

**Attachment 7**

**Suppression Pool pH and Iodine Re-Evolution Methodology  
Engineering Report GGNS-98-0039, Revision 1**

**GRAND GULF NUCLEAR STATION**

**ENGINEERING REPORT**

**FOR**

**SUPPRESSION POOL PH**  
**AND IODINE RE-EVOLUTION**  
**METHODOLOGY**

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## 1.0 INTRODUCTION

Section 5.2 of NUREG-1465 [1] reports that the re-evolution of iodine can impact the plant radiological analyses if the suppression pool pH drops below a value of 7. Specifically, for those BWRs that credit the long-term retention of iodine in the suppression pool via sprays or pool scrubbing, NUREG-1465 suggests that the maintenance of a pH at or above a level of 7 should be demonstrated. Since BWRs generally do not have a requirement to control post-accident pool pH, the expected pool pH transient has not been evaluated. This report develops a methodology for calculating the suppression pool pH transient using the available NRC research results. This methodology explicitly considers the acids and bases expected to be available in BWR containments under post-accident conditions.

This methodology develops a reasonably bounding negative pH transient for application in radiological analyses in order to quantify (i) the timing requirements for pH control actions, (ii) the required inventories of pH control chemicals, and (iii) as input to the iodine re-evolution calculation in the event the pool pH is uncontrolled. In reality, the pool pH is not anticipated to experience this chemistry transient in the event of a recirculation line break since the EP actions directing operators to flood the containment with outside water sources would result in the significant dilution of any acids in the suppression pool.

Some background on pool pH issues is reported in Section 2. The GGNS model is developed in Section 3 and applied to a sample plant in Section 4. Section 5 develops a method for determining the amount of iodine re-evolution in the event the pool pH is calculated to drop below 7.0. Section 6 lists the references applied in this report.

## 2.0 BACKGROUND

Unlike PWRs, BWRs currently do not have requirements to control post-accident suppression pool pH. PWRs include boric acid in the reactor coolant which introduces a negative pH transient at the onset of the accident and the PWR sump dose rates are an order of magnitude higher than in BWRs as reported in Section 2.2.4 of NUREG/CR-5950 [2] increasing the production rate of nitric acid (as discussed in Section 3.2). BWRs contain a much larger water inventory in the suppression pool since this volume is credited for condensation of the released reactor coolant, thereby suppressing the containment pressurization transient. As a result, the extent of iodine re-evolution can be significantly higher in PWRs. As illustrated in Figure 4.1 of NUREG/CR-5732 [3], an uncontrolled sump pH can result in the re-evolution of nearly 100% of the dissolved iodine in a PWR sump and as much as ~25% in BWR suppression pools. This figure also illustrates that essentially no iodine is re-evolved if the pool pH is controlled.

### 3.0 GGNS MODEL DESCRIPTION

Through basic chemistry relationships, the pH of a solution is directly related to the concentration of  $H^+$  ions by the formulas:

$$pH = -\log ([H^+]) \text{ and } [H^+] \cdot [OH^-] = 10^{-14} \quad (3-0a)$$

where:

$[H^+]$  = concentration of  $H^+$  ions in moles per liter, and  
 $[OH^-]$  = concentration of  $OH^-$  ions in moles per liter.

Therefore, a methodology to calculate the concentration of  $H^+$  ions in the suppression pool will be developed in this section. Equation 3-0a can then be applied to determine the pool pH value.

As discussed in Section 2 of NUREG/CR-5950, a variety of acids and bases are produced in containment during accidents. These chemicals are addressed individually below:

**Boric Acid** is an acid introduced from the reactor coolant system, refueling water storage tanks, and containment sprays. These sources are not borated in BWRs and are consequently not considered in this methodology.

**Hydriodic Acid** is a strong acid introduced into the containment with the release of iodine. As reported in Section 2.2.2 of NUREG/CR-5950 and Section 4.5 of NUREG-1465, no more than 5% of the core iodine inventory is expected to be released from the RCS in this chemical form. As such, the production of this acid is explicitly considered in this methodology.

**Carbon Dioxide** depresses the pH of pure water by absorption. Carbonic acid is a weak acid and is expected to be insignificant compared to other acids produced in containment during an accident. However, the initial pool pH may be depressed below 7.0 during normal operations by the absorption of  $CO_2$ . As such, the effects of carbon dioxide will be considered in the initial condition assumed for pool pH.

**Nitric Acid** is a strong acid produced by the irradiation of water and air during accidents. The production of this acid is explicitly considered in this methodology.

**Hydrochloric Acid** is a strong acid produced by the radiolysis of chloride-bearing insulation during accidents. The production of this acid is explicitly considered in this methodology. The pyrolysis of chloride-bearing insulation produces HCl at temperatures near 572 °F (per Section 2.2.5.3 of NUREG/CR-5950). Since drywell or containment temperatures above 330 °F are not postulated during accidents in BWRs, pyrolysis is not considered in this methodology.

**Cesium Hydroxide** is a strong base introduced into the containment with the release of cesium. The production of this base is explicitly considered in this methodology.

**Core-Concrete Aerosols** are basic materials produced from the interaction of the molten core materials with the concrete containment. Since SECY-94-302 [5] reports that the core damage may be assumed to be arrested after the in-vessel release phase, these chemicals are not considered in this methodology.

### 3.1 Hydriodic Acid Production

Iodine is released from the core as fuel failure occurs. Table 3.12 of NUREG-1465 indicates that 5% of the core halogen inventory is released during the gap release phase while an additional 25% is released during the early in-vessel phase. The core damage is assumed to be arrested after the in-vessel release phase in accordance with the NRC recommendation in SECY-94-302. Consistent with Section 4.5 of NUREG-1465, no more than 5% of the iodine exiting the reactor coolant system will be composed of I and HI. This methodology will conservatively assume that all 5% of this release is in the form of HI in order to maximize the acid generation. This release process is assumed to occur at a constant rate over the release period (*i.e.*, 30 and 90 minutes for the gap and early in-vessel release phases, respectively). The core iodine inventory includes the stable  $I^{127}$  species to maximize the amount of acid produced. The following equations describe this release.

$$\frac{d}{dt}[\text{HI}] = \frac{0.05 * 0.05m_i}{V_{pool} * 0.5 \text{ hr}} \quad (\text{Gap Release Phase}) \quad (3-1a)$$

$$\frac{d}{dt}[\text{HI}] = \frac{0.05 * 0.25m_i}{V_{pool} * 1.5 \text{ hr}} \quad (\text{Early In-Vessel Release Phase}) \quad (3-1b)$$

where:

- $m_i$  = core iodine inventory (gram-mols), and
- $V_{pool}$  = volume of the suppression pool (liters).

A conservatively small pool volume should be applied as generally used in the plant containment thermal-hydraulic analyses. In addition, any changes to the pool volume throughout the duration of the accident should be addressed such as losses due to humidity and ESF leakage and increases from the reactor coolant inventory and any expected pool water supplements. For example, at GGNS, the suppression pool makeup system would automatically transfer water from the upper containment pools into the suppression pool within 30 minutes in the event of a LOCA.

