


MITSUBISHI HEAVY INDUSTRIES, LTD.
16-5, KONAN 2-CHOME, MINATO-KU
TOKYO, JAPAN

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Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Attention: Mr. Jeffrey A. Ciocco

Docket No. 52-021
MHI Ref: UAP-HF-09407

Subject: MHI's Response to US-APWR DCD RAI No. 416-2912 Rev. 0

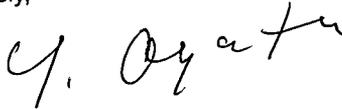
Reference: 1) "Request for Additional Information No. 416-2912 Revision 0, SRP Section: 06.05.02 – Containment Spray as a Fission Product Cleanup System, Application Section: 6.5.2" dated 6/29/2009.

With this letter, Mitsubishi Heavy Industries, Ltd. ("MHI") transmits to the U.S. Nuclear Regulatory Commission ("NRC") documents entitled "Response to Request for Additional Information No. 416-2912 Rev. 0".

Enclosed are the responses to 2 RAIs contained within Reference 1. Of these RAIs, 1 RAI will not be answered within this package. That is #6.5.2-6. The question requires additional time for analyses and internal discussions, and will be answered by 28th of August 2009.

Please contact Dr. C. Keith Paulson, Senior Technical Manager, Mitsubishi Nuclear Energy Systems, Inc. if the NRC has questions concerning any aspect of the submittals. His contact information is below.

Sincerely,



Yoshiaki Ogata,
General Manager- APWR Promoting Department
Mitsubishi Heavy Industries, LTD.

Enclosure:

1. Response to Request for Additional Information No. 416-2912 Revision 0

CC: J. A. Ciocco
C. K. Paulson

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WRO

Contact Information

C. Keith Paulson, Senior Technical Manager
Mitsubishi Nuclear Energy Systems, Inc.
300 Oxford Drive, Suite 301
Monroeville, PA 15146
E-mail: ck_paulson@mnes-us.com
Telephone: (412) 373-6466

Docket No. 52-021
MHI Ref: UAP-HF-09407

Enclosure 1

UAP-HF-09407
Docket No. 52-021

Response to Request for Additional Information No. 416-2912
Revision 0

July 2009

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

7/28/2009

US-APWR Design Certification

Mitsubishi Heavy Industries

Docket No. 52-021

RAI NO.: NO. 416-2912 REVISION 0
SRP SECTION: 06.05.02 – CONTAINMENT SPRAY AS A FISSION PRODUCT CLEANUP SYSTEM
APPLICATION SECTION: 6.5.2
DATE OF RAI ISSUE: 6/29/2009

QUESTION NO.: 06.05.02-5

Background

RAI 06.05.02-1 (Reference 1) requested that the applicant explain the rise in pH of the RWSP water under accident conditions. The importance of such a calculation is to ensure that iodine dissolved in RWSP water does not revolatilize, which it could do if the pH is not maintained above 7. In fact, acceptance criterion II.1.G of SRP 6.5.2 requires that pH of 7 should be achieved before the onset of containment sprays. The staff's concern was motivated by the statement in DCD 6.3.2.2.5 that the primary pH control chemical (NaTB) would not be fully dissolved for 12 hours.

In the applicant's response (Reference 2), it was claimed that the pH would be raised above 7 very early in the accident by dissolution of fission product cesium, which would exist primarily as the strong base CsOH. Specifically, it was stated that in about 1 hour, sufficient CsOH would be released from fuel, escape the RCS, and be washed into the RWSP, so as to raise the pH in the RWSP above 7. In fact, a plot prepared of the time variation of pH indicates that pH will rise above 8, and even to 9, depending on pool temperature.

The staff has been unable to corroborate this calculation, a simplification of which appears here. We assume the data given below:

RCS water = $510 \text{ m}^3 \approx 5.1 \times 10^5 \text{ kg}$
RWSP water = $2810 \text{ m}^3 \approx 2.81 \times 10^6 \text{ kg}$
Total Cs released to water (30% of core inventory) = 1068 mol
Concentration of boric acid = 4000 ppm

Assuming that all Cs is CsOH (in reality, about 10% would exist as CsI), concentrations of boric acid and CsOH are about 0.223 m (molal) and 0.0004 m, respectively. Using the methodology of the EPRI Guidelines (Reference 3), the pH of such a solution was calculated to be about 5.75 at 350 K (77°C). This is well below the pH calculated by the applicant in Reference 2.

Requested Information

Describe in more detail the calculation that indicates fission product cesium raises containment water pH above 7. Include all amounts of water, boric acid, fission products, and other solutes. Describe assumptions and any factors contributing to the calculation.

References

1. "Request for Additional Information No. 234-2040 Revision 1, SRP Section: 06.05.02 - Containment Spray as a Fission Product Cleanup System, Application Section: Section 6.5.2" dated February 26, 2009. (ADAMS Accession No. ML0906102970)
2. Letter from Yoshiki Ogata, MHI, to NRC dated April 22, 2009; Docket No. 52-021 MHI Ref: UAP-HF-09199; Subject: MHI's Second Response to US-APWR DCD RAI No. 234 (ADAMS Accession No. ML0911804351)
3. *Pressurized Water Reactor Primary Water Chemistry Guidelines*, Vol. 1, Rev. 6, Electric Power Research Institute (December 2007).

