Attachment 6

Redacted Calculation No. PSAT 224CT.QA.03

CALCULATION TITLE PAGE

CALCULATION NUMBER: PSAT 224CT.QA.03

CALCULATION TITLE:

"Calculation of Post-Accident pH for Hope Creek Nuclear Power Plant"

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Purpose

The purpose of this calculation is to determine the pH of the suppression pool of the Hope Creek plant as a function of time following a severe accident in support of alternate source term studies. This calculation is being performed using Polestar QA software STARpH 1.04 code [1] in accordance with the reference [2] and [3] procedures and the reference [4] PSEG request, included as Attachment 1.

Methodology

- Apply the Radiolysis of Water model from the STARpH 1.04 code [1] to calculate the [HNO_3] concentration in the water pool vs. time.
- Calculate conversion factors for cable geometry, including shielding of conduit.
- Apply the Radiolysis of Cable model of STARpH 1.04 to calculate the [HCl] concentration in the water pool vs. time.
- Manually calculate the [H^+] concentration added to the pool vs. time from the Radiolysis of Water model results and from the Radiolysis of Cable model results.
- Determine the sodium pentaborate buffer concentration added to the pool from the standby liquid control system (SLCS), the buffer dissociation constant, and the buffer starting pH.

- Calculate the pH of the water pool considering the concentration of sodium pentaborate in the pool and [H^+] additions as a function of time using the Add Acid model of STARpH 1.04.

Assumptions

Assumption 1: The fission product inventory is based on values for BWRs of similar thermal power, including a multiplication factor of 1.1 [5].

Justification: The fission product inventory currently available for the Hope Creek plant is in terms of curies of the fission product isotopes, but the STARpH code requires the inventory in terms of mass per fission product element. The inventory used for the Hope Creek plant in this calculation is based on those of BWRs of similar thermal power, scaled to the 3458 MWth power of Hope Creek, including a multiplier of 1.1 to provide conservatism in the radiolytic production of nitric acid.

Assumption 2: The fraction of the aerosol source term in the water pool is 0.75.

Justification: If drywell sprays were being credited, a value of 0.9 could be justified. Since sprays are not being credited, this number will be somewhat lower. PSEG concurs with the Polestar estimate of 0.75 for this value [6].

Assumption 3: Organic acid from paints can be neglected.

Justification: Proprietary information deleted

Assumption 4: The SLCS is actuated and the sodium pentaborate is injected into the pool within several hours of accident initiation.

Justification: A core damage event large enough to release the substantial quantities of fission products in the time frame considered for the alternate source term in reference [8] will be very evident to the operators (e.g., core outlet temperature, radiation level in the drywell, pressure and temperature in the drywell, hydrogen level in the drywell) within minutes of the initiating event. Thus it is reasonable to assume for purposes of this calculation that the Hope Creek EOPs and SAMGs provide for SLCS actuation within ~1 hour of accident initiation.

If SLCS injection is into the pool (i.e., into the reactor vessel with the vessel communicating with the pool as in a recirculation line break), significant mixing will occur quickly, on the order of 1 hour based on a total RHR flow rate of about 10,000 gpm and the pool volume of 1E6 gallons.

If the reactor vessel is not immediately communicating with the pool, an additional few hours is assumed to transpire before the operators flood the vessel up to the break to assure communication with the pool or inject sodium pentaborate to the pool via an alternate pathway.

Assumption 5: The unbuffered pH of the pool should remain above 7 for at least several hours.

Justification: Proprietary information deleted

Assumption 6: The Hypalon jacket and EPR insulation are modeled as a single unit with a thickness of 0.158 in (0.401 cm) and a weighted average density of 1.40 g/cm^3.

Justification: The EPR insulation contains 11% chlorine and the 9000 lbs of jacket includes the weight of the insulation [Attachment 1]. The thickness of the entire jacket plus EPR insulation is that given by ref. [11] as is the value for the average weighted density. The radiation G value for the production of HCl from Hypalon in the STARpH 1.04 code is applied to the entire thickness of Hypalon jacket plus EPR insulation.