This release can be integrated considering the 1/2-hour BWR gap release duration to yield the following equations during the gap and in-vessel release periods.

$$[\text{HI}](t) = \frac{m_i}{200 * V_{pool}} * (t - t_{gap}) \quad (\text{Gap Release Phase}) \quad (3-1c)$$

$$[\text{HI}](t) = \frac{m_i}{120 * V_{pool}} * [t - (0.5 + t_{gap})] + \frac{m_i}{400 * V_{pool}} \quad (\text{Early In-Vessel Release Phase}) \quad (3-1d)$$

where:

- $t$  = time into accident (hrs), and
- $t_{gap}$  = onset of gap release (hrs).

### 3.2 Nitric Acid Production

Section 2.2.4 of NUREG/CR-5950 reports the experimental results of irradiation-assisted nitric acid production with the following constant:

$$7.3E-6 \frac{\text{mol HNO}_3}{\text{L - Megarad}}$$

Since nitric acid is a strong acid,  $[\text{H}^+]$  and  $[\text{NO}_3^-]$  increase by  $7.3E-6$  for each Megarad received by the pool, the following formula can be developed.

$$\frac{d}{dt}[\text{HNO}_3] = 7.3E-6 \frac{\text{mol HNO}_3}{\text{L - Megarad}} * \dot{X}(t)_{\text{pool}} \quad (3-2a)$$

where:

$\dot{X}(t)_{\text{pool}}$  = the time-dependent dose rate in the suppression pool (Megarads/hr)

The previous equation can be integrated to yield the nitric acid concentration throughout the accident.

$$[\text{HNO}_3](t) = 7.3E-6 \int_0^t \dot{X}(t)_{\text{pool}} dt \quad (3-2b)$$

Since the 30-day suppression pool dose rates generated with TID-14844 source terms have been shown to bound those generated with NUREG-1465 (per Figure 5 of SECY-98-154), EQ dose rates generated by the current TID methods are conservative and acceptable for determining the  $\text{HNO}_3$  production rate.

### 3.3 Hydrochloric Acid Production

The radiolysis of chloride-bearing cable jacketing will result in the production of HCl vapor as reported in Section 2.2.5.2 of NUREG/CR-5950. A model for the production of HCl from cable jacketing is developed in Appendix A based on the approach in NUREG/CR-5950 and concludes the HCl produced from the radiolysis of a cable is predicted by the following formula.

$$[\text{HCl}](t) = \frac{G \cdot m_H \cdot f}{V_{\text{pool}}} \cdot (1 - e^{-\mu \cdot th}) \cdot \int_0^t \dot{X}(t, R_o) dt \quad (3-3a)$$

where:

$G$  = radiation G value for production of HCl ( $2.192E-6$  g-mols HCl/Megarad-g),

$m_H$  = mass of Hypalon =  $\rho_H \cdot \pi \cdot [R_o^2 - (R_o - th)^2] \cdot \ell$ ,

$\rho_H$  = density of Hypalon ( $1.55$  g/cm<sup>3</sup>),

$R_o$  = cable radius (cm),

$th$  = thickness of the Hypalon jacket (cm),

$\ell$  = cable length (cm),

$f$  = average-to-incident radiation flux ratio =  $\frac{\frac{1}{\mu^2} [e^{-\mu \cdot th} (\mu \cdot th + 1) - 1] - \frac{R_o}{\mu} (e^{-\mu \cdot th} - 1)}{R_o \cdot th - \frac{th^2}{2}}$ ,

$\mu$  = linear absorption coefficient for radiation in Hypalon from Table A-1 ( $\text{cm}^{-1}$ ), and  
 $\dot{X}(t, R_o)$  = time-dependent radiation dose rate at the surface of the cable jacket  
 (Megarad/hr).

This methodology considers the effects of cable self-shielding where applicable consistent with the approach in NUREG-1081. The production from both beta and gamma doses should be considered with the appropriate dose rate and linear absorption coefficient. Equation 3-3a can be applied to all cables in the containment to determine the total HCl generation in containment. Dose rates and the cable inventories may vary throughout containment such that local dose rates can be applied to local cable quantities. Although it is anticipated that a significant portion of the HCl produced from cable radiolysis would react with the metal components in the containment (e.g., gratings, etc.), the gaseous HCl will be conservatively assumed to be immediately dissolved in the suppression pool water. In the suppression pool, the HCl concentration is given by:

$$[\text{HCl}](t) = \frac{1}{V_{\text{pool}}} \sum_{\text{all cables}} M_{\text{HCl}}^{\gamma}(t) + M_{\text{HCl}}^{\beta}(t) \quad (3-3b)$$

The following considerations may be used for determining the HCl production from chloride-bearing cable jackets.

1. Consistent with NUREG-0588 [4], Rev. 1, Section 1.4(9), the beta dose to cables arranged in cable trays is reduced by a factor of 2 due to localized shielding by other cables and the cable tray itself.
2. Cables in conduit or totally enclosed raceways will not contribute any HCl to the suppression pool. This assumption is consistent with Section 2.2 of NUREG-1081 and Table 2.2 of NUREG/CR-5950, which does not include the 15% of cables at Fermi that are routed in conduit. These conduits are water-resistant and generally routed between sealed terminal boxes at which the cables terminate or are routed through other conduit. There is no significant driving force for source terms to enter this conduit and any potential diffusion of containment atmosphere into these conduits would be a long-term process occurring after a significant decay time and result in minimal dose rates.

In addition, these cables are shielded from any beta dose from the containment and drywell atmosphere outside the conduit due to the metal conduit structure. Although some HCl production may occur due to gamma radiation from the containment and drywell atmosphere outside the conduit, the limited amounts of gaseous HCl evolved from these cables would most likely react with the metal conduit structure considering the tortuous path out of the conduit and therefore is assumed to not enter the suppression pool.

3. Since the airborne dose rates generated with TID-14844 source terms have been shown to bound those generated with NUREG-1465 in SECY-98-154 [6], EQ dose rates generated by the current TID methods are acceptable in determining the HCl evolution rate.

### 3.4 Cesium Hydroxide Production

Cesium is released from the core as fuel failure occurs. Table 3.12 of NUREG-1465 indicates that 5% of the core alkali metal inventory (including cesium) is discharged during the gap release phase while an additional 20% is discharged during the early in-vessel phase. The core damage is assumed to be arrested after the in-vessel release phase in accordance with the NRC recommendation in SECY-94-302. For iodine, Table 3.12 of NUREG-1465 indicates that 5% of the core halogen inventory is discharged during the gap release phase while an additional 25% is discharged during the early in-vessel phase.

Consistent with Section 4.5 of NUREG-1465, the iodine exiting the reactor coolant system will be composed of at least 95% cesium iodide (CsI). These cesium and iodide inventories include the stable isotopes of  $I^{127}$  and  $Cs^{133}$ . The cesium that is not in the chemical form of CsI is assumed to exit the RCS in the form of cesium hydroxide (CsOH) and be deposited into the suppression pool<sup>1</sup>. This CsOH inventory is illustrated in Figure 3-1 below.