ANSWER:

The pH of recirculation water after an accident is calculated with the following factors contributing to pH:

- (1) Contribution by contained boric acid
- (2) Contribution by the production of hydriodic acid (HI) in concurrence with the release of iodine contained in FPs (fission products)
- (3) Contribution by the production of nitric acid (HNO₃) resulting from the radiolysis of dissolved nitrogen
- (4) Contribution by the production of hydrogen chloride (HCl) by the radiolysis of a jacket (chlorine-based rubber) for insulated cables
- (5) Contribution by the production of cesium hydroxide (CsOH) in concurrence with the release of cesium contained in FPs
- (6) Contribution by the addition of a pH adjuster (NaTB) after LOCA

It is assumed that the contribution by the production of carbonic acid (H₂CO₃) resulting from the dissociation of dissolved carbon dioxide to be small and negligible because carbonic acid is a weak acid. The calculation method with (1) to (6) above taken into account is described in detail below.

(1) Contribution by contained boric acid

The concentration of boric acid in recirculation water was set at 4200 ppm (as boron: 0.39 [mols/l]). With this setting, pH can be calculated using the dissociation constants of water and boric acid. The calculated pHs at temperatures of 50°C, 100°C, and 150°C are shown below.

T ₀	50°C	100°C	150°C
K _w (T ₀)	5.21E-14	5.37E-13	2.28E-12
[H ⁺]	6.81E-5	5.31E-5	4.09E-5
[OH]	7.65E-10	1.01E-8	5.57E-8

(2) Contribution by the production of hydriodic acid in concurrence with the release of iodine contained in FPs

Based on NUREG-1465, the contribution by iodine released from the core in cases of fuel damage is evaluated. It is conservatively presumed that all HI produced would remain in the liquid phase. In other words, this assumption is that all the HI produced would dissociate and all the hydrogen in HI would be transformed into hydrogen ions (H⁺). It is assumed that 5% of the core iodine inventory would be released into the containment (gap release phase) and 35% into the containment (the early in-vessel release phase) and only 5% of iodine released into the containment would be transformed into HI as one of prerequisites.

The production rate and time change in concentration of HI in this case can be represented by the expressions below.

<Up to 0.5 hour after LOCA> For the gap release phase

The production rate of HI and the time change in concentration in recirculation water are given by the expressions below.

$$d[HI]/dt = (0.05 \cdot 0.05 m_i) / (V_{RW} \cdot t_p) \quad 1-1$$

$$[HI]_{t \leq 0.5} = (0.05 \cdot 0.05 m_i) / (V_{RW} \cdot t_p) \cdot (t - t_{gap}) \quad 1-2$$

Where:

- t : Time elapsed after LOCA [hours]
- [HI] : Concentration of HI in recirculation water [mols/l]
- [HI]_{t ≤ 0.5} : Concentration of HI in recirculation water up to half an hour after LOCA [mols/l]
- m_i : Core iodine inventory [g-mols] 3.4E+2
- V_{RW} : Volume of the recirculation water [l] 3.33E6
- t_p : Cycle of release to the gap release phase [hours] 0.5
- t_{gap} : Time until the start of gap release [hours] 0.01

<After 0.5 hour after LOCA> For the early in-vessel release phase

$$d[HI]/dt = (0.05 \cdot 0.35 m_i) / (V_{RW} \cdot t_{pv}) \quad 1-3$$

$$[HI]_{t > 0.5} = (0.05 \cdot 0.35 m_i) / (V_{RW} \cdot t_{pv}) \cdot [t - (t_{gd} + t_{gap})] + (0.05 \cdot 0.05 m_i) / V_{RW} \quad 1-4$$

Where:

- t_{pv} : Cycle of release to the early in-vessel release phase [hours] 1.3
 - t_{gd} : Release duration of the gap release phase [hours] 0.5
 - [HI]_{t > 0.5} : HI concentration in recirculation water after 0.5 hour after LOCA [mols/l]
- However, after 1.8 hours (t ≥ 1.8 hours):
- $$[HI] = (0.05 \cdot 0.4 m_i) / V_{RW}$$

(3) Contribution by the production nitric acid resulting from the radiolysis of dissolved nitrogen

If LOCA occurs, nitric acid may be produced by radiolysis by the γ and β rays of dissolved nitrogen in recirculation water. For this reason, the amount of nitric acid produced in recirculation water from the effective G value is evaluated. The effective G value of the nitric acid produced (G_{HNO₃}) is given as shown below from experimental values (86°F: 30°C) at ORNL, which are contained in NUREG/CR-5950 and NUREG/CR-5732.

$$G_{HNO_3} = 0.007 \text{ [molecules-HNO}_3\text{ / 100 eV]} \quad 1-5$$

Since the solubility of nitrogen decreases as the water temperature rises, the value shown above is conservative in evaluating when LOCA occurs.

