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Subject: Response to NRC Request for Additional Information Letter Nos. 90 and 142 Related to the ESBWR Design Certification – Safety Analyses – RAI Numbers 15.4-28, 15.4-35 through 15.4-39

The purpose of this letter is to submit the GE Hitachi Nuclear Energy (GEH) responses to the U.S. Nuclear Regulatory Commission (NRC) Request for Additional Information (RAI) sent by NRC letters dated January 29, 2007 and January 14, 2008, respectively. GEH responses to RAI Numbers 15.4-28, 15.4-35 through 15.4-39 are addressed in Enclosure 1. DCD Markups related to these responses are provided in Enclosure 2.

If you have any questions or require additional information, please contact me.

Sincerely,

James C. Kinsey
Vice President, ESBWR Licensing

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NRC

Enclosure 1

MFN 08-315

**Response to Portion of NRC Request for
Additional Information Letter Nos. 90 and 142
Related to ESBWR Design Certification Application**

Safety Analyses

RAI Numbers 15.4-28, 15.4-35 through 15.4-39

NRC RAI 15.4-28:

In order to complete its evaluation, the staff needs to review the general assumptions and calculations used to prove that the containment sump pH will be maintained above 7 for 30 days following a loss-of-coolant accident (LOCA).

(A) Please provide this information by completing the attached table (see below) for each pool in the ESBWR design (Reactor Pressure Vessel, Lower Dry Well, Gravity Driven Cooling System, and Wet Well) in sufficient detail for the staff to perform independent calculations.

(B) In addition to completing the table for each pool, please complete the attached table for each different pH cases A through F as presented in General Electric Research Report No. VTT-R-04413-06, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment - Part 1, October 2006."

(PLEASE GO TO REQUEST MFN TO VIEW TABLE ATTACHED)

(C) In addition, please discuss the injection time of the buffer solution (sodium pentaborate) and its distribution from the moment it is injected to the time of 30 days after the accident.

GEH Response:

(A) The requested information is contained in Appendix D of VTT-R-006671-07, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment – Part 3," Revision 2, which was submitted to the NRC via MFN 07-466, Supplement 1 dated March 31, 2008.

(B) The requested information was provided for "Case A" for each accident scenario in Appendix D to VTT-R-06671-07. Cases B through F, as documented in VTT-R-04413-06, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment - Part 1, October 2006," were intended as initial sensitivity studies for evaluating pH levels early in the event. The doses used to calculate HCl and other compounds in cases B through F do not represent doses based on ESBWR specific calculations. While the analyses were useful in studying the potential impact on pH, the information for those cases is now historical in nature; therefore, detailed tables are not warranted. Case A utilizes dose rates determined using ESBWR specific releases; therefore, Case A represents the licensing basis case for the ESBWR. Case A is evaluated for all three Accident Scenarios. Detailed information is provided for the sensitivity studies crediting 0 to 100% of CsOH in Appendix D as well (see response to RAI 15.4-13 submitted via GEH letter MFN 08-223 dated April 1, 2008).

(C) The sodium pentaborate solution was released from Standby Liquid Control System (SLCS) into the RPV in each calculated scenario. In AS-1, the sodium pentaborate injection starts at 6080 s, in AS-2 at 5140 s and in AS-3 at 13800 s, respectively. The mass fraction of sodium pentaborate in SLCS injection is 12.5 %. The volume of solution in SLCS tanks was given as 15.6 m³. The density of soluble sodium pentaborate was estimated to be 1 kg/dm³. The amount of water in SLCS was set to

13650 kg and the mass of sodium pentaborate to 1950 kg. The release rate was 36.8 kg/s (2*18.4 kg/s).

After injection, a significant portion of the sodium pentaborate injected via the SLC system travels to the lower drywell through the break. Flow rates through the break, and the flows between the various pools (suppression pool, lower drywell, and RPV) are based on those calculated in the MELCOR evaluations. The flow rates utilized are summarized in Figure 1 of the VTT "Part 3" Report (Revision 2) for AS-1 (low pressure bottom drain line break), Figure 2 for AS-2 (high pressure bottom drain line break), and Figure 23 for AS-3 (loss of AC power, loss of feedwater). Details concerning the concentrations of sodium pentaborate in the various pools are contained in Appendix D of the report.

DCD Impact:

No DCD changes will be made in response to this RAI.

NRC RAI 15.4-35:

Research Report VTT-R-04413-06 (Part 2), Page 60, indicates that all of the HNO₃ is assumed to be released into the Upper Drywell atmosphere for accident scenario 1, while Pages 63 and 68 of the same report indicate that 100% of all the HNO₃ is assumed to form in the GDCS for accident scenarios 2 and 3. Please explain why your assumptions are different depending in the accident scenario. In addition, please clarify whether these assumptions are conservative.

GEH Response:

The formation of HNO₃ in water pools was not included in the pH calculations of the VTT "Part 1" and "Part 2" reports. This error was corrected in VTT-R-006671-07, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment – Part 3," Revision 2, which was submitted to the NRC via MFN 07-466, Supplement 1 dated March 31, 2008. The VTT "Part 3" report modeled the HNO₃ formation rate in the reactor pressure vessel (RPV), lower drywell (LDW), gravity drain cooling system (GDCS), and wetwell (WW), by calculating the radiation dose rate of fission products in the water in the various pools. HNO₃ formation rates in the atmosphere utilize the airborne dose rates in the drywell. All HNO₃ formed in the atmospheric steam is added in the HNO₃ balance of the Upper Drywell (this was changed from the "Part 1" and "Part 2" VTT report calculations where the HNO₃ was formed in the GDCS). Most of the HNO₃ in the Upper Drywell flows through the passive containment cooling system (PCCS) into the GDCS pool, and from the GDCS to the RPV and to the LDW. Flow rates used to model the transport are based on the MELCOR results.

HNO₃ formation rate is calculated for both containment atmosphere and immersion in the various containment pools using the methodology presented in NUREG/CR-5950, *Iodine Evolution and pH Control*, December 1992. Additional details are presented in Section 5.1, 5.2, and Appendix A of Revision 2 of the VTT "Part 3" report.

DCD Impact:

No DCD changes will be made in response to this RAI.

NRC RAI 15.4-36:

MFN 07-466, dated August 24, 2007:

Research Report VTT-R-06771-07 (Part 3), in the description of accident scenarios 1 and 2 on Pages 18 and 25, it states that the direction of mixing between the RPV and the LDW is changed at each time step between +0.1 Kg/s and -0.1 Kg/s. Please provide the basis for this value. In addition, please clarify if this is more conservative than assuming that there is no mixing between the RPV and the LDW.

