area under each of these curves from the beginning of the event to 30 days post-LOCA, a time-dependent integrated dose fraction can be calculated for each time point. Table 4 gives the time, energy release rate, and integrated energy release for gamma radiation using the trapezoidal rule. For example, at time of 19 seconds, the integrated energy release is calculated as follows:

$$E_{release} = \frac{(\text{Current Rate} + \text{Previous Rate})}{2} \times (\text{Current Time} - \text{Previous Time}) + \text{Previous Energy}$$

$$E_{release} = \frac{\left(9.87E+6 \frac{MeV}{s-W} + 1.89E+7 \frac{MeV}{s-W}\right)}{2} \times (1.90E+1s - 1.80E+1s) + 8.90E+7 \frac{MeV}{W}$$

$$E_{release} = 1.03E+8 \frac{MeV}{W}$$

**Table 4: Gamma radiation signature and integrated energy releases**

Time (sec)	Energy Release Rate (MeV/sec/W)	Energy Release (MeV/W)
1.80E+01	9.87E+06	8.90E+07
1.90E+01	1.89E+07	1.03E+08
4.61E+01	2.71E+08	4.04E+09
5.16E+01	3.36E+08	5.71E+09
5.59E+01	3.85E+08	7.23E+09
6.07E+01	4.30E+08	9.18E+09
9.53E+01	7.53E+08	2.97E+10
9.71E+01	7.60E+08	3.11E+10
1.88E+02	1.11E+09	1.16E+11



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Time (sec)	Energy Release Rate (MeV/sec/W)	Energy Release (MeV/W)
2.08E+02	1.09E+09	1.38E+11
4.65E+02	8.91E+08	3.93E+11
5.54E+02	8.59E+08	4.71E+11
9.30E+02	7.25E+08	7.69E+11
1.06E+03	7.02E+08	8.63E+11
1.86E+03	5.66E+08	1.37E+12
2.16E+03	5.41E+08	1.54E+12
3.39E+03	4.37E+08	2.14E+12
3.90E+03	4.06E+08	2.35E+12
4.71E+03	3.56E+08	2.66E+12
5.23E+03	3.43E+08	2.84E+12
9.37E+03	2.37E+08	4.04E+12
1.09E+04	2.25E+08	4.40E+12
1.92E+04	1.64E+08	6.02E+12
2.08E+04	1.61E+08	6.28E+12
4.20E+04	1.15E+08	9.19E+12
4.48E+04	1.13E+08	9.51E+12
5.34E+04	1.07E+08	1.05E+13
8.14E+04	8.87E+07	1.32E+13
8.56E+04	8.81E+07	1.36E+13
1.02E+05	8.58E+07	1.50E+13
1.95E+05	7.31E+07	2.24E+13
2.02E+05	7.29E+07	2.29E+13
3.45E+05	6.91E+07	3.31E+13
3.48E+05	6.90E+07	3.32E+13
5.00E+05	6.62E+07	4.35E+13
5.08E+05	6.61E+07	4.41E+13
8.37E+05	6.25E+07	6.52E+13
8.44E+05	6.25E+07	6.57E+13
1.96E+06	6.14E+07	1.35E+14
2.01E+06	6.14E+07	1.38E+14
2.59E+06	6.10E+07	1.73E+14