Assuming that the density of recirculation water is 1 [kg/ℓ], the amount of nitric acid produced by 1 kGy absorption energy of radiation is given by the expression below.

$$(\text{HNO}_3) = G_{\text{HNO}_3} * 1/1.60\text{E-}19(\text{J/eV}) * 1/6.02\text{E}23 \text{ (moles/molecule)} \quad 1-6$$

$$* 10^3(\text{J/kg-kGy}) * 1(\text{kg/ℓ})$$

$$= 0.007/100/1.60\text{E-}19/6.02\text{E}23 * 1\text{E}+3$$

$$= 7.3\text{E-}7[\text{moles/ ℓ-kGy}] \quad 1-7$$

Consequently, from Expression 1-7), the time change in the concentration of nitric acid taking into account the absorbed dose rate is given by the expression below.

$$d[\text{HNO}_3]/dt = 7.3\text{E-}7 [\text{mol HNO}_3/\ell\text{-kGy}] * X(t)_{\text{RW}} \quad 1-8$$

$$[\text{HNO}_3]_{(t)} = 7.3\text{E-}7 * \int X(t)_{\text{RW}} dt \quad 1-9$$

$$= 7.3\text{E-}7 * (E_{(t)}^\gamma + E_{(t)}^\beta) \quad 1-10$$

Where:

t : Time elapsed after an LOCA [hours]

$[\text{HNO}_3]_{(t)}$: Concentration of nitric acid in recirculation water at t (hours) after an LOCA [mols/ ℓ]

$X(t)_{\text{RW}}$: The absorbed doses rate of γ and β rays in recirculation water [kGy/hour]

$E_{(t)} = \int X(t)_{\text{RW}} dt$: Integrated absorbed dose of γ and β rays in recirculation water for time t (hours) after LOCA [kGy]

- (4) Contribution by the production of hydrochloric acid by the radiolysis of a jacket (chlorine-based rubber) for insulated cables

The source of hydrochloric acid is assumed to be hydrogen chloride (HCl) produced by the radiolysis of a chlorine-containing jacket covering insulated cables. The cable model used corresponds with NUREG-1081 cable model. NUREG-1081 cable model consists of a copper wire, insulating material (non-chlorine-based: ethylene-propylene rubber (EPR)) wrapped around the copper wire, and a chlorine-based rubber (chloro-sulfonated polyethylene: Hypalon) jacket covering the insulating material. The calculation model is based on NUREG-1081 and NUREG/CR-5950. For the purpose of providing conservative results, it is assumed all gaseous HCl produced by the radiolysis of the chlorine-based rubber transfers to the recirculation water and contributes as hydrochloric acid. Two types of radiation – γ and β rays – are considered.

A specific method for evaluating the amount of hydrochloric acid produced is described below. The production rate of HCl is given by the expression below. (NUREG/CR-5950 Appendix B)

$$R = G * S * \phi * A \quad 1-11$$

Where:

R : Production rate of HCl [g-mol/hour]

G: HCl production G value for the chlorine-based rubber [g-mols/MeV]

S : Total surface area of the cable [cm²]

ϕ : Energy flux of radiation [MeV/hour-cm²]

A : Radiation absorption fraction in the chlorine-based rubber jacket [-]

Each factor contained in Expression 1-11) is detailed below.

<HCl production G value>

Assuming that the HCl production G value for the chlorine-based rubber (Hypalon) is

defined as G_{HCl} (molecules/100eV), G' is given by the expression below. (NUREG/CR-5950 Appendix B)

$$\begin{aligned} G' &= G_{\text{HCl}} (\text{molecules}/100 \text{ eV}) * 1/6.02\text{E}23 (\text{g-mol}/\text{molecule}) * 1\text{E}+6 (\text{eV}/\text{MeV}) \\ &= G_{\text{HCl}} * 1.66\text{E}-20 [\text{g-mols}/\text{MeV}] \end{aligned} \quad 1-12)$$

NUREG/CR-5950 adopts 2.115 (molecules/100 eV) for the G value of Hypalon. However, the G value by γ and β rays are assumed to be the same.

<Total surface area of the cable>

The surface area of the cable depends on its radius and length.

$$S = 2\pi * R_o * \ell \quad 1-13)$$

Where:

- S : Total surface area of the cable [cm^2]
- R_o : Radius of the cable [cm] 1.1304cm
- ℓ : Length of the cable [cm] 5.63E6 (This length used in response to RAI No.234 is the twice as the expected length.)

<Energy flux of radiation>

The energy flux of γ rays on the surface of the cable is based on NUREG-1081 and evaluated using the expression below.

$$\phi_\gamma = E_\gamma / V * (1 - e^{-\mu_\gamma^{\text{air}} * r}) / \mu_\gamma^{\text{air}} \quad 1-14)$$

Where:

- ϕ_γ : Energy flux of γ rays in the containment [MeV/hour- cm^2]
- E_γ : Release rate of γ ray energy into the containment free volume [MeV/hour]
This is a time-variable function.
- V : Containment free volume [cm^3]
- μ_γ^{air} : Radiation absorption coefficient of γ rays in the air [1/cm] 3.74E-5
- r : Average distance from the center of the containment to the surface of the cable given that the containment is spherical [cm] 2.68E+3

The radiation absorption coefficient μ of β rays is about 1000 times that of γ rays and $(1 - e^{-\mu * r}) \approx 1$ when the distance is several dozen meters. Hence, the approximate expression shown below is used to evaluate the energy flux ϕ_β of radiation.

$$\phi_\beta = E_\beta / V * (1 / \mu_\beta^{\text{air}}) \quad 1-15)$$

Where:

- ϕ_β : Energy flux of β rays in the containment [MeV/hour- cm^2]
- E_β : Release rate of β ray energy into the containment free volume [MeV/hour]
This is a time-variable function.
- V : Containment free volume [cm^3]
- μ_β^{air} : Radiation absorption coefficient of β rays in the air [1/cm] 0.0198

<Radiation absorption fraction>

The expression below is used to calculate the absorption fraction of γ rays in the chlorine-based rubber.

$$A = 1 - e^{-\mu * th} \quad 1-16)$$

Where:

- A : Absorption fraction of radiation [-]

μ : Absorption coefficient of γ rays in the chlorine-based rubber [1/cm] 0.099
 th : Thickness of the chlorine-based rubber jacket [cm] 0.183
 (Calculated from the outside diameter of the cable and the inside diameter of the sheath)

Conservatively assuming that the β rays are completely absorbed:

$$A_{\beta} = 1 \quad 1-17)$$

As a result of the steps described above, the amount of HCl produced M [g-mol] can be evaluated using the expression below.

(In the case of γ rays)

$$\begin{aligned}
 M_{HCl}^{\gamma}(t) &= G \cdot S \cdot A \int \phi_{\gamma} dt \\
 &= G \cdot 1.66E-20 \cdot 2\pi \cdot R_o \cdot \ell \cdot (1 - e^{-\mu_{\gamma}^{air} \cdot \ell}) / \mu_{\gamma}^{air} \cdot (1 - e^{-\mu_{\gamma}^R \cdot th}) \cdot \int E_{\gamma} dt / V \\
 &= G \cdot 1.66E-20 \cdot 2\pi \cdot R_o \cdot \ell \cdot (1 - e^{-\mu_{\gamma}^{air} \cdot \ell}) / \mu_{\gamma}^{air} \cdot (1 - e^{-\mu_{\gamma}^R \cdot th}) \cdot X_{\gamma}(t)
 \end{aligned} \quad 1-18)$$

(In the case of β rays)

$$\begin{aligned}
 M_{HCl}^{\beta}(t) &= G \cdot S \cdot A \int \phi_{\beta} dt \\
 &= G \cdot 1.66E-20 \cdot 2\pi \cdot R_o \cdot \ell \cdot 1 / \mu_{\beta}^{air} \cdot \int E_{\beta} dt / V \\
 &= G \cdot 1.66E-20 \cdot 2\pi \cdot R_o \cdot \ell \cdot 1 / \mu_{\beta}^{air} \cdot X_{\beta}(t)
 \end{aligned} \quad 1-19)$$

Where:

$M_{HCl}^{\gamma}(t)$: Amount of HCl produced in the recirculation water by contribution by γ rays t (hours) after an LOCA [g-mols]

$M_{HCl}^{\beta}(t)$: Amount of HCl produced in the recirculation water by contribution by β rays t (hours) after an LOCA [g-mols]

μ_{γ}^{air} : Radiation absorption coefficient of γ rays in the air [1/cm] 3.74E-5

μ_{β}^{air} : Radiation absorption coefficient of β rays in the air [1/cm] 0.0198

μ_{γ}^R : Radiation absorption coefficient of γ rays in the chlorine-based rubber [1/cm] 0.099

$\int E_{\gamma} / dt$: Amount of γ ray energy released per unit volume inside the containment $X_{\gamma}(t)$

$\int E_{\beta} / dt$: Amount of β ray energy released per unit volume inside the containment $X_{\beta}(t)$

From Expressions 1-18) and 1-19), the concentration of hydrochloric acid in recirculation water after LOCA is given by the expression below.

$$[HCl]_{(t)} = 1 / V_{RW} \cdot \sum_{(all\ cables)} (M_{HCl}^{\gamma}(t) + M_{HCl}^{\beta}(t)) \quad 1-20)$$

Where:

$[HCl]_{(t)}$: Total concentration of hydrochloric acid in recirculation water t (hours) after an LOCA [mols/l]

V_{RW} : Volume of the recirculation water [l] 3.33E6

$M_{HCl}^{\gamma}(t)$: Amount of HCl produced in the recirculation water by contribution by γ rays of the cable t (hours) after LOCA [g-mols]

$M_{HCl}^{\beta}(t)$: Amount of HCl produced in the recirculation water by contribution by β rays of the cable t (hours) after LOCA [g-mols]

- (5) Contribution by the production of cesium hydroxide (CsOH) in concurrence with the release of cesium contained in FPs

Cesium, an FP is considered as a source of the base (alkali). The contribution by cesium released from the core in cases of fuel damage is evaluated based on NUREG-1465, and the chemical form of this cesium in the liquid phase is assumed to be cesium hydroxide (CsOH). In the initial gap release phase (up to 0.5 hour after LOCA), the value calculated by subtracting 95% of the produced CsI out of the 5% of the iodine inventory from the amount of

released cesium of the 5% of the core cesium inventory is defined as the net amount of CsOH produced. In the early in-vessel release phase, the value calculated by adding the amount in the initial gap release phase to the value obtained by subtracting 95% of produced CsI out of 35% of the iodine inventory from the amount of the released cesium of 25% of the core cesium inventory is defined as the net amount of CsOH produced. The release rates of iodine and cesium differ between the gap release phase and the early in-vessel release phase. In this case, the production rate of CsOH and the change in its concentration are given by the expressions below.