GEH Response:

VTT-R-006671-07, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment – Part 3," has been revised to Revision 2, which was submitted to the NRC via MFN 07-466, Supplement 1 dated March 31, 2008. The revised report more accurately models the mixing between the RPV and Lower Drywell. The flows assumed for the mixing after 24 hours are based on those predicted by MELCOR from 1 to 2 days post accident.

- AS-1: Flow from RPV to LDW is +1.34 kg/s, -1.48 kg/s per Figure 1 of the VTT "Part 3" Report, Revision 2. Detailed discussion is contained in Section 7 of this report, and flow information is presented in Figure 2b.
- AS-2: Flow from RPV to LDW is +1.13 kg/s, -0.93 kg/s per Figure 12. Detailed discussion is contained in Section 8 of this report, and flow information is presented in Figure 13b.
- AS-3: Since there is no break in the LDW, no mixing between the RPV and LDW occurs for AS-3

Sensitivity studies evaluating the impact of the above mixing assumptions are provided in Appendix B of the VTT "Part 3" Report, Revision 2. The studies show that there is not a significant difference between the mixing rates discussed above and cases where no mixing occurs.

DCD Impact:

No DCD changes will be made in response to this RAI.

No changes to the subject LTR will be made in response to this RAI.

NRC RAI 15.4-37:

MFN 07-466, dated August 24, 2007:

Research Report VTT-R-06771-07 (Part 3), Figures 6, 13, and 20 show the distribution of elementary boron in the three accident scenarios, respectively.

For accident scenarios 1 (AS-1) and 2 (AS-2), you stated that due to slow mixing during $2.5E+06$ (about 30 days), about 10% and 6% of boron, respectively, is removed from the LDW and moved to the RPV. Please clarify this statement and describe the flow mechanisms more in detail. In addition, there seems to be a discrepancy between the amount of boron removed and its illustration in the figures. For example, for AS-1, the amount of boron moved to the RPV is 10%, which according to Figure 6 represents approximately 2500 moles, however, for AS-2; the amount of boron moved is 6%, which according to Figure 13 represents 7500 moles. Please clarify this discrepancy.

GEH Response:

GEH concurs that a discrepancy exists in the referenced Tables and Figures. These discrepancies were corrected in Revision 2 to VTT-R-06671-07, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment – Part 3," which was transmitted to the NRC via MFN 07-466, Supplement 1 dated March 31, 2008. The distribution of boron is contained in Figures 3 (AS-1), 14 (AS-2), and 25 (AS-3) in the revised VTT-R-06671-07 Part 3 Report. For the bottom drain line break scenarios, boron is injected into the RPV via SLCS. The majority of the boron then drains to the lower drywell through the break. Mixing between the lower drywell and the RPV begins once the lower drywell becomes flooded (mixing assumptions between the RPV and lower drywell were discussed in the response to RAI 15.4-36). The discrepancies identified in this RAI no longer exist based upon Revision 2 to the VTT-R-06671-07 (Part 3).

DCD Impact:

No DCD changes will be made in response to this RAI.

NRC RAI 15.4-38:

MFN 07-466, dated August 24, 2007:

Research Report VTT-R-06771-07 (Part 3), Figures 7 and 14, show the calculated pH in scenarios AS-1 and AS-2 for the different CsOH formation rates, respectively. For AS-2, during the early stages of the accident, there seems to be a rapid increase in pH followed by a decrease, then a small increase followed by a sudden decrease (not shown). Finally, the pH seems to level off between 8 and 8.5. Please discuss the pH behavior in the RPV during the early stages (between 1000 and 10,000 seconds) of scenario AS-2. In addition, given that scenario AS-2 is similar to AS-1, and that the pH behavior is similar for all of the other pools in AS-1 and AS-2, please discuss why the pH behavior in the RPV during AS-2 is different from the pH behavior during AS-1.

GEH Response:

The information discussed in this RAI was updated in Revision 2 to VTT-R-06671-07, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment – Part 3," which was transmitted to the NRC via MFN 07-466, Supplement 1, dated March 31, 2008. The pH behavior described in this RAI also appears in the revised calculations for Revision 2 of the Part 3 report. pH analysis for the RPV in AS-2 is not appropriate for the time period from 2436 seconds to 5145 seconds following the break. Section 8.1 of the revised report explains that MELCOR calculations indicate that the RPV is in "dryout" conditions. It is the lack of water in the lower head of the RPV that causes the erratic behavior predicted in the earlier revision of the "Part 3" report. The MELCOR calculations for AS-1 indicated that the lower head of the RPV does not dry out prior to reflooding due to the lower driving pressure. The other pools' behavior is not significantly different since the driving head of the RPV pressure has little impact on pool parameters.

As seen from the attached Figure 1 of the MELCOR run (of "Part 3" Revision 2), the lower head of the RPV becomes completely dry at approximately 2600 s in the accident scenario AS-2. This is caused by the high-pressure difference across the Bottom Drain Line Break junction. The similar plot from the MELCOR run of AS-1 (Fig. 2) shows that the early depressurization with ADS and DPV valves results in low pressure in the RPV Lower Head and thus lower driving pressure for water discharge from the RPV. In case AS-1, the Lower Head does not become empty during the balance of the simulation. The pH calculated by ChemSheet addresses the pH of the RPV water pool. MELCOR calculations indicate that the RPV is dry between 2436 s to 5145 s; therefore, the pH is calculation is not applicable since no pooling exists. This is the reason for discontinuity of the pH curve in case of AS-2.