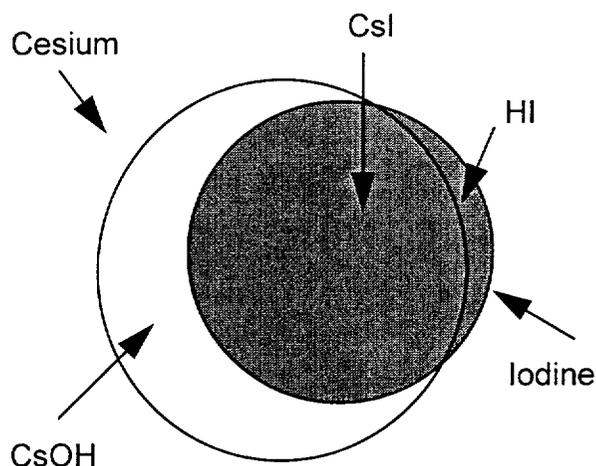


Figure 3-1 CsOH Inventory Assumption

Both the cesium and iodine core inventories grow throughout the cycle with the cesium inventory increasing significantly. Therefore, the EOC core exposure will result in the largest CsOH release. Although a BOC exposure may result in a reduced CsOH release and lower pool pH, the core source term inventory, pool iodine concentration, EQ dose rates, and core decay heat would all be lower at this BOC exposure. Since the radiological analyses are based on EOC conditions, the EOC core source terms for cesium and iodine are considered appropriate for the pool pH analysis.

This release process is assumed to occur at a constant rate over the release period (*i.e.*, 30 and 90 minutes for the gap and early in-vessel release phases, respectively). The following equations describe this release.

<sup>1</sup> Although, in reality, some CsOH may remain airborne in the containment, this assumption is expected to be sufficiently conservative when taken in conjunction with the assumption in Section 3.3 that all HCl evolved from cable radiolysis immediately enters the pool. Considering the hygroscopic nature of CsOH and its release in the vicinity of the suppression pool, the probability of CsOH migrating to the pool is considered higher than that of HCl produced from cable radiolysis in locations that may be some distance from the pool and are likely to contain large metal surface areas.

$$\frac{d}{dt}[\text{CsOH}] = \frac{0.05m_{\text{Cs}} - 0.95 * 0.05m_I}{V_{\text{pool}} * 0.5 \text{ hr}} \quad (\text{Gap Release Phase}) \quad (3-4a)$$

$$\frac{d}{dt}[\text{CsOH}] = \frac{0.2m_{\text{Cs}} - 0.95 * 0.25m_I}{V_{\text{pool}} * 1.5 \text{ hr}} \quad (\text{Early In-Vessel Release Phase}) \quad (3-4b)$$

where:

$$m_{\text{Cs}} = \text{core cesium inventory (gram-mols)}^2.$$

This release can be integrated considering the 1/2-hour BWR gap release duration to yield the following equations during the gap and in-vessel release periods.

Gap Release Phase:

$$[\text{CsOH}](t) = \frac{0.1m_{\text{Cs}} - 0.095m_I}{V_{\text{pool}}} * (t - t_{\text{gap}}) \quad (3-4c)$$

Early In-Vessel Release Phase:

$$[\text{CsOH}](t) = \frac{0.4m_{\text{Cs}} - 0.475m_I}{3 * V_{\text{pool}}} * [t - (0.5 + t_{\text{gap}})] + \frac{0.05m_{\text{Cs}} - 0.0475m_I}{V_{\text{pool}}} \quad (3-4d)$$

### 3.5 Summary

The combined effects of the acids and bases that occur during BWR accidents can be calculated as a function of time and initial pool pH with the formulas in Equation 3-0a by separating the acid and base generation terms.

$$\begin{aligned} [\text{H}^+](t) &= [\text{H}^+](t=0) + \int_0^t \frac{d}{dt}[\text{HI}](t)dt + \int_0^t \frac{d}{dt}[\text{HNO}_3](t)dt + \int_0^t \frac{d}{dt}[\text{HCl}](t)dt \\ &= 10^{-\text{pH}_0} + \int_0^t \frac{d}{dt}[\text{HI}](t)dt + \int_0^t \frac{d}{dt}[\text{HNO}_3](t)dt + \int_0^t \frac{d}{dt}[\text{HCl}](t)dt \end{aligned} \quad (3-5a)$$

$$[\text{OH}^-](t) = [\text{OH}^-](t=0) + \int_0^t \frac{d}{dt}[\text{CsOH}](t)dt = \frac{10^{-14}}{10^{-\text{pH}_0}} + \int_0^t \frac{d}{dt}[\text{CsOH}](t)dt \quad (3-5b)$$

where:

- pH<sub>0</sub> is the initial pool pH value,
- [HI](t) is given in Equations 3-1c and 3-1d,
- [HNO<sub>3</sub>](t) is given is Equation 3-2b,
- [HCl](t) is given in Equation 3-3b, and
- [CsOH](t) is given in Equations 3-4c and 3-4d.

<sup>2</sup> Since cesium is being credited for a beneficial effect, a conservatively small cesium iodide inventory should be applied.

Some of the generated  $H^+$  ions will be neutralized with the  $OH^-$  ions such that Equation 3-0a will be true at the final conditions.

$$([H^+] - x) \cdot ([OH^-] - x) = 10^{-14} \quad (3-5c)$$

Solving for  $x$  leads to the final  $H^+$  concentration of:

$$[H^+]_{final} = [H^+] - x = [H^+] - \frac{[OH^-] + [H^+] - \sqrt{([OH^-] + [H^+])^2 - 4 \cdot ([OH^-] \cdot [H^+] - 10^{-14})}}{2} \quad (3-5d)$$

The pool pH can then be directly calculated from Equation 3-0a as

$$pH = -\log([H^+]_{final}) \quad (3-5e)$$

## 4.0 SAMPLE PH CALCULATION

This section develops a sample calculation applying the methodologies developed in Sections 3 with the following input parameters.

### Sample Case:

The pH transient for a BWR with a suppression pool water volume of 3.5E6 liters is evaluated based on an initial pH value of 6.0. This plant has 100,000 pounds of chloride-bearing cable insulation in containment, of which 50% is run in conduit and the remainder is in cable trays. All this cable is identical to the NRC model cable in Appendix A. The core inventories of cesium and iodine have been calculated to be 2500 (minimum) and 200 (maximum) gram mols, respectively. The BWR generic gap release time is 121 seconds and the TID integrated doses calculated for GGNS in SECY-98-154 are applicable.

### Solution:

This sample can be solved on a spreadsheet with the formulas summarized in Section 3.5. The results are illustrated in Figure 5-1 and reported in Attachment 1. Another case assuming 200,000 lbs of cable insulation is also shown for comparison. The final results can be checked as follows.