Design Inputs

1. Reactor power = 3458 MWth
2. Suppression pool volume = 118,200 ft^3 (min) and 121,900 ft^3 (max)
3. RCS inventory = 11,721 ft^3 liquid, 9089 ft^3 saturated steam at 1040 psia
4. Pool initial pH = 5.8
5. Pool temperature vs. time, see Table 3
6. Fission product inventory - see Assumption 1
7. Electrical cable insulation (Hypalon jacket + EPR insulation) mass = 9,000 lbm
8. Electrical cable OD = 1.0 in
9. Electrical cable insulation thickness (Hypalon jacket + EPR insulation) thickness = 0.158 in, see Assumption 6
10. Electrical cable insulation average weighted density = 0.140 g/cm^3, see Assumption 6
11. Fraction of cable with chloride-bearing insulation that is in conduit = 38%
12. Average conduit diameter = 2 in

13. Average conduit wall thickness = 0.154 in
14. Drywell free volume = 165,520 ft^3
15. Torus free volume = 133,311 ft^3
16. Mass of sodium pentaborate in SLCS available for injection = 5776 lbm
17. Chemical formula for sodium pentaborate = $Na_2B_{10}O_{16} \bullet 10H_2O$
18. Boron enrichment in the sodium pentaborate is natural
19. Containment surface area covered with paint: drywell, 32,750 ft^2; torus, 34,537 ft^2
20. Date since last painting: 1985

Items 1 to 5, 7, 8, and 11 to 20 are from Attachment 1. Item 6 is from Assumption 1, and items 9, and 10 are from Assumption 6.

References

1. PSAT C107.02, STARpH, A code for Evaluating Containment Water Pool pH During Accidents, Code Description and Validation and Verification Report, Revision 4, February, 2000.

2. PSAT 224CT.QA.01, Project QA Plan for Calculation of Post-Accident pH for Hope Creek Nuclear Power Plant, July 2, 2001.

3. PSAT 224CT.QA.02, Implementing Procedure for Calculation of Post-Accident pH for Hope Creek Nuclear Power Plant, July 2, 2001.

4. PSEG, e-mail from B. L. Barkley to D. E. Leaver, "Final Transmittal of pH Data", June 29, 2001.

5. R. R. Hobbins, e-mail to D. E. Leaver, "Hope Creek Inventory", June 14, 2001.

6. PSEG, e-mail from B. L. Barkley to D. E. Leaver, "Design Input for Hope Creek pH Calculation", June 8, 2001.

7.

8. "Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors," Regulatory Guide 1.183, July, 2000.

10.

11.

12. W. C. Reynolds and H. C. Perkins, "Engineering Thermodynamics," McGraw-Hill.

13. D. R. Lide, Editor-in-Chief, Handbook of Chemistry and Physics, 77th Edition, CRC Press, 1996.

14.

15.

16.

17.

Calculation

Calculation of $[OH^-]$ and $[HNO_3]$ in Water Pool vs. Time

The BWR version of the Radiolysis of Water model in the STARpH 1.04 code [1] calculates the hydroxyl ion concentration, $[OH^-]$, from fission product cesium, and nitric acid concentration, $[HNO_3]$, in the containment water pool generated by radiolysis. Per Assumption 3, organic acid from paints is neglected.

Inputs to the Radiolysis of Water model are based on the Design Inputs, Items 1 to 4 [Attachment 1] and Assumptions 1 and 2. The core inventories by radionuclide group are:

Group Title	Elements in Group	Core Inventory (Kg)
I	I, Br	31.8
Cs	Cs, Rb	349
Te	Te, Sb, Se	67.0
Sr	Sr	91.7
Ba	Ba	154
Ru	Ru, Rh, Mo, Tc, Pd	954
Ce	Ce, Pu, Np	1305
La	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am	1209

Containment water pool volume = water volume of wetwell + RCS liquid volume

Calculate mass of liquid from condensation of saturated steam at 1040 psia in RCS,

$$9080 \text{ ft}^3 \bullet 2.33 \text{ lbm/ft}^3 = 21{,}156 \text{ lbm}$$

where 2.33 lbm/ft^3 is the density of saturated steam at 1040 psia [12].