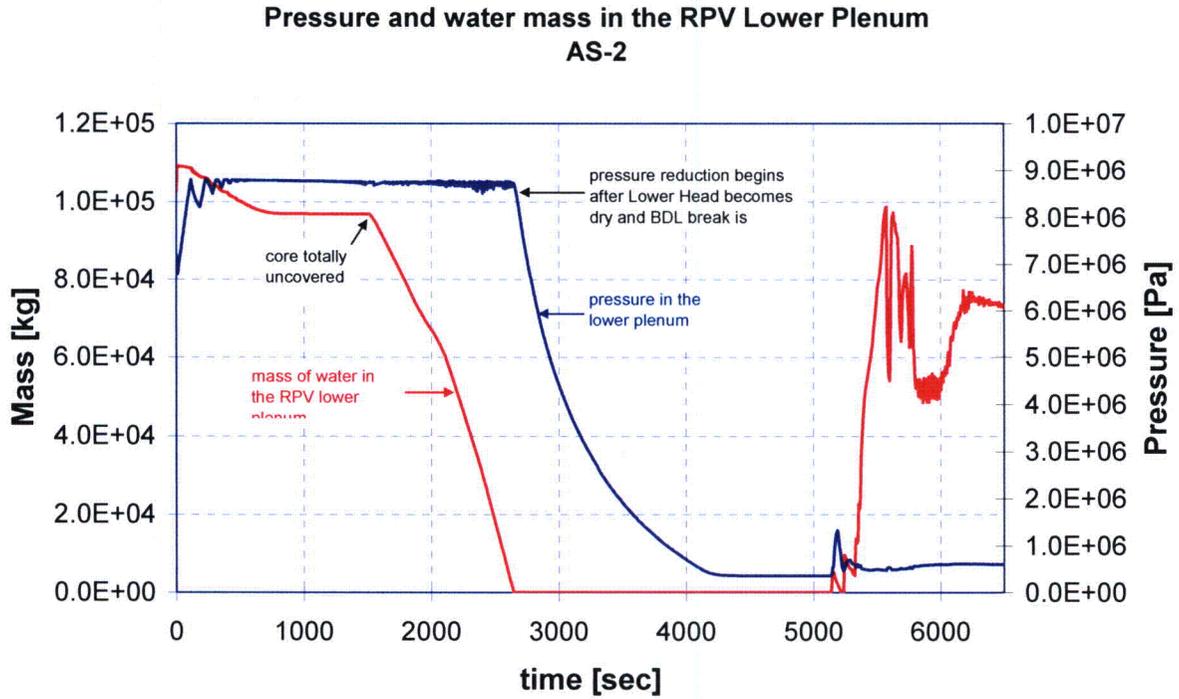


Figure 1. Pressure and Water mass in the RPV Lower Head in accident scenario AS-2, no MSIV leak. This figure illustrates dry out of the Lower Head caused by high driving pressure across the BDL break.

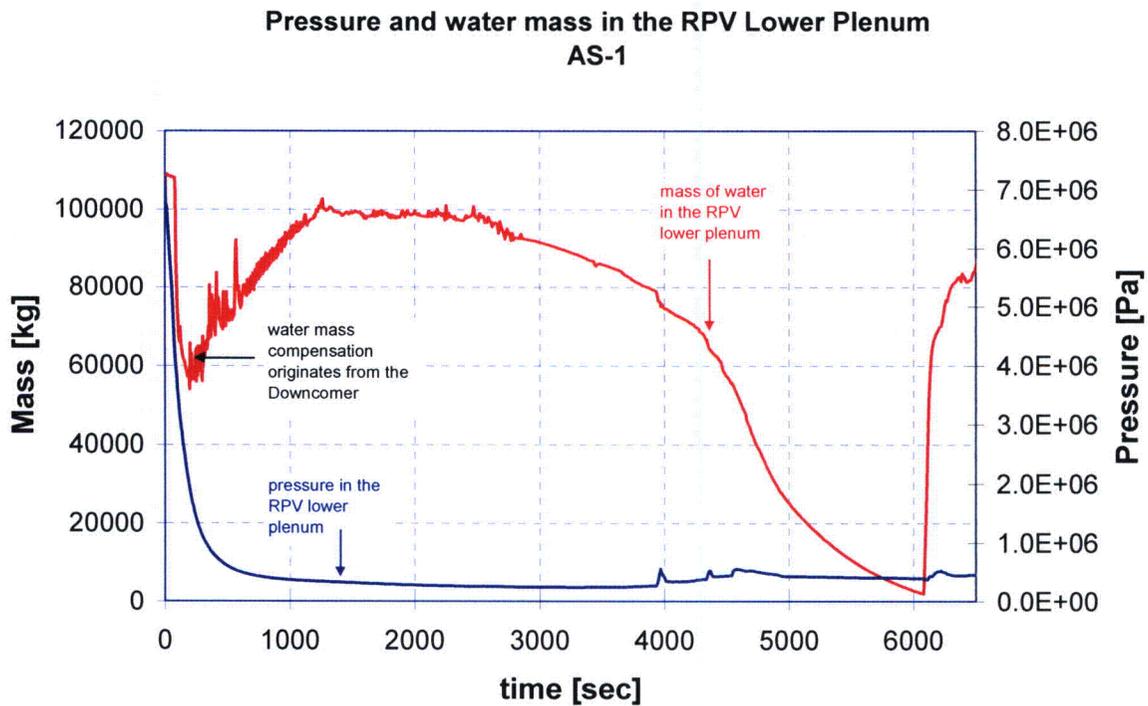


Figure 2. Pressure and Water mass in the RPV Lower Head in accident scenario, AS-1, no MSIV leak. This figure illustrates the significantly lower driving pressure across the BDL break due to operating ADS, which also prevents dry out of the Lower Head in contrast to the case AS-2.

DCD Impact:

No DCD changes will be made in response to this RAI.

NRC RAI 15.4-39:

MFN 07-466, dated August 24, 2007:

Research Report VTT-R-06771-07 (Part 3), Figures 7-10, 14-17, and 21-24, show the results of CsOH sensitivity calculations. It appears that there is only a relatively small difference, if any, in pH with varying CsOH formation rates. Given these results, please discuss if you still plan to assume in your calculations a formation rate of 100% CsOH. The staff still believes CsOH may also exist in the form of cesium compounds other than CsOH (i.e., cesium molybdate, cesium manganate). Use of a formation rate of less than 100% will provide conservatism to the calculation. If your plans are not to use a reduced CsOH formation rate, please discuss what other conservatisms are introduced in your pH calculation.

GEH Response:

GEH will conservatively credit only 50% of the CsOH available following an assumed reaction with iodine in the licensing basis pH evaluations for the ESBWR, rather than the 100% assumed in the previous analyses. VTT-R-006671-07 Research Report, "Estimation and Modeling of Effective Fission Product Decontamination Factor for ESBWR Containment – Part 3," has been revised (Revision 2 submitted to the NRC via MFN 07-466, Supplement 1 on March 31, 2008) to reflect the use of the 50% CsOH credit in the pH calculations for the accident scenario cases, and will be used as the licensing basis for the ESBWR.