<Up to 0.5 hour after LOCA> For the gap release phase

The production rate of CsOH and the time change in concentration in recirculation water are given by the expressions below.

$$d[\text{CsOH}]/dt = (0.05m_{\text{cs}} - 0.95 \cdot 0.05m_i) / (V_{\text{RW}} \cdot t_p) \quad 1-21$$

$$[\text{CsOH}]_{t \leq 0.5} = (0.05m_{\text{cs}} - 0.95 \cdot 0.05m_i) / (V_{\text{RW}} \cdot t_p) \cdot (t - t_{\text{gap}}) \quad 1-22$$

Where:

t:	Time elapsed after an LOCA [hours]
[CsOH]	Concentration of CsOH [mols / ℓ]
[CsOH] _{t ≤ 0.5} :	Concentration of CsOH in recirculation water at t (hours) after an LOCA [mols/ℓ]
m _i	Iodine inventory of the core [g-mols] 3.4E+2
m _{cs}	Cesium inventory of the core [g-mols] 3.9E+3
V _{RW}	Volume of the recirculation water [ℓ] 3.33E6
t _p	Cycle of release to the gap release phase [hours] 0.5
t _{gap}	Time to the start of gap release [hours] 0.01

<Over 0.5 hour after accident> For the early in-vessel release phase

$$d[\text{CsOH}]/dt = (0.25m_{\text{cs}} - 0.95 \cdot 0.35m_i) / (V_{\text{RW}} \cdot t_{\text{pv}}) \quad 1-23$$

$$[\text{CsOH}]_{t > 0.5} = (0.25m_{\text{cs}} - 0.95 \cdot 0.35m_i) / (V_{\text{RW}} \cdot t_{\text{pv}}) \cdot [t - (t_{\text{gd}} + t_{\text{gap}})] + (0.05m_{\text{cs}} - 0.95 \cdot 0.05m_i) / V_{\text{RW}} \quad 1-24$$

Where:

[CsOH] _{t > 0.5} :	Concentration of CsOH in recirculation water at t (hours) after an LOCA [mols/ℓ]
t _{pv} :	Cycle of release to the early in-vessel release phase [hours] 1.3
t _{gd} :	Gap release duration [hours] 0.5
However, after 1.8 hours (t ≥ 1.8 hours):	
[CsOH]	$(0.3m_{\text{cs}} - 0.95 \cdot 0.4m_i) / V_{\text{RW}}$

(6) Calculating pH after an LOCA (when no pH adjuster is added)

It is calculated the pH of recirculation water at t (hours) after the start of an LOCA from the contributions of (1) to (5) above and the condition of dissociation equilibrium of water. Additionally, pH is evaluated 0.5 hour after the LOCA and over 0.5 hour after that because the release mechanism of iodine and cesium takes into account the gap release and early in-vessel release phases. They are represented by the expressions shown below.

<Up to 0.5 hour after accident>

(H⁺ accrual argument)

$$\begin{aligned} [\text{H}^+]_{(t)} &= [\text{H}^+]_{t=0} + \text{Expression 1-2} + \text{Expression 1-10} + \text{Expression 1-20} \\ &= [\text{H}^+]_{t=0} + [\text{H}^+]_{t < 0.5} + [\text{HNO}_3]_{(t)} + [\text{HCl}]_{(t)} \\ &= [\text{H}^+]_{t=0} + (0.05 \cdot 0.05 m_i) / (V_{\text{RW}} \cdot t_p) \cdot (t - t_{\text{gap}}) + 7.3\text{E-}7 \cdot E(t) \\ &\quad + 1/V_{\text{RW}} \cdot \sum_{(\text{all cables})} (M_{\text{HCl}}^{\gamma}(t) + M_{\text{HCl}}^{\beta}(t)) \end{aligned} \quad 1-25$$

(OH⁻ accrual argument)

$$\begin{aligned}
 [\text{OH}^-]_{(t)} &= K_w(T_0)/[\text{H}^+]_{t=0} + \text{Expression 1-22} \\
 &= K_w(T_0)/[\text{H}^+]_{t=0} + [\text{CsOH}]_{t<0.5} \\
 &= K_w(T_0)/[\text{H}^+]_{t=0} + (0.05 m_{\text{cs}} - 0.95 \cdot 0.05 m_i) / (V_{\text{RW}} \cdot t_p) \cdot (t - t_{\text{gap}})
 \end{aligned}
 \tag{1-26}$$

<Over 0.5 hour after LOCA>

(H⁺ accrual argument)

$$\begin{aligned}
 [\text{H}^+]_{(t)} &= [\text{H}^+]_{t=0} + \text{Expression 1-4} + \text{Expression 1-10} + \text{Expression 1-20} \\
 &= [\text{H}^+]_{t=0} + [\text{HI}]_{t>0.5} + [\text{HNO}_3]_{(t)} + [\text{HCl}]_{(t)} \\
 &= [\text{H}^+]_{t=0} + (0.05 \cdot 0.35 m_i) / (V_{\text{RW}} \cdot t_{\text{pv}}) \times [t - (t_{\text{gd}} + t_{\text{gap}})] + 0.05 \cdot 0.05 m_i / V_{\text{RW}} \\
 &\quad + 1/V_{\text{RW}} \cdot \sum_{(\text{all cables})} (M_{\text{HCl}}^\gamma(t) + M_{\text{HCl}}^\beta(t))
 \end{aligned}
 \tag{1-27}$$