At an average pool temperature of 155 °F (see Table 3), the volume of this condensed steam is

$$21{,}156 \text{ lbm} \bullet \text{cm}^3/0.979 \text{ g} \bullet 454\text{g/lbm} \bullet \text{ft}^3/2.83\text{E}4 \text{ cm}^3 = 347 \text{ ft}^3$$

where 0.979 g/cm^3 is the density of water at 155 °F (68 C) [13].

Thus, the containment water pool volume is

$$(121{,}900 \text{ ft}^3 + 11{,}721 \text{ ft}^3 + 347 \text{ ft}^3) \bullet 2.83\text{E}1 \text{ L/ft}^3 = 3.79\text{E}6 \text{ L}$$

The maximum suppression pool volume is used here to maximize the moles of H^+ associated with the initial pH of the water (5.8).

The core inventory of fission products in the table above is entered in column F of the Radiolysis of Water model spread sheet and a burnup value of 33,000 MWd/t is used in cell K2 so that the fission product inventory is not modified when calculating values for HI and CsOH.

The output of the calculation with the Radiolysis of Water model in the form of net $[OH^-]$ and $[HNO_3]$ as a function of time is provided in the first and last columns of the output portion of Exhibit 1.

Calculation of [HCl] in Water Pool vs. Time

The concentration of HCl in the water pool as a result of radiolysis of electrical cable insulation is calculated using the Radiolysis of Cable model of the STARpH 1.04 code. Inputs to the Radiolysis of Cable model are based on the Design Inputs, Items 1 to 3 [Attachment 1] and Items 7 to 15 [Attachment 1], and Assumptions 2 and 6.

The containment free volume is the sum of the drywell free volume and the torus free volume (Design Input, Items 14 and 15 [Attachment 1]). The minimum torus free volume is used since the containment volume appears in the denominator of expression for HCl production, maximizing the result.

Containment free volume = drywell free volume + torus free volume
$= 165{,}520\ ft^3 + 133{,}311\ ft^3$
$= 2.988E5\ ft^3 \times (12\ in/ft)^3 \times (2.54\ cm/in)^3$
$= 8.46E9\ cm^3$

To account for gamma radiation leakage from the containment, the STARpH 1.04 BWR Mark 1 default value of 0.068 for one minus fraction of gamma leakage is used [1].

The cable insulation characteristics are listed in the Design Inputs [Attachment 1] and are shown in Table 1 in both English and metric units. As described in [Attachment 1] the EPR insulation layer contains 11.33% chlorine, so the insulation thickness in Table 1 is the sum of the EPR and Hypalon jacket thicknesses. Although the density of the Hypalon is given as 1.55 g/cm^3 in [Attachment 1], the value of 1.40 g/cm^3 is used for the combined EPR/Hypalon thickness per reference [11].

Table 1. Hope Creek Containment Cable Characteristics

Insulation Thickness (in)	Insulation Thickness (cm)	Cable OD (in)	Cable OD (cm)	Insulation ID (in)	Insulation ID (cm)	Insulation Mass (lbm)
0.158	0.401	1.0	2.54	0.684	1.74	9,000

The conversion factors, R_γ and R_β, found in cells H2 and I2 of STARpH [1], have been calculated for this Hope Creek cable geometry.

Proprietary information deleted.

Proprietary information deleted.

The output of the calculation with the Radiolysis of Cable model in the form of [HCl] as a function of time is provided as Exhibit 2.

Calculation of [H^+] Added to the Pool

The net hydrogen ion concentration added to the pool is the sum of the Net [OH^-] and [HCl] shown as a function of time in Exhibit 1 and Exhibit 2, respectively. These data are combined in Table 2 below to give Net [H^+] Added. The parenthetical values for Net [H^+] Added mean that the values indicated are actually [OH^-] since the amount of hydroxide in the Net [OH^-] column exceeds the [HCl]. The Net [OH^-] is taken from the first column of Exhibit 1, and is the [OH^-] concentration in mol/L which results from the [OH^-] from CsOH less the [H^+] from initial pH, HI, and HNO_3. Also shown in Table 2 is the hydrogen ion concentration, [H^+] Added, due to [HNO_3] and [HCl] only (i.e., neglecting the [OH^-] from CsOH).