The initial  $H^+$  concentration (in gram-mols per liter) can be determined from the initial pool pH as  $1.0E-6$  from Equation 3-0a. From Section 3.1, 5% of the released iodine is assumed to enter the pool as HI. With 30% of the core iodine inventory released, the HI concentration can be calculated as  $8.5714E-7$ .

$$[HI]_{final} = \frac{0.05 * 0.3 * m_i}{V_{pool}} = \frac{0.05 * 0.3 * 200}{3.5E6} = 8.5714E - 7$$

From Section 3.2, the final  $HNO_3$  concentration can be calculated from the final integrated sump dose as  $1.8728E-5$ .

$$[HNO_3]_{final} = 7.3E - 6 * \int_0^{720} \dot{X}(t)_{pool} dt = 7.3E - 6 * 2.57 = 1.8728E - 5$$

From Appendix A, the HCl generation from the NRC model cable is given as  $5.55E-4$  mols HCl per lb of insulation per Megarad. The HCl concentration can then be calculated from the final integrated airborne dose. Neglecting the cable in conduit and reducing the beta dose by a factor of two for the 50,000 pounds of cable run in trays, the HCl concentration can be calculated to be  $7.2740E-5$ .

$$[HCl]_{final} = \frac{5.55E - 4 * M_{cable} * \left[ 0.112 * 0.5 * \int_0^{720} \dot{X}_\beta(t) dt + 0.0179 * 0.991 * \int_0^{720} \dot{X}_\gamma(t) dt \right]}{3.5E6}$$

$$= \frac{5.55E - 4 * 50,000 * [0.112 * 0.5 * 160.4 + 0.0179 * 0.991 * 10.77]}{3.5E6} = 7.2740E - 5$$

From Section 3.4, 95% of the released iodine is assumed to enter the pool as CsI with the remainder of the cesium as CsOH. With 25% of the core cesium inventory released, the CsOH concentration can be calculated as 1.62286E-4.

$$[\text{CsOH}]_{\text{final}} = \frac{0.25 * m_{\text{Cs}} - 0.95 * 0.3 * m_{\text{I}}}{V_{\text{pool}}} = \frac{0.25 * 2500 - 0.95 * 0.3 * 200}{3.5\text{E}6} = 1.62286\text{E} - 4$$

The total  $\text{H}^+$  concentration is the sum of the previous results.

$$[\text{H}^+]_{\text{calc}} = 1\text{E} - 6 + 8.5714\text{E} - 7 + 1.8728\text{E} - 5 + 7.2740\text{E} - 5 = 9.33247\text{E} - 5$$

$$[\text{OH}^-]_{\text{calc}} = 1\text{E} - 14 / 1\text{E} - 6 + 1.62286\text{E} - 4 = 1.62296\text{E} - 4$$

The final pH is determined with the neutralized portion,  $x$ , calculated with Equation 3-5d to be 9.33246E-5. The pH can then be calculated to be 9.839.

$$\text{pH} = -\log([\text{H}^+]_{\text{calc}} - 9.33246\text{E} - 5) = -\log(1.44988\text{E} - 10) = 9.839$$

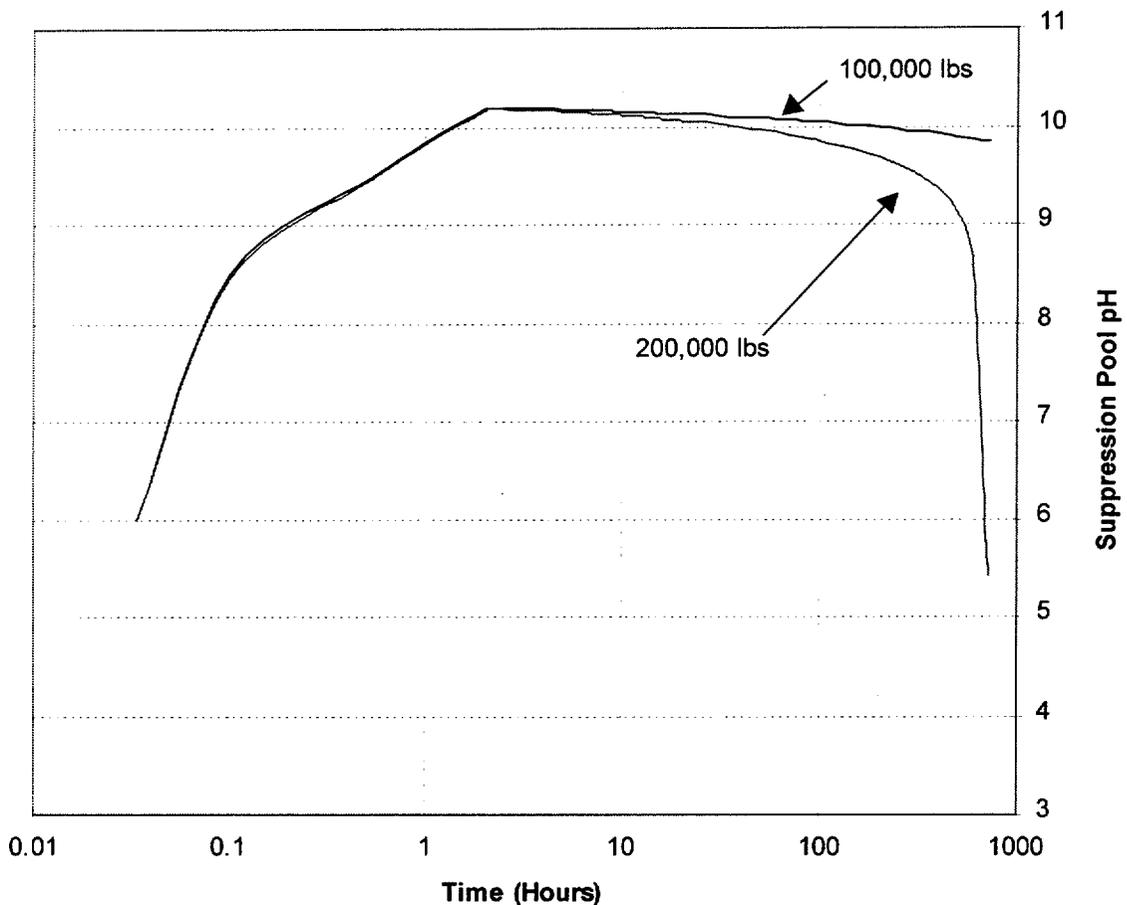


Figure 4-1 Sample Results

## 5.0 IODINE RE-EVOLUTION

As shown in Figure 4-1, the pool pH may drop below a value of 7 depending on plant-specific parameters such as the plant cable inventory or pool volume. This section develops a methodology for determining the amount of iodine that may evolve from a pool with a pH less than 7 based on the NRC research in NUREG/CR-5950. Specifically, an equation describing the equilibrium concentration of elemental iodine in the air volume above the pool is developed as a function of the pool pH, temperature, and iodine concentration.

### 5.1 Methodology

Aqueous iodine will exist in water pools in both I<sup>-</sup> and I<sub>2</sub> species. Appendix C of NUREG/CR-5950 derives the following relationship between the dissolved iodine ions [I<sup>-</sup>] and the aqueous I<sub>2</sub> concentration.

$$[I_2]_{aq} = \frac{[H^+]^2 [I^-]_{aq}^2}{d + e[H^+]} \quad (5-1)$$

where:

- [I<sub>2</sub>] = concentration of elemental iodine (g-moles/liter)
- d = 6.05E-14 ± 1.83E-14
- e = 1.47E-09
- [H<sup>+</sup>] = concentration of H<sup>+</sup> ion (g-moles/liter)
- [I<sup>-</sup>] = concentration of ionic iodine (g-moles/liter)

In order to maximize the amount of I<sub>2</sub> in solution (and consequently the amount in the gas phase), the conservative value of the "d" parameter should be the lower of the specified range or 4.22E-14. Although these values are based experimental data at 25 °C, Appendix C of NUREG/CR-5950 indicates that this model conservatively over-predicts the conversion to I<sub>2</sub> at higher temperatures.