(OH⁻ accrual argument)

$$\begin{aligned}
 [\text{OH}^-]_{(t)} &= K_w(T_0)/[\text{H}^+]_{t=0} + \text{Expression 1-24} \\
 &= K_w(T_0)/[\text{H}^+]_{t=0} + [\text{CsOH}]_{t>0.5} \\
 &= K_w(T_0)/[\text{H}^+]_{t=0} \\
 &\quad + (0.25 m_{\text{cs}} - 0.95 \cdot 0.35 m_i) / (V_{\text{RWSP}} \cdot t_{\text{pv}}) \cdot [t - (t_{\text{gd}} + t_{\text{gap}})] \\
 &\quad + (0.05 m_{\text{cs}} - 0.95 \cdot 0.05 m_i) / V_{\text{RWSP}}
 \end{aligned}
 \tag{1-28}$$

However, [HI] and [CsOH] are considered constant after 1.8 hours.

Expressions 1-25) to 1-28) represent freely produced acids and bases, and cases in which all of them are dissolved in recirculation water are assumed.

According to the theory of ionic equilibrium of solutions, the product of the concentration of hydrogen ions [H⁺] and that of hydroxide ions [OH⁻] cannot take a given value and must be set to fulfill the expression shown below.

$$[\text{H}^+] \cdot [\text{OH}^-] = K_w(T) \tag{1-29}$$

Where:

$K_w(T)$: Dissociation constant of water at temperature T (°K) [(mols / l)²]

The relational expression below is established assuming that the concentrations of hydrogen and hydroxide ions freely produced for t hours after LOCA are [H⁺]_(t) and [OH⁻]_(t), respectively, and the amount to be neutralized to fulfill Expression 1-29) is λ [mols/l].

$$([\text{H}^+]_{(t)-\lambda}) \cdot ([\text{OH}^-]_{(t)-\lambda}) = K_w(T) \tag{1-30}$$

Solve λ from Expression 1-30).

$$\lambda = 1/2 \times \{[\text{H}^+]_{(t)} + [\text{OH}^-]_{(t)} - A\} \tag{1-31}$$

$$A = \{([\text{H}^+]_{(t)} - [\text{OH}^-]_{(t)})^2 + 4 K_w(T)\}^{0.5} \tag{1-32}$$

The concentration of hydrogen ions [H⁺]_{final} at a corrected given time t is given by the expression below.

$$[\text{H}^+]_{\text{final}} = ([\text{H}^+]_{(t)-\lambda}) \tag{1-33}$$

Consequently, the pH of recirculation water at the given time t can be obtained from the expression below.

$$\text{pH} = -\log([\text{H}^+]_{\text{final}}) \tag{1-34}$$

(7) Contribution by the addition of a pH adjuster after LOCA

Evaluate pH with emphasis placed on NaTB as a pH adjuster.

<Dissolution rate>

The pH adjustment equipment is designed to dissolve 20 tons of NaTB in 12 hours after an accident occurs. In the evaluation, it is assumed conservatively that 18 tons of NaTB are dissolved in 12 hours. Assuming that NaTB is dissolved at a constant rate, the dissolution rate can be considered conservative. For this reason, the dissolution rate is set at 18 (tons)/12 (hours) = 1.5 (ton/hours).

<Dissolution time delay>

The dissolution time delay to uniform mixing is set at 3.5 hours by considering the actuation of the C/V spray, NaTB basket overflow time, and circulation time in recirculation water. Hence, the time dissolution begins is considered to be 3.5 hours after an accident.

A method for calculating pH when NaTB is dissolved in recirculation water is shown below. The dissociation of boric acid $B(OH)_3$ is represented below under the assumption that is a single-stage dissociation.



The dissociation constant K_a is defined as follows:

$$K_a = [H^+] \times [B(OH)_4^-] / [B(OH)_3] \quad 1-36$$

$B(OH)_4^-$ acts as a base (alkali) in the form of $B(OH)_4^- \rightleftharpoons B(OH)_3 + OH^-$.

On the other hand, $Na_2B_4O_7$ is completely dissociated in water as represented by the expression below, by which Na^+ , $B(OH)_4^-$, and $B(OH)_3$ will be produced.



The representation of Expression 1-36) can be transformed as follows:

$$K_a = [H^+] \times [Borate] / [Acid] = [H^+] \times [Base] / [Acid] \quad 1-38$$

When the degree of dissociation of boric acid is low, the concentration of borate (boric acid ions: $B(OH)_4^-$) in the solutions is most dependant on the contribution by $Na_2B_4O_7$. Expression 1-38) is applicable when the concentrations of a weak acid (boric acid) and its conjugate base (NaTB) are higher than those of hydrogen ions $[H^+]$ and hydroxide ions $[OH^-]$. From Expression 1-38), pH after $Na_2B_4O_7$ is added is given by the expression below.

$$pH = pKa + \log [Borate] / [Acid] \quad 1-39$$

Where:

pKa: $-\log K_a$

K_a is the dissociation constant of boric acid.