ESBWR chemical release inventories (stable and radioactive) corresponding to Regulatory Guide 1.183, Table 1 release fractions at the end of the early release phase are presented below:

Element	Chemical Group [1]	Release Mass (mol) [2]
RB	Alkali Metal	210
CS	Alkali Metal	1077
SR	Ba, Sr	44
BA	Ba, Sr	41
NP	Cerium Group	0
PU	Cerium Group	4
CE	Cerium Group	2
BR	Halogen	16
I	Halogen	104
AM	Lanthanides	0
CM	Lanthanides	0
Y	Lanthanides	0
ZR	Lanthanides	2
NB	Lanthanides	0
LA	Lanthanides	0
PR	Lanthanides	0
ND	Lanthanides	1
PM	Lanthanides	0
SM	Lanthanides	0
EU	Lanthanides	0
KR	Noble Gas	921
XE	Noble Gas	7590
ZN	Noble Metal	0
MO	Noble Metal	17
TC	Noble Metal	4
RU	Noble Metal	11
RH	Noble Metal	2
PD	Noble Metal	5
SE	Tellurium	7
SB	Tellurium	2
TE	Tellurium	35

A review of the fission product inventories indicates that there is 10 times as much cesium released as iodine (on a molar basis). The excess cesium would most likely react with water to produce hydrogen gas and CsOH, like all the alkali metal-water

reactions, and a substantial fraction of the excess cesium should form CsOH. The alkali metal hydroxides are highly soluble in water, nearly 100% dissociated, and will elevate the pH of the water as presented in the VTT-R-006671-07, Part 3, Revision 2 Report.

The amount of Cs removed from the system through reaction with halogens is limited by the total halogen release. Assuming 100% of halogens (I and Br) react with Cs, 957 moles of Cs remain available for CsOH formation. Reaction kinetics do not favor reactions between cesium and the other chemical groups considered in the core release source term relative to the alkali metal-water reaction. While other chemical reactions with cesium are possible, the extent of the reactions will also be limited by the counter ion release rates relative to cesium (i.e., similar to halogens). Reviewing the list of core release constituents indicates that there should be more water available to promote the alkali metal-water reaction than combined molar quantities of other species that could react with cesium.

The pH and MELCOR analyses summarized in Revision 2 of VTT-R-006671-07 Part 3 conservatively scavenge the cesium necessary to form 100% CsI for every iodine ion. Based on a review of Appendix D concentration summary tables for the three accident scenarios evaluated, the maximum release mass of Cs assumed to form CsOH in any of the 50% CsOH credit cases is 754 moles. Thus, substantial margin is available in all accident scenario pH analyses to account for any anticipated cesium reactions that may limit CsOH production. Substantial additional margin is provided in that the release of rubidium is not accounted for in the pH calculations, but would also result in alkali metal hydroxides and contribute to pH elevation.

DCD Impact:

DCD, Tier 2, Section 15.4.4 is revised as indicated on the attached markup. Appendix 15C was added to DCD, Tier 2, Revision 5, as documented in MFN 07-523, dated November 30, 2007. Appendix C is revised by this response as indicated in the attached write-up.

NEDE-33279P, Revision 1, *ESBWR Containment Fission Product Removal Evaluation Model*, contains a detailed discussion concerning pH and the amount of CsOH produced following a LOCA. NEDE-33279P will be revised based on this response with an anticipated submittal date of June 30, 2008.

Enclosure 2

MFN 08-315

DCD Markups

15.4.4.5.2.2 Aerosol Removal from Containment

There are several natural processes which can remove airborne aerosols from the primary containment atmosphere following a LOCA. The PCCS is used to condense steam and control pressure in the event of a LOCA. The PCCS effectively scrubs the containment atmosphere by removing aerosols from the containment atmosphere. Aerosols are also removed via natural deposition onto containment internal structures. The removal mechanisms for the PCCS and natural deposition of airborne aerosols are similar, therefore one integral model is used. The removal coefficients are based on the results of the ESBWR MELCOR model as discussed in NEDE-33279P, *ESBWR Containment Fission Product Removal Evaluation Model* (Reference 15.4-13).

Aerosols can be released from the RPV via several potential pathways, including the break itself, the DPVs, and the SRVs. Flow through the SRVs is released through submerged spargers in the suppression pool. Flow through the break or through the DPVs would not be scrubbed by the suppression pool. The impact of suppression pool scrubbing is discussed in Subsection 15.4.4.5.2.5. ~~will be airborne in the containment.~~ One path for the aerosols airborne in containment to contribute to the off-site dose is via containment leakage from containment atmosphere to the Reactor Building and subsequently to the environment. Aerosols must be airborne in the containment atmosphere to leave via this pathway. Since aerosols are suspended in the containment atmosphere, they will circulate with the bulk gas movement, which is from the RPV to the PCCS. Figure 6.2-16 shows the PCCS heat exchanger and its associated piping. Steam, nitrogen and any airborne fission products will enter the PCCS heat exchanger inlet line from the drywell, which discharges to a header at the top of the PCCS tube bundles. Steam vapor will condense on the header and inside walls of the PCCS heat exchanger tubes, which are cooled on the outside by the water in the PCC/IC pool. The deposition processes of aerosol are gravity, Brownian diffusion, thermophoresis and diffusiophoresis. Aerosol and fission product vapors can deposit directly on surfaces such as heat structures and water pools. In addition, aerosol can agglomerate and settle. The aerosols deposited on the various surfaces can relocate. If a water film drains from a heat structure to the pool in the associated volumes, fission products deposited on that structure are transported with the water. This relocation is proportional to the fraction of the film that is drained. Aerosols and fission product vapors are transported between control volumes by bulk fluid and gas flows. Aerosols may also settle from a volume to a lower volume in the absence of bulk flow. Diffusiophoresis, the phenomenon of aerosol movement in condensing vapor, will drive the aerosol particles to the condensate film on the PCCS tube inner wall. In addition to condensation, some fraction of the airborne activity will also "plate out" in the PCCS. The PCCS effectiveness in removing aerosols has been demonstrated in third party tests. For example, in "Investigation on Aerosol Deposition in a Heat Exchanger Tube" (Reference 15.4-8), a short length of PCC tube was capable of removing a significant portion of in-flowing aerosols, and removing them with the condensate flow.

The condensate from the PCCS will drain into the GDCS pool, and then back into the reactor pressure vessel. The PCCS heat exchanger vents non-condensables, including noble gases to the suppression pool. Aerosols which do not deposit in the PCCS are transported by non-condensable gases via PCCS vent line into the wetwell. The vent mass flow rate is less than one-quarter of the PCCS flow rate, and aerosol and iodine transport to the suppression pool would be a small fraction of the total decontamination factor credited to the PCCS.