The total iodine concentration in the pool is given by the following expression per Section 3.2 of NUREG/CR-5950 and would include the non-radioactive isotope of iodine (*i.e.*, I<sup>127</sup>).

$$[I]_{aq} = 2 * [I_2]_{aq} + [I^-]_{aq} \quad (5-2)$$

where:

- [I]<sub>aq</sub> = total iodine concentration (g-atoms/liter)<sup>3</sup>

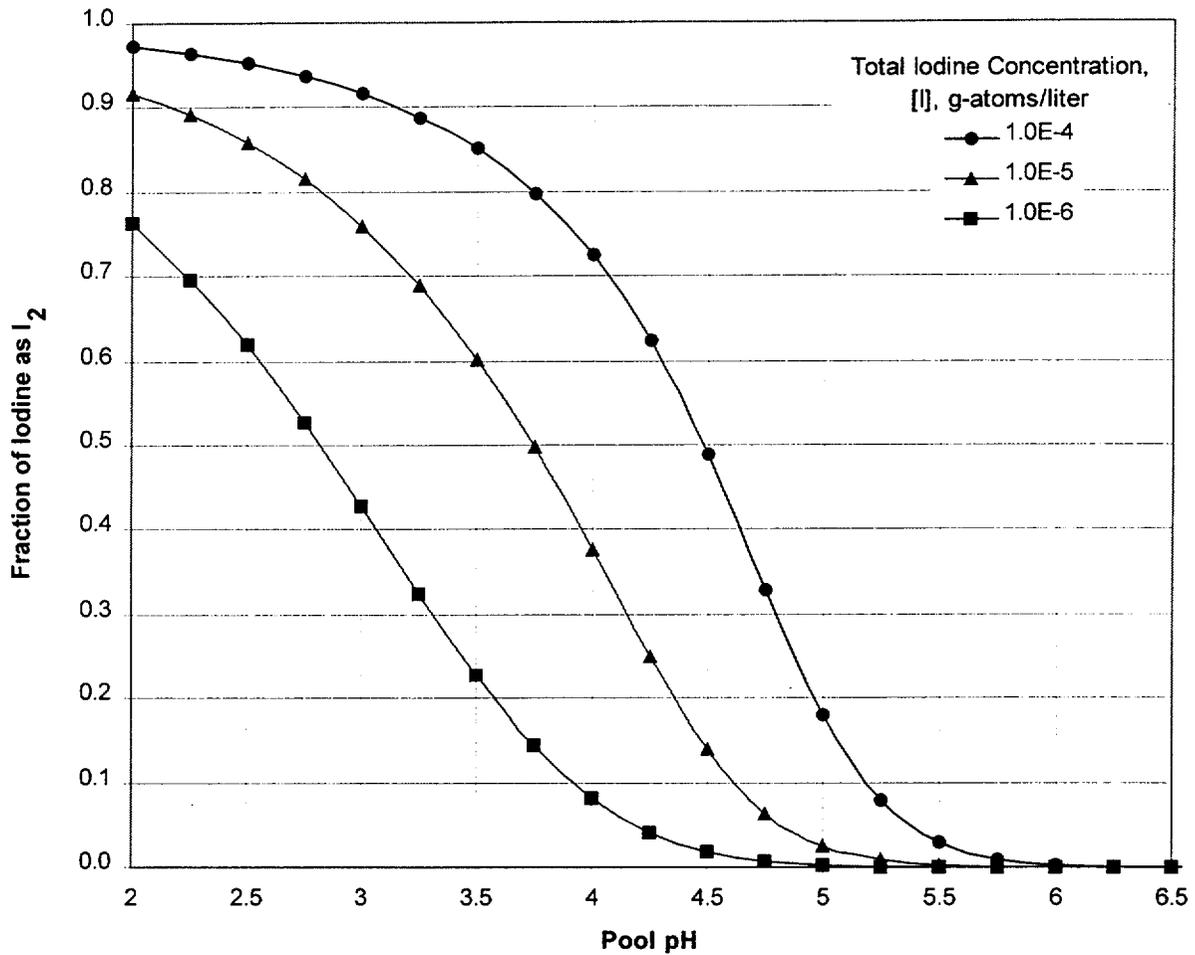
<sup>3</sup> As described in Section 3.2 of Reference 5, it is convenient to use g-atom rather than mol in aqueous radioactive iodine concentrations because I<sub>2</sub> contains 2 g-atom I per mol while I<sup>-</sup> contains only 1 g-atom. For each radioactive isotope of iodine, the total iodine concentration in g-atoms/liter can be calculated from the activity and pool volume as:

$$[I]_{aq} = \frac{A_i (Ci) * 3.7E10 \frac{atoms}{Ci - s}}{\lambda_i (s^{-1}) * 6.022E23 \frac{atoms}{g - atom} * Vol(liters)}$$

Eliminating the variable for the ionic iodine parameter [I<sup>-</sup>] and considering that [H<sup>+</sup>]=10<sup>-pH</sup>, the following equation relates the aqueous I<sub>2</sub> concentration to the pool pH and the total iodine concentration [I].

$$[I_2]_{aq} = \frac{[I]_{aq}}{2} + \frac{d + e10^{-pH}}{8 * 10^{-2pH}} - \frac{1}{8 * 10^{-pH}} \sqrt{\frac{(d + e10^{-pH})^2}{10^{-2pH}} + 8[I]_{aq} * (d + e10^{-pH})} \quad (5-3)$$

Applying the nominal value of the "d" parameter of 6.05E-14, the fraction of iodine in the I<sub>2</sub> species (i.e., 2[I<sub>2</sub>]/[I]) can be determined as a function of pH for various total iodine concentrations, [I]. The results are plotted below and are identical to those presented in Figure 3.1 of NUREG/CR-5950.



**Figure 5-1 Benchmark Model Results for Aqueous Iodine**

Considering the non-linear behavior of this Equation 5-3, the aqueous I<sub>2</sub> concentration for each isotope cannot merely be calculated individually for each isotope, but must be calculated based on the total iodine concentration. For example, the total aqueous iodine concentration for the isotopic concentrations reported in Table 5-1 is 8E-6 g-atoms/L. Based on this total iodine

concentration, Equation 5-3 predicts a total aqueous  $I_2$  concentration of  $3.63E-6$  g-mols/L at a pool pH of 4 while, if this concentration were calculated for each isotope and summed, a total aqueous  $I_2$  concentration of  $3.417E-6$  g-mols/L would be predicted as shown in Table 5-1.

**Table 5-1 Example Isotopic Distribution**

Isotope	Aqueous Concentration (g-atoms/L)	Isotopic $I_2$ Concentration based on Eq. 4-1 (g-mols/L) at pH of 4
I-131	5E-6	2.21E-6
I-132	1E-6	3.81E-7
I-133	2E-6	8.26E-7
Totals	8E-6	3.417E-6

Consequently, the total pool iodine concentration (including the stable isotope I-127) should be applied to calculate the total aqueous  $I_2$  concentration. For the case above, since the I-131 is 62.5% of the pool iodine inventory, the  $I_2^{131}$  concentration in the pool would be  $2.27E-6$  g-mols/L (62.5% of  $3.63E-6$  g-mols/L) instead of the  $2.21E-6$  concentration based on only the I-131 concentration. The isotopic distribution for this example is listed in Table 5-2.

**Table 5-2 Applied Aqueous Isotopic Distribution**

Isotope	Percent of Pool Iodine	Isotopic $I_2$ Concentration (g-mols/L) at pH of 4
I-131	62.5	2.27E-6
I-132	12.5	4.54E-7
I-133	25	9.08E-7
Totals	100	3.63E-6

Section 3.1 of NUREG/CR-5950 cautions that the data at very low iodine concentrations ( $< \sim 10^{-6}$  g-atom/L) are less reliable due to the formation of iodate. Fortunately, at these low concentrations, there is little iodine available for re-evolution.