"Borate" is the value calculated by subtracting $[H^+]_{final}$ from boric acid 2y produced from NaTB, and "Acid" is the sum of boric acid 2y produced from NaTB, the initial concentration of boric acid x, and $[H^+]_{final}$. Expression 1-39) can, therefore, be replaced with the expression shown below.

$$pH = pKa + \log \{ (2y - Hf) / (2y + x + Hf) \} \quad 1-40$$

Where:

x: Initial concentration of boric acid (mols/l)

y: Concentration of pH adjuster at each elapsed time (mols/l)

H_f: Final concentration of hydrogen ions in the RWSP at each elapsed time [H⁺]_{final}
(mols/l)

The method for calculating pH when the dissociation of boric acid is not negligible is not contained herein because it is described in the draft answer to RAI No. 234. Table 1-1 shows a list of the data used for the pH calculations described above. Absorption doses used in pH analysis will be listed in response to RAI No.420.

Table 1-1: List of Data Used for pH Analyses (Sheet 1 of 2)

Symbol	Name/Value	Unit	Remarks
$K_w(T_0)$	Dissociation constant of water at the initial state of an LOCA: Temperature function	[mols/l] ²	
T_0	Initial temperature of LOCA: 50°C, 100°, 150°C	[°C]	
$K_w(T)$	Dissociation constant of water: Temperature function: 50°C: 5.21E-14, 100°C: 5.37E-13, 150°C: 2.28E-12	[mols/l] ²	
T	Temperature: 50°C, 100°, 150°C	[°C]	
C_B	Concentration of boric acid in recirculation water (as boron) 4,200	[ppm]	
$[H^+]_{(t=0)}$	Initial concentration of hydrogen ions in recirculation water: 50°C : 6.81E-5, 100°C : 5.31E-5, 150°C: 4.09E-5	[mols/l]	
$[OH]_{(t=0)}$	Initial concentration of hydroxide ions in recirculation water ($K_w(T_0)/[H^+]_{(t=0)}$)	[mols/l]	
V_{RWSP}	Volume of RWSP 3.33E6	[l]	
m_i	Iodine inventory of core 3.4E+2	[g-mols]	
$[HI]_{t \leq 0.5}$	HI concentration in recirculation water at t hours (up to half an hour) after an LOCA	[mols/l]	Calculated from Expression 1-2).
$[HI]_{t > 0.5}$	HI concentration in recirculation water at t hours (over half an hour) after an LOCA	[mols/l]	Calculated from Expression 1-4).
t	Time elapsed after an LOCA	[hrs]	
t_p	Cycle of release to the gap release phase 0.5	[hrs]	
t_{gap}	Time until the start of release in the gap 0.01	[hrs]	
t_{pv}	Cycle of release to the early in-vessel release phase 1.3	[hrs]	
t_{gd}	Release duration in the gap 0.5	[hrs]	
G_{HNO_3}	Effective G value of the production of nitric acid in the liquid phase: 0.007 at 30°C	[molecules/100eV]	
$[HNO_3]_{(t)}$	Concentration of nitric acid in recirculation water at t (hours) after LOCA	[mols/l]	Calculated from Expression 1-10).
$E_{(t)}^\gamma$	Integrated absorbed amount of γ rays in recirculation water from the occurrence of LOCA (0 hours) to t (hours) after that (from an LOCA analysis)	[kGy]	See response to RAI No.420.
$E_{(t)}^\beta$	Total absorbed amount of β rays in recirculation water from the occurrence of an LOCA (0 hours) to t (hours) after that (from an LOCA analysis)	[kGy]	See response to RAI No.420.
G_{HCl}	HCl production G value of γ and β rays to the chlorine-based rubber 2.115	[molecules/100eV]	
S	Total surface area of the cable	[cm ²]	Calculation from Expression 1-13).
R_0	Radius of the cable 1.1304	[cm]	
l	Length of the cable 5.63E6	[cm]	
μ_γ^{air}	Radiation absorption coefficient of γ rays in the air 3.74E-5	[1/cm]	
r	Average distance from the center of the containment to the surface of the cable given that the containment is spherical 2684.1	[cm]	
μ_β^{air}	Radiation absorption coefficient of β rays in the air 0.0198	[1/cm]	

Table 1-1: List of Data Used for pH Analyses (Sheet 2 of 2)