Since the net effect is the removal of activity from the drywell atmosphere, one set of removal coefficients are applied to model the effect on the airborne activity. Because non-condensables will leave the suppression pool for the WW airspace, and flow back into the DW during vacuum breaker openings, and because the PCCS removal mechanisms are not effective for organic iodines, no credit for noble gas or organic iodine decontamination is taken in the analysis (the decontamination factor is 1).

The thermal hydraulic conditions in the primary containment for the three Accident Scenarios chosen (see Subsection 15.4.4.2.1) are used to determine the removal rate of airborne particulate iodine for each event. The airborne concentration of particulate iodine is obtained using the computer code MELCOR. The resultant airborne masses are determined and presented in Figure 15.4-2 for all three scenarios.

Removal coefficients are calculated for all three scenarios. However, the computer code RADTRAD only allows up to 10 removal coefficients. The removal coefficients are presented in Figures 15.4-3, 15.4-4, and 15.4-5 for AS-1, AS-2, and AS-3, respectively. The values for RADTRAD are summarized in Table 15.4-4d. AS-2 is bounding, therefore doses are only presented for that scenario. The dose calculation conservatively neglects the "coolant" release phase as discussed in Subsection 15.4.4.5.1.1, therefore the timing for the removal coefficients are adjusted accordingly.

The IC/PCCS pools cooling and cleaning subsystem is completely independent and separated from FAPCS cooling and cleaning subsystem that serves other pools (FPC, GDCS, suppression pools, and upper pools). There is no physical (pipe) connection between the FAPCS cooling and cleaning subsystem and the IC/PCCS pools cooling and cleaning subsystem, which is supported by the discussion in Subsection 9.1.3. There is no concern of contamination of the PCC/IC pool when injecting into GDCS, RPV, and suppression pools post-accident.

The various containment pools were evaluated to determine the pH levels following a LOCA with a release of fission products. Appendix 15C contains information on the methodology used. Credit is taken buffering as a result of the sodium pentaborate injected into the RPV via the SLC system. The formation of CsOH also assists in buffering pool pH levels. Early in the event pool pH increases to 8 to 10 for the various pools, primarily as a result of CsOH. Acids produced as a result radiation, such as HCl produced as result of electrical cables, lower the pH levels in the various pools. Calculations confirm that the GDCS pool could become acidic roughly 12-9 hours following the event, however at that point the pool is essentially depleted and contains minimal fission products. The pH in the RPV could drop below 7 late in the event (~28 days), however, due to hold up and plateout in the containment, reactor building, and condenser (consistent with the main analysis assumptions), doses are insignificant after this pH transition, and any doses as a result of the re-evolution of elemental iodine are within the conservative assumptions of the dose analysis. Similarly, doses from re-evolution of iodine in the lower drywell is not of concern due to either release timing and the small amount of CsI present in the pool. Therefore, re-evolution of iodine is not of concern do to the extremely low overall activity level in that pool. The remaining pools' pH remains above 7 for at least 20 days the first 24 hours. After 96 hours, dose calculation assumptions, such as atmospheric dispersion factors and control room occupancy factors, ensure that any re-evolution of iodine would not have significant impact on calculated doses. Re-evolution is therefore not included in the doses presented in Table 15.4-9.

15C. POOL pH METHODOLOGY

15C.1. SOURCE TERM DISCUSSION

Regulatory Guide 1.183 (Reference 15C-1) provides guidance on acceptable assumptions used in evaluating the dose consequences from a LOCA. The assumptions include the chemical distribution for radioiodines. Specifically, dose calculations assume that the iodine source term is predominantly aerosol iodine (CsI) as discussed in Section 15.4.4. In order to utilize this chemical distribution, licensees must evaluate the pH of the pools that could contain fission products and ensure that the pools remain basic (pH > 7). This Appendix discusses the methodology used to assess the pH of the various pools for the ESBWR.

15C.2. NUREG/CR-5950 ASSUMPTIONS AND METHODOLOGY

The iodine chemical distribution recommended by Regulatory Guide 1.183 and NUREG-1465 (Reference 15C-2) is assumed to be predominately aerosol iodine. Regulatory Guide 1.183 states that the iodine chemical distribution is applicable if sump or suppression pool pH is maintained above 7. The general concern is that iodine could change chemical forms and re-evolve to the containment atmosphere if pool pH is not maintained.

The ESBWR has several separate pool volumes that could potentially contain fission products following a LOCA. A detailed chemistry analysis was performed to determine the pH in the various containment pools following an accident. The methodology used is consistent with NUREG/CR-5950, "Iodine Evolution and pH Control" (Reference 15C-3). NUREG/CR-5950 discusses a number of chemicals that would potentially be affected post-accident in the containment pools. Each contributor is discussed below.

15C.2.1 Carbon Dioxide

Carbon Dioxide (CO₂) depresses the pH of pure water by absorption. Carbonic acid is a weak acid and is insignificant compared to the other acids produced in the primary containment during an accident. However, the initial pool pH may be depressed below 7.0 during normal operations by the absorption of CO₂. NUREG/CR-5950, Section 2.2.3 states that pure water will attain a pH approaching 5.65 due to absorption of CO₂ from air and the subsequent formation of Carbonic Acid. The effects of carbon dioxide are considered and bounded by evaluations by assuming the minimum pool pH allowed by plant specifications. No detailed calculations explicitly accounting for CO₂ were performed.

15C.2.2 Cesium Hydroxide

Cesium Hydroxide (CsOH) is a strong base introduced into the primary containment and subsequently to the containment pools with the release of cesium post-accident. The production of this base is considered within this assessment. ~~For the main analysis, the cesium that is not in the chemical form of CsI is assumed to exit the RCS in the form of cesium hydroxide (CsOH).~~ The pH analyses scavenge the cesium necessary to form a CsI molecule for every iodine ion released, however there is significantly more cesium than iodine (on a molar basis). The excess cesium would most likely react with water to produce hydrogen gas and CsOH, like all the alkali metal-water reactions. Cesium hydroxide is a strong base. However, only 50% of the remaining cesium is credited in forming CsOH for conservatism.