## 5.2 Partition Coefficient

The gaseous concentration of iodine above the pool can be determined from the aqueous concentration of iodine in the pool via the partition coefficient (PC). The iodine partition coefficient is defined in Section 3.3.1 of NUREG/CR-5950 as:

$$PC = \frac{[I_2]_{aq}}{[I_2]_{gas}} = 10^{6.29 - 0.0149T} \quad (5-4)$$

where

$T$  = pool temperature (Kelvin)

$[I_2]_{aq}$  = the iodine concentration in the pool (g-moles/liter)

$[I_2]_{gas}$  = the iodine concentration in the air (g-moles/liter)

The temperature dependence of the iodine partition factor is illustrated below. As the pool temperature increases the iodine partition factor decreases, driving the iodine into the airborne phase.

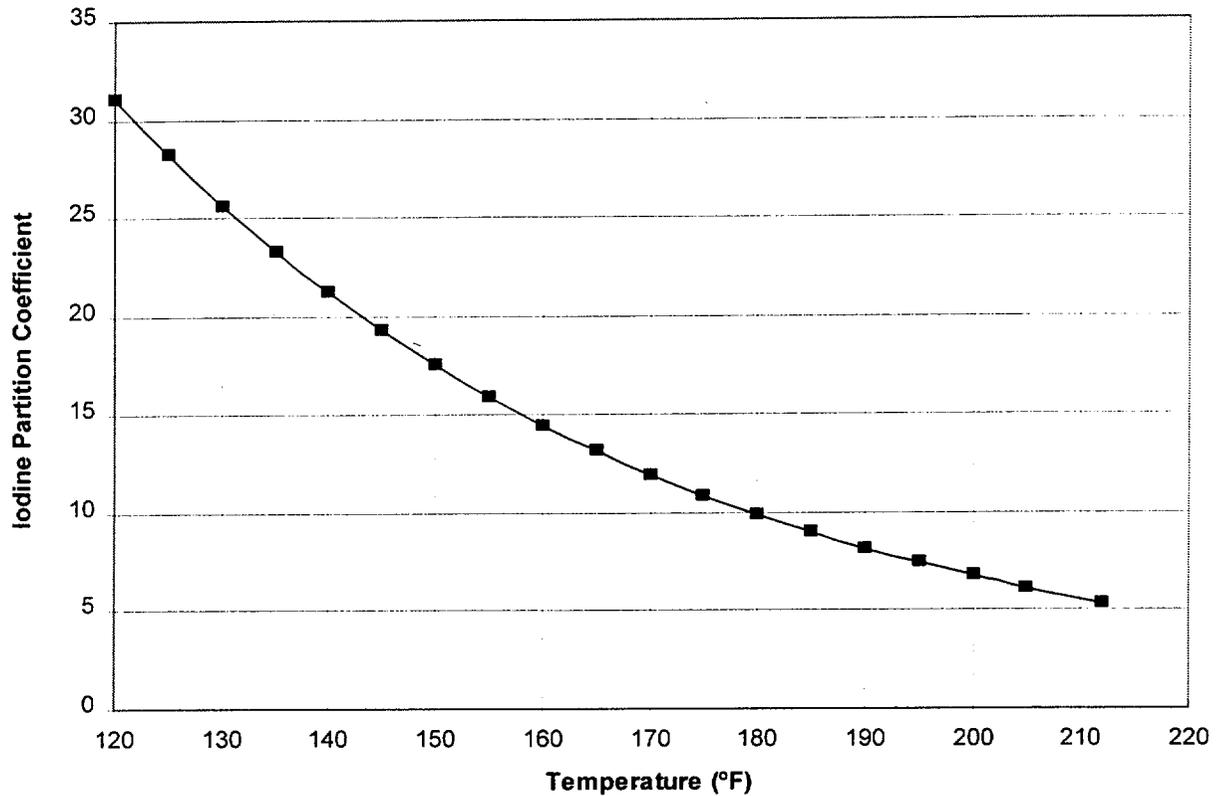


Figure 5-2 Iodine Partition Coefficient versus Temperature

### 5.3 Governing Formula

Combining Equations 5-3 and 5-4, the equilibrium concentration of iodine in the gaseous phase can be determined from the pool pH and temperature, and total aqueous iodine concentration as follows:

$$[I_2]_{gas} = \frac{[I_2]_{aq}}{PC} = \frac{\frac{[I]_{aq}}{2} + \frac{d + e^{10^{-pH}}}{8 * 10^{-2pH}} - \frac{1}{8 * 10^{-pH}} \sqrt{\frac{(d + e^{10^{-pH}})^2}{10^{-2pH}} + 8[I]_{aq} * (d + e^{10^{-pH}})}}{10^{6.29 - 0.0149T}} \quad (5-5)$$

where:

$[I_2]_{gas}$  = iodine concentration in the air above the pool (g-moles/liter)

$[I]_{aq}$  = total iodine concentration in the pool (g-atoms/liter)

pH = pool pH

$d$  = 4.22E-14

$e$  = 1.47E-09

$T$  = pool temperature (K)

Any differences in vapor pressure among the iodine isotopes in the pool are assumed to be negligible based on the relatively small differences in atomic weight. This assumption is conservative since the iodine isotopes with the relatively lower weights are I-127 and I-129 which have little or no dose consequences. As such, the iodine isotopic distribution in the gaseous phase above the pool can be assumed to be identical to the isotopic distribution in the pool.

## 6.0 REFERENCES

1. NUREG-1465, Accident Source Terms for Light-Water Nuclear Power Plants, dated February 1995.
2. NUREG/CR-5950, Iodine Evolution and pH Control, dated December 1992.
3. NUREG/CR-5732, Iodine Chemical Forms in LWR Severe Accidents, dated April 1992.
4. NUREG-0588, Interim Staff Position on Environmental Qualification of Safety-Related Electrical Equipment, dated July 1981.
5. SECY-94-302, "Source Term-Related Technical and Licensing Issues Pertaining to Evolutionary and Passive Light-Water-Reactor Designs", dated December 19, 1994.
6. SECY-98-154, "Results of the Revised (NUREG-1465) Source Term Rebaselining for Operating Reactors", dated June 30, 1998.

## APPENDIX A - HYDROCHLORIC ACID PRODUCTION MODEL

The evolution of gaseous HCl from chloride-bearing cable is described in Section 2.2.5.2 of NUREG/CR-5950 [A-1]. Based on this description and the production model in Appendix B to NUREG/CR-5950, this appendix develops a generic methodology for calculating the HCl production rate for cables based on the individual cable dimensions.

### A.1 Model Cable

The NRC's model for a cable is illustrated in Figure A-1. It is a 600-volt reactor power cable consisting of a copper core with ethylene-propylene rubber (EPR) elastomer insulation and a chloro-sulfonated polyethylene rubber (Hypalon) jacket. The dimensions are illustrated in Figure A-1 which is repeated from Section 4.2 of NUREG-1081 [A-2]. The material properties of the cable components are listed in Table A-1 as reported in Section 4.2 of NUREG-1081. This model was originally reported in NUREG/CR-1237 [A-3] and has been referenced in NUREG-1081 and Appendix B to NUREG/CR-5950. The chloride-bearing component of this cable is the Hypalon jacket which is 27 weight percent chlorine per Section 2.2.5.1 of NUREG/CR-5950.