Symbol	Name/Value	Unit	Remarks
th	Thickness of the chlorine-based rubber jacket 0.183	[cm]	
μ_{γ}^R	Radiation absorption coefficient of γ rays in the chlorine-based rubber 0.099	[1/cm]	
$X_{\gamma(t)}$	Integrated absorbed dose in the containment by γ rays from the occurrence of LOCA (0 hours) to t (hours) after that	[MeV/cm ³]	The absorbed dose [kGy] shown in response to RAI No.420 is converted into the unit of [MeV/cm ³].
$X_{\beta(t)}$	Integrated absorbed dose in the containment by β rays from the occurrence of LOCA (0 hours) to t (hours) after that	[MeV/cm ³]	The absorbed dose [kGy] shown in response to RAI No.420 is converted into the unit of [MeV/cm ³].
$M_{HCl}^{\gamma}(t)$	Amount of HCl produced in recirculation water by the contribution by γ rays of the chlorine-based rubber t (hours) after LOCA	[g-mols]	Calculated from Expression 1-18).
$M_{HCl}^{\beta}(t)$	Amount of HCl produced in recirculation water by the contribution by β rays of the chlorine-based rubber t (hours) after LOCA	[g-mols]	Calculated from Expression 1-19).
$[HCl]_{(t)}$	Total concentration of hydrochloric acid in recirculation water at t (hours) after LOCA	[mols/l]	Calculated from Expression 1-20).
$[CsOH]_{t \leq 0.5}$	Concentration of CsOH in recirculation water at t hours (up to half an hour) after LOCA	[mols/l]	Calculated from Expression 1-21).
$[CsOH]_{t > 0.5}$	Concentration of CsOH in recirculation water at t hours (over half an hour) after LOCA	[mols/l]	Calculated from Expression 1-23).
m_{cs}	Cesium inventory of the core 3.9E+3	[g-mols]	
$[H^+]_{(t)}$	Concentration of hydrogen ions produced t hours after LOCA	[mols/l]	Calculated from Expressions 1-24) and 1-26).
$[OH^-]_{(t)}$	Concentration of hydroxide ions produced t hours after LOCA	[mols/l]	Calculated from Expressions 1-25) and 1-27).
λ	Required neutralization concentration ($[H^+]_{(t)} - \lambda * ([OH^-]_{(t)} - \lambda) = K_w(T)$)	[mols/l]	Calculated from Expressions 1-30) and 1-31).
$[H^+]_{final}$	Final concentration of hydrogen ions at a given time t	[mols/l]	Calculated from Expression 1-33).
X	Initial concentration of boric acid in recirculation water 0.39 (4200 ppm as boron)	[mols/l]	
y	Concentration of the pH adjuster 1.42E-2	[mols/l]	
η	Dissolution rate of the pH adjuster	[-]	
K_a	Dissociation constant of boric acid (temperature function) $K_a = 10^{-10 * (0.0585 * F + 1.309)}$ F: °F (9/5 * °C + 32)	[mols/l]	
t_r	Time delay in uniform mixing of the pH adjuster 3.5hr	[hr]	

Impact on DCD

There is no impact on the DCD.

Impact on COLA

There is no impact on the COLA.

Impact on PRA

There is no impact on the PRA.

RESPONSE TO REQUEST FOR ADDITIONAL INFORMATION

7/28/2009

US-APWR Design Certification

Mitsubishi Heavy Industries

Docket No. 52-021

RAI NO.: NO. 416-2912 REVISION 0
SRP SECTION: 06.05.02 – CONTAINMENT SPRAY AS A FISSION PRODUCT CLEANUP SYSTEM
APPLICATION SECTION: 6.5.2
DATE OF RAI ISSUE: 6/29/2009

QUESTION NO.: 06.05.02-6

Background

RAI 06.05.02-2 (Reference 1) requested that the applicant explain how "ineffective pools" in containment will affect the dissolution and retention of fission products (particularly iodine). They were asked to explain the pH of such pools, the concentration of borate, and the concentrations of iodine and other fission products. This explanation was desired because there was concern that the pH control chemical (NaTB) might not reach some of these pools, allowing dissolved iodine to revolatilize and evaporate.

The applicant's response (Reference 2) mentions principal locations where ineffective pools would be located. For one (containment recirculation air distribution chamber), it was stated that a connection to the RWSP would ensure that this region would have a pH identical to the RWSP itself. For other regions, it was stated that bulk pH was lower than re-circulating water. However, a numerical pH was not provided. In reference to the ineffective pools the response also stated, "the surface of these pools would be exposed to re-circulating water." This explanation is unclear to the staff. Does the statement imply that some of the ineffective pools will eventually be diluted by higher-pH containment spray water such that their pH will increase with time? Regarding the distribution of borate in ineffective pools, the staff has reworded its question to clarify that a quantitative response is needed. The applicant does provide a good estimate of the distribution of fission product iodine in the various ineffective pool locations.

Requested Information

1. Define what is meant by "ineffective pools." Provide a more detailed description of all containment locations containing water that do not directly participate in recirculation through containment sprays. Note how they accumulate water. If water volumes are indirectly connected to the RWSP, provide detail on how they are connected (pipe size, expected flow patterns, etc.). Note any volumes that are completely unconnected to the RWSP, but that still could accumulate spray water.
2. For all volumes not directly a part of the RWSP-spray recirculation loop (i.e., those

noted in question 1), provide an estimate of the (time-varying) pH, NaTB concentration, and fission product concentration.

References

1. "Request for Additional Information No. 234-2040 Revision 1, SRP Section: 06.05.02 - Containment Spray as a Fission Product Cleanup System, Application Section: Section 6.5.2" dated February 26, 2009. (ADAMS Accession No. ML0906102970)
 2. Letter from Yoshiki Ogata, MHI, to NRC dated March 24, 2009; Docket No. 52-021 MHI Ref: UAP-HF-09121; Subject: MHI's Response to US-APWR DCD RAI No. 234 (ADAMS Accession No. ML0908502111)
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ANSWER:

This question will be answered later, within 60 days after RAI issue date.

Impact on DCD

There is no impact on the DCD.

Impact on COLA

There is no impact on the COLA.

Impact on PRA

There is no impact on the PRA.