**Table 5: Beta radiation signature and integrated energy releases**

Time (sec)	Energy Release Rate (MeV/sec/W)	Energy Release (MeV/W)
1.80E+01	9.36E+06	8.45E+07
1.90E+01	9.86E+06	9.38E+07
4.61E+01	1.75E+08	2.60E+09
5.16E+01	2.09E+08	3.66E+09
5.59E+01	2.48E+08	4.63E+09
6.07E+01	2.92E+08	5.92E+09
9.53E+01	5.41E+08	2.04E+10
9.71E+01	5.54E+08	2.13E+10
1.88E+02	7.57E+08	8.09E+10
2.08E+02	8.02E+08	9.66E+10
4.65E+02	6.53E+08	2.83E+11
5.54E+02	6.00E+08	3.39E+11
9.30E+02	4.90E+08	5.44E+11
1.06E+03	4.51E+08	6.07E+11
1.86E+03	3.63E+08	9.30E+11
2.16E+03	3.29E+08	1.03E+12
3.39E+03	2.69E+08	1.40E+12
3.90E+03	2.44E+08	1.53E+12
4.71E+03	2.16E+08	1.72E+12
5.23E+03	1.99E+08	1.83E+12
9.37E+03	1.49E+08	2.55E+12
1.09E+04	1.30E+08	2.76E+12
1.92E+04	9.47E+07	3.70E+12
2.08E+04	8.79E+07	3.85E+12
4.20E+04	5.91E+07	5.40E+12
4.48E+04	5.54E+07	5.56E+12
5.34E+04	5.10E+07	6.02E+12
8.14E+04	4.04E+07	7.30E+12
8.56E+04	3.89E+07	7.46E+12
1.02E+05	3.63E+07	8.09E+12
1.95E+05	2.85E+07	1.11E+13
2.02E+05	2.80E+07	1.13E+13
3.45E+05	2.47E+07	1.51E+13



Time (sec)	Energy Release Rate (MeV/sec/W)	Energy Release (MeV/W)
3.48E+05	2.46E+07	1.51E+13
5.00E+05	2.28E+07	1.87E+13
5.08E+05	2.27E+07	1.89E+13
8.37E+05	2.09E+07	2.61E+13
8.44E+05	2.09E+07	2.62E+13
1.96E+06	1.85E+07	4.82E+13
2.01E+06	1.84E+07	4.90E+13
2.59E+06	1.81E+07	5.97E+13

The tables above can be used to generate the general shape of the integrated dose for the containment air and sump. The total integrated dose at each time is divided by the 30 day integrated dose to obtain an integrated dose fraction. These fractions are multiplied by the Turkey Point specific nominal 30 day integrated doses for the containment air and sump. An example of this calculation is completed below to obtain the integrated beta dose fraction to the containment air at 1.8E+1 seconds.

$$F = \frac{8.45E+07}{5.97E+13} \times 2.5E+8 \text{ rad} = 3.54E+02 \text{ rad}$$

This process is repeated for the sump and air beta and gamma doses. The total doses for the sump and containment air are added together and provided in the tables below.

**Table 6: Integrated containment air dose**

Time (sec)	Integrated Dose (Rads)
1.80E+01	3.82E+02
1.90E+01	4.25E+02
4.61E+01	1.22E+04
5.16E+01	1.72E+04
5.59E+01	2.17E+04
6.07E+01	2.77E+04
9.53E+01	9.47E+04
9.71E+01	9.92E+04
1.88E+02	3.75E+05
2.08E+02	4.48E+05
4.65E+02	1.31E+06



Turkey Point Units 3 & 4 Post-LOCA  
Sump pH Report

<b>Time (sec)</b>	<b>Integrated Dose (Rads)</b>
5.54E+02	1.57E+06
9.30E+02	2.52E+06
1.06E+03	2.81E+06
1.86E+03	4.33E+06
2.16E+03	4.82E+06
3.39E+03	6.55E+06
3.90E+03	7.16E+06
4.71E+03	8.04E+06
5.23E+03	8.55E+06
9.37E+03	1.19E+07
1.09E+04	1.30E+07
1.92E+04	1.74E+07
2.08E+04	1.81E+07
4.20E+04	2.55E+07
4.48E+04	2.63E+07
5.34E+04	2.85E+07
8.14E+04	3.48E+07
8.56E+04	3.56E+07
1.02E+05	3.87E+07
1.95E+05	5.37E+07
2.02E+05	5.46E+07
3.45E+05	7.36E+07
3.48E+05	7.39E+07
5.00E+05	9.23E+07
5.08E+05	9.33E+07
8.37E+05	1.30E+08
8.44E+05	1.31E+08
1.96E+06	2.45E+08
2.01E+06	2.49E+08
2.59E+06	3.05E+08