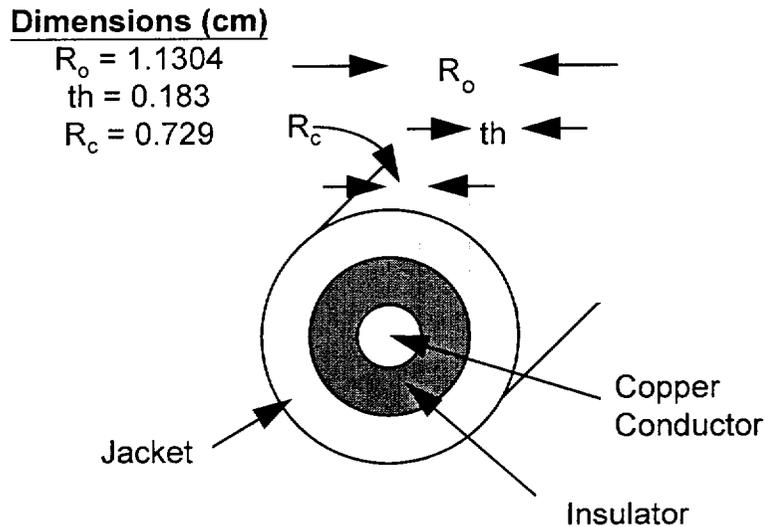


Figure A-1 NRC Cable Model

Table A-1 Cable Material Properties

Material	Density (g/cm <sup>3</sup> )	Linear Absorption Coefficient (cm <sup>-1</sup> )	
		Beta Radiation	Gamma Radiation
Hypalon	1.55	52.08	0.099
EPR	1.27	42.67	0.081

### A.2 GGNS DETAILED MODEL

For the cable illustrated in Figure A-1, the attenuation of a radiation flux at a radius,  $r$ , can be described from basic principles as:

$$\phi(r) = \phi(R_o)e^{-\mu(R_o-r)}$$

where:

- $\mu$  = linear absorption coefficient (from Table A-1), and  
 $R_o$  = outside cable radius.

Similar to the approach in Appendix B to NUREG/CR-5950, the production of HCl from radiolysis can be given by the following formula.

$$R = G \cdot S \cdot \bar{\phi} \cdot A \quad (A-1)$$

where:

- $R$  = HCl production rate  
 $G$  = radiation G value for Hypalon,  
 $S$  = surface area of cable,  
 $\bar{\phi}$  = average radiation energy flux in the Hypalon jacket<sup>4</sup>, and  
 $A$  = absorption fraction of energy flux in the Hypalon jacket.

### Radiation G Value

The radiation G value for Hypalon adopted in Section 2.2.5.2 of NUREG/CR-5950 is 2.115 molecules HCl per 100 eV<sup>5</sup>. This value corresponds to 3.512E-20 g-mols HCl/MeV and represents a balance between the increased HCl production at elevated temperatures expected during accidents and the neutralization potential of fillers in the cable.

### Cable Surface Area

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

$$S = 2\pi \cdot R_o \cdot \ell \quad (A-2)$$

where:

- $S$  = cable surface area (cm<sup>2</sup>),  
 $R_o$  = cable radius (cm), and  
 $\ell$  = cable length (cm).

### Average Energy Flux

With the linear absorption coefficient, the resulting radiation flux can be calculated through the jacket as illustrated for beta radiation in Figure A-2. The average flux to the jacket can then be calculated based on the jacket thickness,  $t_h$ , and the outside cable radius,  $R_o$  by integration.

<sup>4</sup> Energy flux in the insulator need not be considered since this component does not contain chlorine.

<sup>5</sup> This G value is based on the energy absorbed by the polymer consistent with the footnote to Table 3 of NUREG-1081.

$$\bar{\phi}(th) = \frac{\int_{R_o}^{R_o-th} \phi(r) \cdot 2\pi r dr}{\int_{R_o}^{R_o-th} 2\pi r dr} = \frac{\int_{R_o}^{R_o-th} \phi(R_o) e^{-\mu(R_o-r)} \cdot 2\pi r dr}{\int_{R_o}^{R_o-th} 2\pi r dr} \Rightarrow \frac{\bar{\phi}(th)}{\phi(R_o)} = \frac{\frac{1}{\mu^2} [e^{-\mu \cdot th} (\mu \cdot th + 1) - 1] - \frac{R_o}{\mu} (e^{-\mu \cdot th} - 1)}{R_o \cdot th - \frac{th^2}{2}} \quad (A-3)$$

For the NRC's model cable where  $R_o=1.1304$  cm and  $th=0.183$  cm, the above equation would predict an average beta flux in the Hypalon jacket of 11.2% of the surface beta flux as illustrated in Figure A-2. For gamma radiation, the average flux is 99.1% of the surface flux due to the smaller linear absorption coefficient (per Table A-1). This result is also consistent with the conclusion in Section 4.2 of NUREG-1081 that the radiolysis of the insulator by beta radiation is negligible.

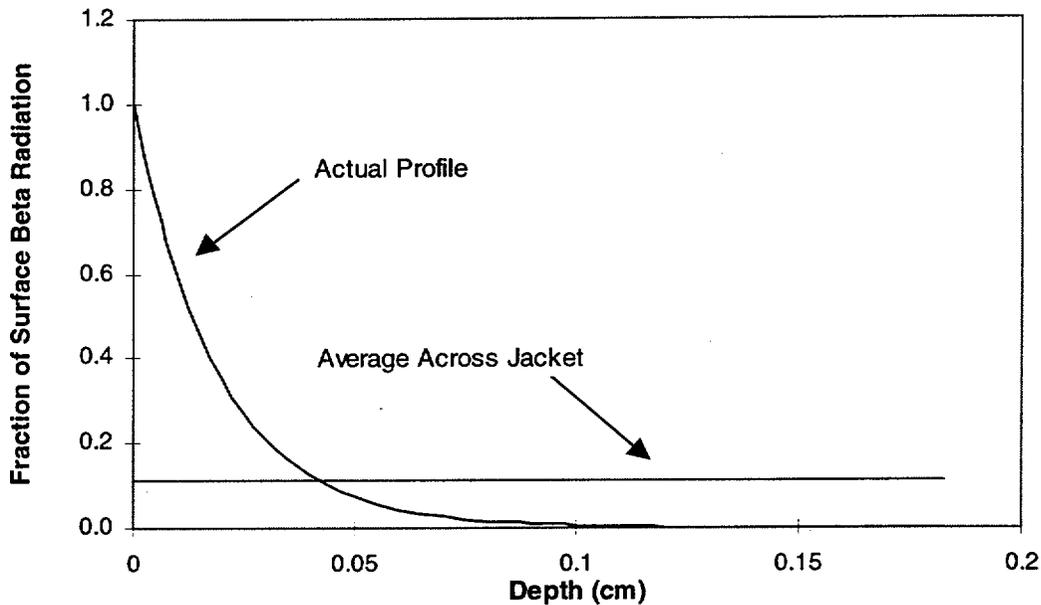


Figure A-2 Model Cable Beta Dose Profile

**Absorption Fraction**

The absorption fraction is the fraction of incident radiation energy flux absorbed by the Hypalon. As shown above, this factor is nearly 1.0 for beta radiation and very small for gamma radiation. As reported in Section 4 of NUREG-1081, this factor is calculated with the following equation.