15C.2.3 Hydriodic Acid

Hydriodic Acid (HI) is a strong acid introduced into the primary containment with the release of post accident elemental iodine. Per Section 4.5 of NUREG-1465 and Subsection 2.2.2 of NUREG/CR-5950, no more than 0.15% of the core iodine inventory is released from the RCS in this chemical form. As such, the production of this acid is considered within this assessment. The calculated mole fraction of HI in the gas phase in the containment was calculated to be negligible. The amount of HI that could be potentially produced is insignificant to the amount of hydrochloric acid that could be produced (Subsection 15C.2.4).

15C.2.4 Hydrochloric Acid

Hydrochloric Acid (HCl) is also a strong acid which is produced by the radiolysis of chloride-bearing cable insulation during accidents. The production of this acid is considered within this assessment. Pyrolysis of chloride-bearing cable insulation produces HCl as well; however, only at temperatures near 570°K (572°F) (NUREG/CR-5950). Because the RB primary containment temperature is evaluated to be significantly less than 570°K (572°F), pyrolysis is not considered within this assessment.

The production of HCl by irradiating cables is estimated to be 1.0×10^{-3} mol per kg (4.6×10^{-4} mol per lb) of insulation per Mrad. This estimate is based on the model description of electrical cable and a radiation G value of 2.1.

Dose rates and doses were determined for the containment using a simple RADTRAD model with the 60 isotopes used for off-site doses. RADTRAD was used to determine the radioactivity that remains airborne in the containment volume, and the airborne concentration was determined. The following dose rate formulas from are used to determine submersion doses.

Infinite Cloud (Cloud centered)

$$\begin{aligned} {}_{\beta}D_{\infty}'(R/s) &= 0.457 \bar{E}_{\beta} (MeV) \chi (Ci/m^3) \\ {}_{\gamma}D_{\infty}'(R/s) &= 0.507 \bar{E}_{\gamma} (MeV) \chi (Ci/m^3) \end{aligned}$$

Semi-infinite Cloud (Surface body)

$$\begin{aligned} {}_{\beta}D_{\infty}'(R/s) &= 0.23 \bar{E}_{\beta} (MeV) \chi (Ci/m^3) \\ {}_{\gamma}D_{\infty}'(R/s) &= 0.25 \bar{E}_{\gamma} (MeV) \chi (Ci/m^3) \end{aligned}$$

Because this application is for cables, the cables themselves would provide self-shielding for beta radiation; therefore, the "semi-infinite cloud" model was used for beta dose rates. Due to the penetrating nature of gamma radiation, self-shielding of gamma is negligible. However, this penetrating ability also makes the "infinite cloud" model overly conservative. To account for the finite volume of the containment a finite model geometry factor (GF) was applied. NUREG/CR-604 (Reference 15C-4) provides such a factor for main control room dose calculations:

$$GF = \frac{1173}{V^{0.338}}$$

where the volume (V) is in the units of cubic feet. Accounting for the GF the containment dose rates then become

$$\gamma D_f' (R/s) = \frac{0.507 \bar{E}_\gamma (MeV) \chi (C/m^3)}{GF}$$

Dose rates and time-integrated dose (TID) were then determined, which in turn was used to determine the HCl released as a result of radiolysis.

15C.2.5 Nitric Acid

Nitric Acid (HNO₃) is also a strong acid that is introduced into the primary containment with the release of post accident source terms. This acid is produced by irradiation of air and water. According to the NUREG/CR-5950 report the radiation G value for nitric acid production is 0.007 molecules/100 eV and this value corresponds to 7.3 x 10⁻⁶ mol HNO₃/L/Mrad. The dose rates and doses discussed previously also used to evaluate the HNO₃ production in air. Nitric acid production in the water in the various pools is calculated using pool specific dose rates. The fission products in each pool are determined using the MELCOR analyses from the containment removal coefficient calculations (documented in Section 15.4.4.5.2.2). An expedient approach was adopted and dose conversion factors from FGR 12, Table III.2 (Reference 15C-5) were used to calculate dose rates and doses within the water pools.

15C.2.6 Sodium Pentaborate

Sodium Pentaborate (Na₂O*5B₂O₃*10H₂O) is a buffering solution primarily utilized as a backup means of criticality control within a post-accident reactor vessel. Sodium pentaborate is supplied by the Standby Liquid Control (SLC) system. The SLC system would be used as an injection source following confirmation of a LOCA. Buffering by the SLC system is considered in this evaluation. The density of soluble sodium pentaborate was estimated to be 1 kg/dm³. The amount of water in SLCS was set to 13650 kg and the mass of sodium pentaborate to 1950 kg. The release rate was 36.8 kg/s (2*18.4 kg/s).

The buffer is mixed into the RPV water inventory and transported according to BDL break flow to the lower drywell.

15C.3. POOL PH DETERMINATION

Chemical reactions taking place in multiphase systems are calculated with Gibbs energy minimization method. As a result of minimization the equilibrium composition of the system is obtained. The method requires that temperature, pressure and initial composition (initial amounts of species like H₂O(l), HCl(g), NaOH(s)) are known and given as input parameters.

The Gibbs energy minimization method is a general method; therefore, knowledge of the exact reaction paths between the chemical species is not required. Chemical species are linked together by their elemental composition, i.e. the elements (like C, H, O) that they are composed of. The equilibrium composition is the composition that gives the minimum Gibbs energy without violating the elementary mass balances (mole number of each element in equilibrium composition must be same as in initial composition). As such, the equilibrium calculation

- OH(-a) Na(+a)
- Cl(-a) OH(-a)
- Cs(+a) I(-a)
- Cs(+a) OH(-a)
- Cs(+a) H(+a)
- H(+a) I(-a)

After calculating the equilibrium composition, the pH of an aqueous solution can be calculated from H^+ ion activity:

$$\underline{pH = -\log_{10} \alpha_{H^+}}$$

The pH scale is logarithmic which means that, in order to change the pH by one, the concentration of H^+ ion must change by 10 times. The equivalence point is the pH where the added base fully neutralizes the acid initially in the solution. When the pH increases and gets closer to equivalent point the number of free H^+ ions is also decreased. This means that as the concentration of free H^+ ion gets smaller then the same added base amount has more striking effect to the H^+ ion concentration and pH. Typically the pH changes very rapidly around the equivalence point.