**Table 7: Integrated containment sump dose**

<b>Time (sec)</b>	<b>Integrated Dose (Rads)</b>
1.80E+01	2.38E+00
1.90E+01	2.75E+00
4.61E+01	1.08E+02
5.16E+01	1.53E+02
5.59E+01	1.93E+02
6.07E+01	2.46E+02
9.53E+01	7.94E+02
9.71E+01	8.31E+02
1.88E+02	3.10E+03
2.08E+02	3.70E+03
4.65E+02	1.05E+04
5.54E+02	1.26E+04
9.30E+02	2.06E+04
1.06E+03	2.31E+04
1.86E+03	3.66E+04
2.16E+03	4.11E+04
3.39E+03	5.71E+04
3.90E+03	6.29E+04
4.71E+03	7.11E+04
5.23E+03	7.60E+04
9.37E+03	1.08E+05
1.09E+04	1.18E+05
1.92E+04	1.61E+05
2.08E+04	1.68E+05
4.20E+04	2.46E+05
4.48E+04	2.54E+05
5.34E+04	2.80E+05
8.14E+04	3.53E+05
8.56E+04	3.63E+05
1.02E+05	4.02E+05
1.95E+05	6.00E+05
2.02E+05	6.13E+05
3.45E+05	8.85E+05



Time (sec)	Integrated Dose (Rads)
3.48E+05	8.89E+05
5.00E+05	1.16E+06
5.08E+05	1.18E+06
8.37E+05	1.74E+06
8.44E+05	1.76E+06
1.96E+06	3.60E+06
2.01E+06	3.68E+06
2.59E+06	4.64E+06

5.1.4 Water Density

The temperature-dependent specific volume of water is taken from Appendix 24.A of Reference [6.5] and is converted to density using the following relation:

$$\rho = \frac{1}{v}$$

The table of specific volume is given as follows.

**Table 8: Water specific volume**

Temp. (deg-F)	Specific Volume (ft <sup>3</sup> /lbm)
40	0.01602
50	0.01602
60	0.01604
70	0.01605
80	0.01607
90	0.0161
100	0.01613
110	0.01617
120	0.01621
130	0.01625
140	0.01629
150	0.01634
160	0.01639
170	0.01645
180	0.01651
190	0.01657
200	0.01663
210	0.0167
212	0.01672



Temp. (deg-F)	Specific Volume (ft <sup>3</sup> /lbm)
220	0.01677
230	0.01685
240	0.01692
250	0.017
260	0.01708
270	0.01717
280	0.01726
290	0.01735
300	0.01745

### 5.1.5 Water Ion Product

The temperature-dependent ion product of water is from the equation given in Table 3.2 of Reference [6.11] which is as follows:

$$-\log(K_w) = \frac{4470.99}{T} - 6.0875 + 0.01706T$$

Note that the temperature,  $T$ , specified in the equation above is in units of Kelvin. This parameter is calculated for temperatures between 0°C and 150°C in 5°C increments. An additional data point for 148.88°C (300°F) is also included. The table generated using this equation is given as follows.

**Table 9: Water ion products**

Temp. (deg-C)	-log(K <sub>w</sub> )
0	14.941
5	14.732
10	14.533
15	14.345
20	14.165
25	13.995
30	13.833
35	13.679
40	13.532
45	13.393
50	13.261
55	13.136
60	13.016
65	12.903
70	12.796
75	12.694
80	12.598

Temp. (deg-C)	-log(K <sub>w</sub> )
85	12.506
90	12.420
95	12.338
100	12.260
105	12.187
110	12.118
115	12.053
120	11.992
125	11.934
130	11.880
135	11.830
140	11.783
145	11.738
148.88	11.706
150	11.697

*5.1.6 Debye-Hückel Constants*

The Debye-Hückel constants that are used to calculate the activity coefficients are taken from Table 1.59 of Reference [6.7]. These parameters are given in the following table. Note that an additional point is added for 148.88°C (300°F) and the value of the constants are assumed to be the same as those at 100°C.