Table 2. Calculation of [H+] added to pool

Time	[HNO_3]	Net [OH^-]	[HCl]	[H^+] Added	Net [H^+] Added
1h	5.18E-6	1.08E-4	5.37E-6	1.06E-5	(1.03E-4)
2h	7.11E-6	1.06E-4	1.01E-5	1.72E-5	(9.59E-5)
5h	1.11E-5	1.02E-4	2.16E-5	3.27E-5	(8.04E-5)
12h	1.76E-5	9.52E-5	4.05E-5	5.81E-5	(5.47E-5)
1d	2.63E-5	8.66E-5	6.43E-5	9.06E-5	(2.23E-5)
3d	5.07E-5	6.22E-5	1.28E-4	1.79E-4	6.58E-5
10d	9.60E-5	1.68E-5	2.19E-4	3.15E-4	2.02E-4
20d	1.25E-4	(1.2E-5)	2.55E-4	3.80E-4	2.67E-4
30d	1.44E-4	(3.1E-5)	2.66E-4	4.10E-4	2.97E-4

Calculation of Sodium Pentaborate Buffer Added to Pool

The concentration of B is calculated below.

The molecular weight of sodium pentaborate ($Na_2B_{10}O_{16} \bullet 10H_2O$) is, with natural boron,

$2 \bullet 22.9898 + 10 \bullet 10.811 + 26 \bullet 15.9994 + 20 \bullet 1.00797 = 590.2$ g/mol

The mass of sodium pentaborate in the SLCS available for injection is 5,776 lbm. Therefore,

5,776 lbm • 454 g/lbm • mol/590.2 g = 4.44E3 mol of sodium pentaborate

There are 10 moles of B per mole of sodium pentaborate, so there are 4.44E4 mol of B and the concentration of B in the water pool is

4.44E4 mol B/3.79E6 L = 1.17E-2 mol B/L

where the pool volume of 3.79E6 L was calculated earlier.

Calculation of pH

The Add Acid model of STARpH 1.04 is used to determine pH vs. time for the above system using the [H^+] Added values from Table 2, 1.17E-2 mol B/L, the boron buffer dissociation constant, and the starting pH of the buffer solution. The dissociation constant, K_A, and the starting pH are temperature dependent and the temperature of the pool as a function of time is shown in Table 3. The average temperature over the period of 30 days

Table 3. Pool temperature

Time (h)	Temp (F)
0	110
3	203
6	212
24	200
96	168
240	153
480	145
720	141

(720 h) is calculated to be 155 °F (68 C).

Proprietary information deleted.

Results

Proprietary information deleted.

For time points 1 hr and 2 hr, pH is indicated simply as >8.0 on the basis of Assumption 5. From 5 hours on, the effect of cesium is neglected and pH is obtained by applying the Table 2, $[H^+]$ Added column to Exhibit 3. The results are shown in Table 4.

Table 4. pH results vs. time

Time	pH
1h	>8.0
2h	>8.0
5h	8.4
12h	8.4
1d	8.4
3d	8.3
10d	8.3
20d	8.3
30d	8.3

Conclusion

The pH of the containment water pool for the Hope Creek plant radiological DBA LOCA is above 8 over a period of 30 days following accident initiation.

			Exhibit 1 Radiolysis of Water Input and Output							
Input										
Proprietary information deleted										
Output										
Proprietary information deleted										

		Exhibit 3 Add Acid Input and Output					
Input:				**Output:**			
Proprietary information deleted					Proprietary information deleted		

			Exhibit 2 Radiolysis of Cable					
Input:								
Proprietary information deleted								
Output:								
Proprietary information deleted								