15C.4. pH EVALUATION RESULTS

Three Accident Scenarios were reviewed—Pool pH calculations were performed for three Accident Scenarios: AS-1 – “low pressure” bottom drain line break, AS-2 – “high pressure” bottom drain line break, and AS-3 – loss of feedwater/loss of preferred power as documented in Subsection 15.4.4.2. The Accident Scenarios are described in detail in NEDE-33279P, Revision 2 (Reference 15C-6). The results of these three scenarios are presented in Figures 15C-1 through 15C-3. Generally speaking, the pH in the GDCS pools drops below 7 early in the event (~78-12 hours); however, by this time the pool is essentially depleted and there is minimal iodine in the pool. Calculations show that for the bounding High Pressure Bottom Drain Line Break (AS-2) bottom line break scenarios, the pH in the RPV could drop below 7 late into the event (>~208-297 days). Similarly, the lower drywell pool could become acidic late in the event as well (~24-25 days) for the bottom line break scenarios (AS-1 and AS-2). The lower drywell becomes acidic much earlier for AS-3 (~ 8 days), however the source term located in the lower drywell is not significant. Scenario 3 is not the bounding scenario with respect to dose consequences even if all of the iodine in the LDW were to re-evolve.

15C.5. COL INFORMATION

None

15C.6. REFERENCES

- 15C-1 Regulatory Guide 1.183, “Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors,” Revision 0.

- 15C-2 NUREG-1465, "Accident Source Terms for Light Water Nuclear Power Plants."
- 15C-3 NUREG/CR-5950, *Iodine Evolution and pH Control*, December 1992.
- 15C-4 NUREG/CR-6604, "RADTRAD: A Simplified Model for Radionuclide Transport and Removal and Dose Estimation," USNRC, April 1998.
- 15C-5 EPA-402-R-93-081, Federal Guidance Report (FGR) 12, "External Exposure to Radionuclides in Air, Water, and Soil," Oak Ridge National Laboratory, 1993.
- 15C-6 NEDE-33279P, "ESBWR Containment Fission Product Removal Evaluation Model," Revision 2.

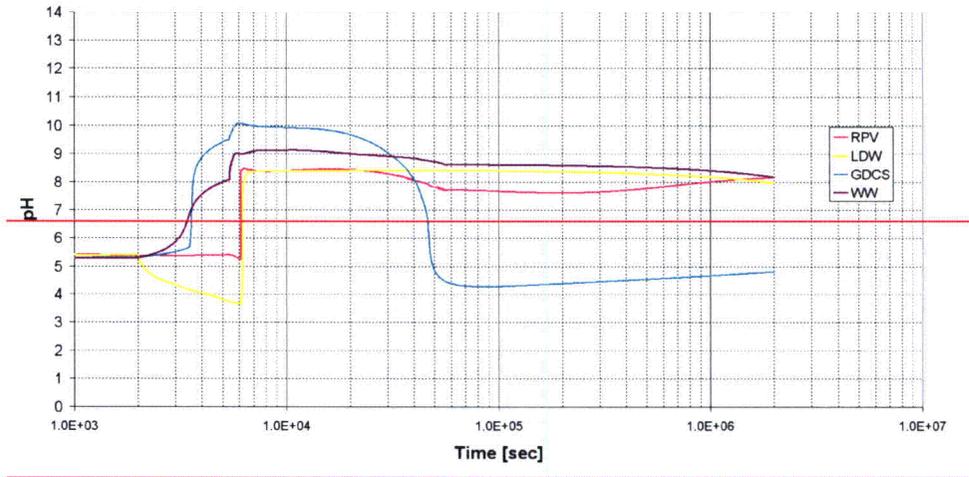
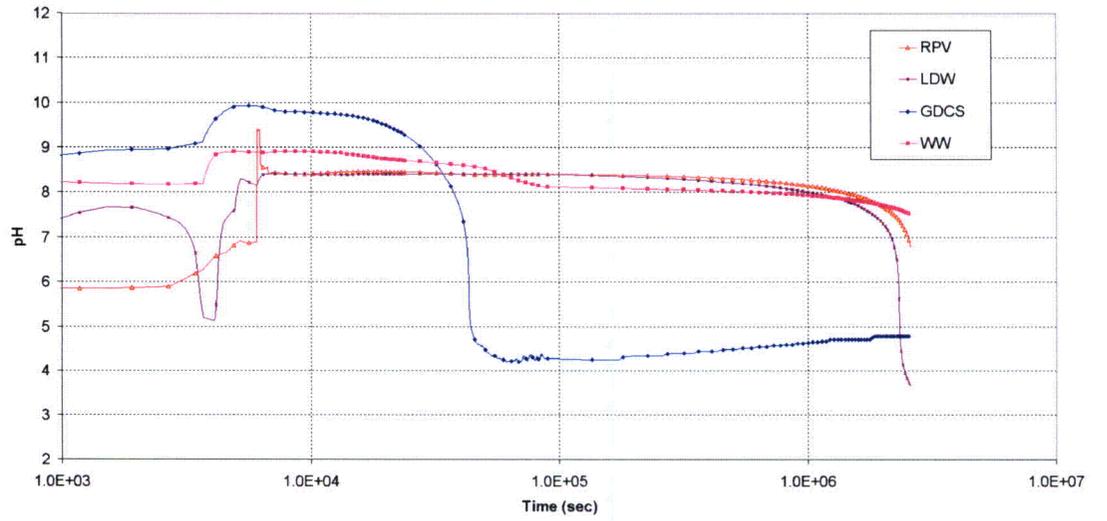
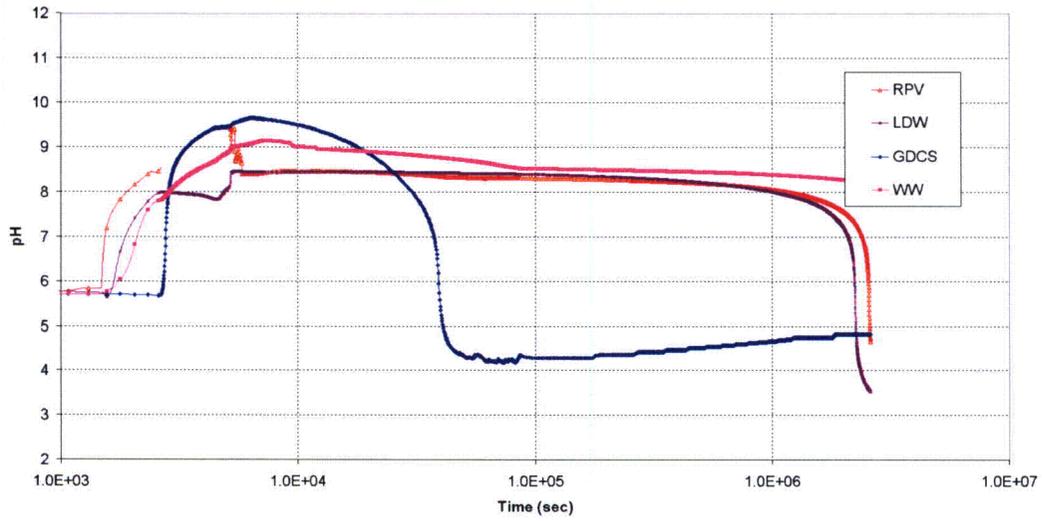
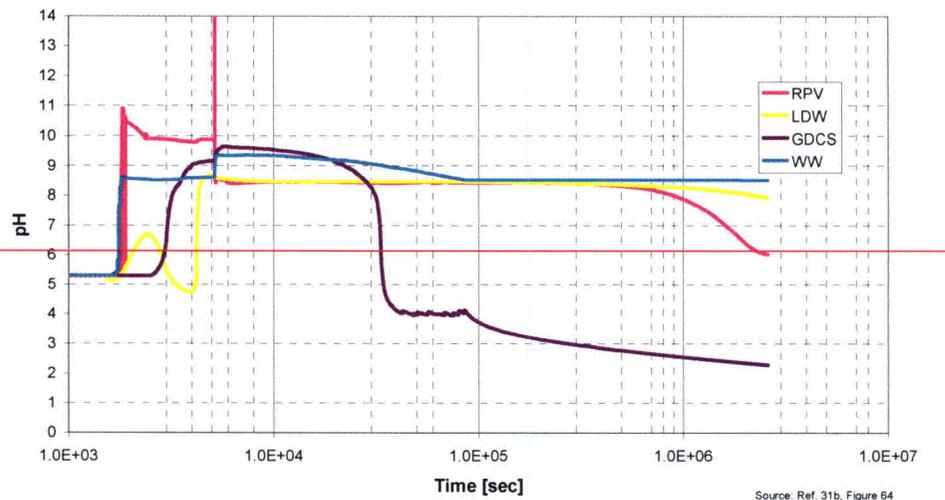