**Table 10: Debye-Hückel constants**

Temp. (deg-C)	A	B
0	0.4918	0.3248
5	0.4952	0.3256
10	0.4989	0.3264
15	0.5028	0.3273
20	0.507	0.3282
25	0.5115	0.3291
30	0.5161	0.3301
35	0.5211	0.3312
40	0.5262	0.3323
45	0.5317	0.3334
50	0.5373	0.3346
55	0.5432	0.3358
60	0.5494	0.3371
65	0.5558	0.3384
70	0.5625	0.3397
75	0.5695	0.3411

Temp. (deg-C)	A	B
80	0.5767	0.3426
85	0.5842	0.3440
90	0.5920	0.3456
95	0.6001	0.3471
100	0.6086	0.3488
148.88	0.6086	0.3488

## 5.2 Minimum Sump pH

Three cases are run for determining the minimum number of baskets of borax required to obtain a sump pH of at least 7.0 prior to the start of recirculation spray. Two different size baskets are available and the three cases are run to provide flexibility in choosing an appropriate basket configuration. The only input difference between these cases is the number of baskets utilized for each. These values are provided as results in Section 2.

### 5.2.1 NaTB Bulk Density

The minimum bulk density for the borax is **48.82 lbm/ft<sup>3</sup>**. The minimum density maximizes the number of baskets required and dissolution time since it maximizes the surface-to-mass ratio.

### 5.2.2 Water Inventory Boron Concentrations

Maximizing boron concentrations in the RWST, RCS, and SIT water inventory requires that more borax be added to the sump and minimizes sump pH. The maximum boron concentrations for the RCS, RWST, and SIT are given below.

$$C_{\text{Boron, RCS, max}} = 1950 \text{ ppm}$$

$$C_{\text{Boron, RWST, max}} = 2600 \text{ ppm}$$

$$C_{\text{Boron, SIT, max}} = 2600 \text{ ppm}$$

### 5.2.3 Cable Insulation Mass

The maximum cable insulation mass for Turkey Point is present in Unit 3 and is **41,742 lbm**.

### 5.2.4 Time Step Sizes

The following time domains were used to complete the analysis:

**Table 11: Time domains**

End Time (sec)	Time Step Size (sec)
2730	5
3600	10
10800	60
86400	3600
2.592E+06	43200

*5.2.5 Sump Temperature for pH*

Use of the minimum sump temperature is conservative for determining the minimum pH. This is primarily due to the higher density increasing the volumetric boron concentration in the sump but also due to other effects related to the dissociation constants and water ion product. Prior to spray recirculation, the sump temperature remains above 110°F. Long-term, the sump temperature is assumed to drop as low as 77°F. For this evaluation, the sump temperature for determining pH will be maintained at 110°F until spray recirculation mode is reached at 2725 seconds and is conservatively assumed to reduce to 77°F at one hour. This temperature is maintained for the remainder of the event. The following table is utilized:

**Table 12: Minimum sump temperature profile**

Time (sec)	Temp. (deg-F)
0	110
1	110
100	110
200	110
300	110
400	110
500	110
600	110
700	110
800	110
900	110
1000	110
1100	110
1200	110
1300	110
1400	110
2725	110
3600	77
10001	77
2.592E+06	77



### 5.2.6 RCS Inventory in Sump

The maximum RCS inventory is given as 381,126 lbm. Using the maximum inventory is conservative since it maximizes the quantity of borax required to achieve a sump pH of 7.0. This entire inventory is assumed to be deposited into the sump during the first time step. This is accomplished using the following input table.

**Table 13: Maximum RCS inventory profile**

Time (sec)	Mass (lbm)
0	0
1	381126
2.592E+06	381126

### 5.2.7 RWST Inventory in Sump

The maximum RWST inventory in the sump is given as 2,394,672 lbm. This entire inventory is assumed to be deposited into the sump during the first time step. This is accomplished using the following input table.

**Table 14: Maximum RWST inventory profile**

Time (sec)	Mass (lbm)
0	0
1	2394672
2.592E+06	2394672

### 5.2.8 SIT Inventory in Sump

The maximum SIT liquid mass is 169,614 lbm. This value is input using the following table.

**Table 15: Maximum SIT inventory profile**

Time (sec)	Mass (lbm)
0	0
1	169614
2.592E+06	169614

5.2.9 *Sump Level*

A time dependent sump level profile was developed based upon minimum ECCS injection rates and conservative assumptions regarding fluid holdup in containment. The sump level profile has the following critical points where specified levels are reached and/or ECCS flow rates change.

**Table 16: Critical sump fill level points**

Description	Time (min)	Level (ft)
14' elevation reached	12.69	14.0000
RHR Injection Ends	31.66	15.6349
RWST drain down terminated	75.14	17.2432

The sump level profile shows that the RWST drain down terminates at a minimum sump level of 17.2432 ft, which occurs at 75.14 minutes. Therefore, the baskets will be covered by the time of switchover, regardless of when switchover occurs. With faster fill rates, the pH will be lower at the time of switchover because there is less time for the surface area of the borax to be in contact with the sump water prior to the baskets being fully submerged. Thus, a fill rate that covers the baskets in the minimum switchover time of 2725 seconds (45.431 minutes) will result in a conservatively low pH. This faster fill rate is achieved by adjusting the fill level profile such that the minimum sump level is reached at 45.431 minutes. This adjustment is made by reducing the times in the table above proportional to the ratio of the maximum 75.14 minutes and minimum fill rate termination times (45.431 / 75.14). Thus, the new points for the sump fill level are as follows:

**Table 17: Critical sump fill level points - adjusted**

Description	Time (min)	Level (ft)
14' elevation reached	7.67	14.0000
RHR Injection Ends	19.14	15.6349
RWST drain down stopped	45.43	17.2432

This sump fill level is applied using the following table.

**Table 18: Sump fill level**

Time (sec)	Level (ft)
0	0.000
460.2	14.00
1148.4	15.635
2725.8	17.243
100000.00	17.243
2.592E+06	17.243

### 5.2.10 Surface Dissolution Rate

The surface dissolution rate utilized to determine the quantity of dissolved borax in the sump is calculated from Reference [6.4]. The SDR for a sample may be calculated as follows:

$$SDR = \frac{m^{1/3} \rho^{2/3}}{2 \times t_d} \quad (62)$$

where  $m$  is the sample mass,  $\rho$  is the sample density, and  $t_d$  is the time required for dissolution.

The SDR determines the rate of borax addition to the sump solution used to determine the mass of dissolved borax (Equation 49) in the sump. The dissolving mass of borax increases the equilibrium pH using Equation 38. A lower surface dissolution rate results from a lower containment sump temperature. Analyses indicate that the PTN minimum post-LOCA containment sump temperature remains above 100°F for the time period during which all of the borax is dissolved. At ~100°F, page 67 of Reference [6.4] shows that a 1.091 gram sample of borax dissolved in 100 seconds. Using equation (62), the SDR for the borax is calculated as:

$$SDR = \frac{m^{1/3} \rho^{2/3}}{2 \times t_d} = \frac{\left(1.091 \text{g} \times \frac{\text{lbm}}{453.6 \text{g}}\right)^{1/3} \times \left(48.82 \frac{\text{lbm}}{\text{ft}^3}\right)^{2/3}}{2 \times 100 \text{sec}} = 0.00895 \frac{\text{lbm}}{\text{ft}^2 \text{-sec}}$$

The SDR of 0.00895 lbm/ft<sup>2</sup>-sec calculated above is conservatively used for all temperatures and boron concentrations in the sump pH analysis. As a demonstration of the conservatism of using the minimum post-LOCA containment sump temperature to determine surface dissolution rate, the surface dissolution rate for borax at ~150°F equals 0.0203 lbm/ft<sup>2</sup>-sec based on the data from page 67 of Reference [6.4]. The SDR value at ~150°F is more than double the value at ~100°F. The SDR value of 0.00895 lbm/ft<sup>2</sup>-sec is, however, conservatively used in the analysis.