Figure 15C-1: Pool pH Calculation Results for a Low Pressure Bottom Line Break (Accident Scenario 1)



* Data not provided for RPV from 2600 - 5200 seconds because MELCOR predicts that the vessel is in "dryout" conditions



Source: Ref. 31b, Figure 64

Figure 15C-2: Pool pH Calculation Results for a High Pressure Bottom Line Break (Accident Scenario 2)

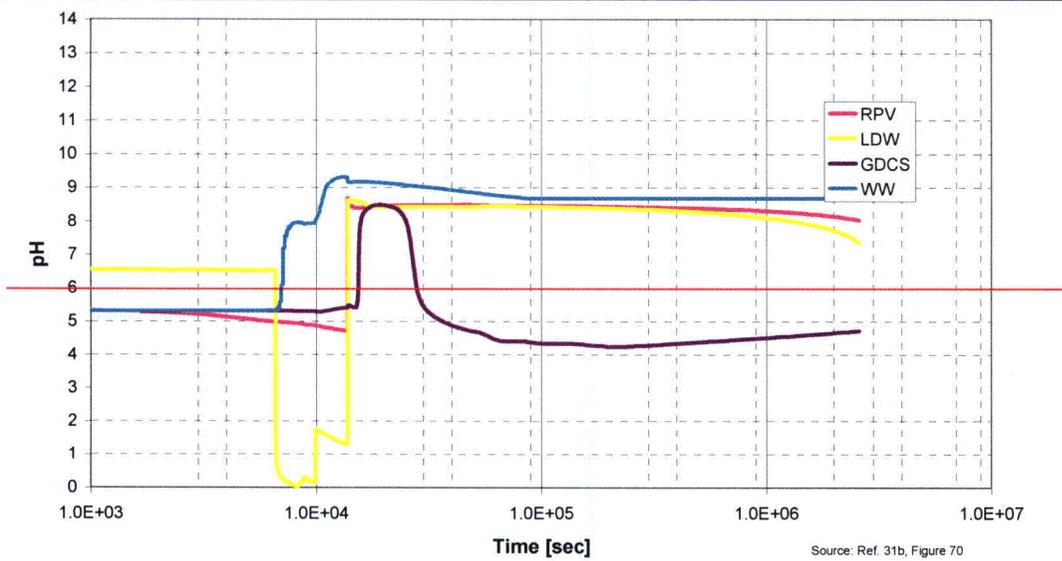
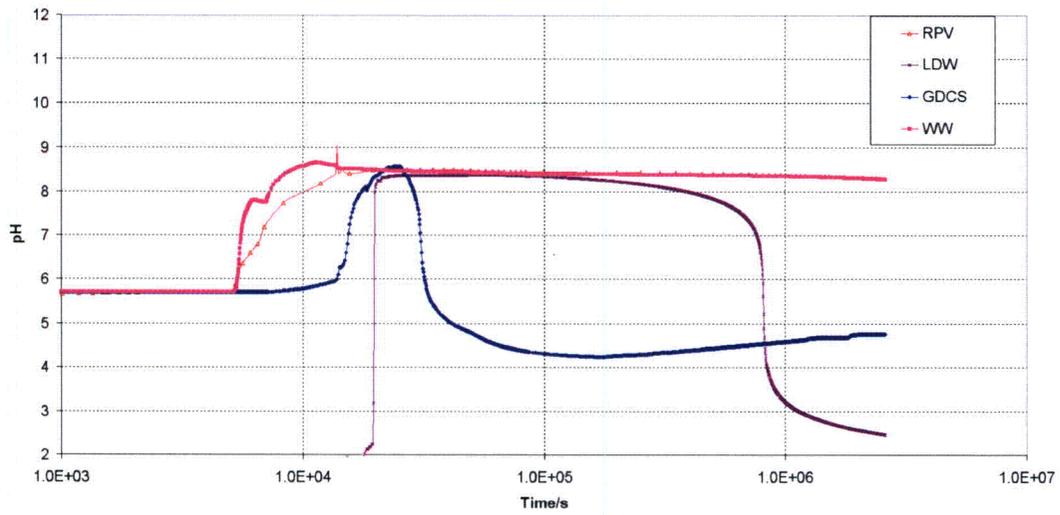


Figure 15C-3: Pool pH Calculation Results for a Loss of Feedwater/Loss of A/C Power (Accident Scenario 3)