### 5.2.11 Sump Temperature for Dissolution

As described in Section 5.2.10, a constant surface dissolution rate at ~100°F is used for the entire transient. Thus, a sump temperature profile for dissolution is not utilized.

## 5.3 Maximum Sump pH

### 5.3.1 NaTB Bulk Density

The maximum bulk density for the borax is **54.13 lbm/ft<sup>3</sup>**. The maximum density increases the mass of borax (for a given number of baskets) and maximizes the sump pH.

### 5.3.2 Water Inventory Boron Concentrations

Minimizing the boron concentrations in the RWST, RCS, and SIT water inventory maximizes the sump pH. The minimum boron concentrations for the RCS, RWST, and SIT are given below.

$$C_{\text{Boron, RCS, min}} = 0 \text{ ppm}$$

$$C_{\text{Boron, RWST, min}} = 2400 \text{ ppm}$$

$$C_{\text{Boron, SIT, min}} = 2300 \text{ ppm}$$

### 5.3.3 Cable Insulation Mass

The cable insulation mass is set to zero so that no hydrochloric acid, which would decrease the sump pH, will be generated.

### 5.3.4 Time Step Sizes

Since no hydrochloric and nitric acid are credited for determining the maximum sump pH, only a few time steps are necessary to calculate the maximum pH. The following time domains were used to complete the analysis:

**Table 19: Time domains**

End Time (sec)	Time Step Size (sec)
100	5
200	10
300	10
400	10
5.000E+02	10

### 5.3.5 Sump Temperature for pH

Use of the maximum sump temperature is conservative for determining the maximum pH. The maximum sump temperature is assumed to be bounded by 300°F. This temperature is used for the entire event.

### 5.3.6 RCS Inventory in Sump

None of the RCS inventory is assumed to be deposited into the sump which is conservative for determining maximum pH. This is accomplished using the following input table.

**Table 20: Minimum RCS inventory profile**

Time (sec)	Mass (lbm)
0	0
1	0
2.592E+06	0

### 5.3.7 RWST Inventory in Sump

The minimum RWST inventory in the sump is given as 2,152,498. This entire inventory is assumed to be deposited into the sump during the first time step. This is accomplished using the following input table.

**Table 21: Minimum RWST inventory profile**

Time (sec)	Mass (lbm)
0	0
1	2152498
2.592E+06	2152498

### 5.3.8 SIT Inventory in Sump

The minimum SIT volume in the sump is given as 107,405 lbm. The entire inventory of two SITs is assumed to be deposited into the sump during the first time step. This inventory is applied in the following table:

**Table 22: Minimum SIT inventory profile**

Time (sec)	Mass (lbm)
0	0
1	107405
2.592E+06	107405

*5.3.9 Sump Level*

In order to dissolve the borax rapidly, the containment sump level is assumed to increase to 17.243 ft within 5 seconds of the event. The conservatively assumed sump fill level is presented in the following table.

**Table 23: Sump fill level**

Time (sec)	Level (ft)
0	0.000
1	14.00
5	17.243
2725.8	17.243
100000.00	17.243
2.592E+06	17.243

*5.3.10 Surface Dissolution Rate*

The surface dissolution rate is increased to an arbitrarily large value to rapidly dissolve the borax in the sump. An SDR of 10 lbm/ft<sup>2</sup>-sec is used.

*5.3.11 Sump Temperature for Dissolution*

Since an arbitrary SDR is utilized for determining the maximum pH, the sump temperature assumed for dissolution is not relevant.

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