$$A = 1 - e^{-\mu \cdot th} \quad (A-4)$$

**HCl Generation**

The HCl generation rate can be calculated with Equations A-1, A-2, A-3, and A-4 as:

$$R = G \cdot S \cdot \bar{\phi} \cdot A = 3.512E20 \cdot 2\pi \cdot R_o \cdot \ell \cdot \phi(R_o) \cdot \frac{1}{\mu^2} \left[ e^{-\mu th} (\mu \cdot th + 1) - 1 \right] - \frac{R_o}{\mu} (e^{-\mu th} - 1) \cdot (1 - e^{-\mu th}) \cdot \left( R_o \cdot th - \frac{th^2}{2} \right) \quad (A-5)$$

where:

- R = HCl production rate (g mols/s),
- $\phi(R_o)$  = radiation energy flux at the surface of the cable jacket (MeV/cm<sup>2</sup>-s),
- $\mu$  = linear absorption coefficient in Hypalon,
- $\ell$  = cable length (cm),
- th = thickness of the Hypalon jacket (cm), and
- $R_o$  = cable radius (cm).

### Conversion to Rads

The available EQ dose rates at the surface of equipment are generally reported in the terms of Megarads/hr. The number of rads can be calculated based on the definition of a rad as 100 ergs of absorbed energy per gram of exposed material.

The radiation G value can be converted to Megarads as follows:

$$G = 3.512E-20 \frac{\text{mols}}{\text{MeV}} \cdot 6.24146E5 \frac{\text{MeV}}{\text{erg}} \cdot 100 \frac{\text{ergs}}{\text{Rad-g}} \cdot 10^6 \frac{\text{Rads}}{\text{Megarad}} = 2.192E-6 \frac{\text{mols}}{\text{Megarad-g}}$$

Since the entire jacket thickness is assumed to be exposed to the average dose rate, the entire jacket mass is considered in this calculation. The mass of Hypalon (g) in a segment of cable of length  $\ell$  cm is calculated as:

$$m_H = \rho_H \cdot \pi \cdot \left[ R_o^2 - (R_o - th)^2 \right] \cdot \ell$$

where:

- $\rho_H$  = density of Hypalon (1.55 g/cm<sup>3</sup> per Table A-1).

The HCl production from a cable from radiation can be finally summarized as:

$$R = G \cdot \rho_H \cdot \pi \cdot \left[ R_o^2 - (R_o - th)^2 \right] \cdot \ell \cdot \phi(R_o) \cdot \frac{1}{\mu^2} \left[ e^{-\mu th} (\mu \cdot th + 1) - 1 \right] - \frac{R_o}{\mu} (e^{-\mu th} - 1) \cdot (1 - e^{-\mu th}) \cdot \left( R_o \cdot th - \frac{th^2}{2} \right) \quad (A-6)$$

where:

- $R$  = HCl production rate (g mols/hr),
- $G$  = 2.192E-6 g-mols HCl/Megarad-g,
- $\rho_H$  = density of Hypalon (1.55 g/cm<sup>3</sup>),
- $R_o$  = cable radius (cm),
- $th$  = thickness of the Hypalon jacket (cm),
- $\dot{X}(R_o)$  = radiation dose rate at the surface of the cable jacket (Megarad/hr),
- $\mu$  = linear absorption coefficient for radiation in Hypalon (from Table A-1), and
- $\ell$  = cable length (cm).

Equation A-6 can be integrated to determine the total HCl generated from an integrated dose.

$$M_{HCl} = G \cdot \rho_H \cdot \pi \cdot [R_o^2 - (R_o - th)^2] \cdot \ell \cdot \frac{1}{\mu^2} \left[ e^{-\mu \cdot th} (\mu \cdot th + 1) - 1 \right] - \frac{R_o}{\mu} (e^{-\mu \cdot th} - 1) \cdot (1 - e^{-\mu \cdot th}) \cdot \int_0^{\ell} \dot{X}(t, R_o) dt \quad (A-7)$$

where:

- $M_{HCl}$  = Total HCl production (g mols).

### A.3 SAMPLE CALCULATION

As a test of this methodology, the HCl production is calculated from an integrated beta dose of 8.93 Megarads at the surface of a 1-cm segment of the NRC model cable.

Solution:

For a cable segment of 1-cm, the weights of Hypalon and EPR can be calculated based on the cable geometry and the densities reported in Figure A-1. This 1-cm cable segment contains 3.31 grams (7.3E-3 pounds) of cable insulation (jacket and insulator only - no conductor).

Hypalon:

$$m_H = \rho \cdot \pi [R_o^2 - (R_o - t)^2] \cdot \ell = 1.55 \frac{\text{g}}{\text{cm}^3} \cdot 3.1416 \cdot [(1.1304 \text{ cm})^2 - (0.9474 \text{ cm})^2] \cdot 1 \text{ cm} = 1.85 \text{ g}$$

EPR:

$$m_E = \rho \cdot \pi [R_o^2 - (R_o - t)^2] \cdot \ell = 1.27 \frac{\text{g}}{\text{cm}^3} \cdot 3.1416 \cdot [(0.9474 \text{ cm})^2 - (0.729 \text{ cm})^2] \cdot 1 \text{ cm} = 1.46 \text{ g}$$

Total:

$$(1.85 \text{ g} + 1.46 \text{ g}) \cdot \left( \frac{\text{kg}}{1000 \text{ g}} \right) \cdot \left( \frac{2.205 \text{ lbs}}{\text{kg}} \right) = 7.30\text{E} - 3 \text{ lbs}$$

As calculated in Section A.2, the average beta dose in the Hypalon jacket is calculated to be 11.2% of the surface dose rate or 1 Megarad. For a 1-cm cable segment, the amount of HCl produced is calculated to be 4.055E-7 gram mols.

$$R = \left( 2.192E - 6 \frac{\text{mols}}{\text{Megarad-g}} \right) \cdot (1.85 \text{ g}) \cdot (1 \text{ Megarad}) \cdot \left( 1 - e^{(-52.08 \text{ cm}^{-1})(0.183 \text{ cm})} \right) = 4.055E - 7 \text{ mols}$$

Considering that this segment is 7.3E-3 pounds of insulation, a rate constant of 5.55E-4 g-mols of HCl per pound of insulation per Megarad of absorbed dose can be calculated for the NRC model cable. This result compares well with (and is conservative with respect to) the 4.6E-4 value reported in Section 2.2.5.2 of NUREG/CR-5950.

$$\frac{4.055E - 7 \text{ mols}}{(7.3E - 3 \text{ lbs})(1 \text{ Megarad absorbed})} = \frac{5.55E - 4 \text{ mols HCl}}{\text{lb of insulation - Megarad absorbed dose}}$$

#### A.4 REFERENCES

- A-1 NUREG/CR-5950, Iodine Evolution and pH Control, dated December 1992.
- A-2 NUREG-1081, Post-Accident Gas Generation from Radiolysis of Organic Materials, dated September 1984.
- A-3 NUREG/CR-1237, Best-Estimate LOCA Radiation Signature, dated January 1980.

# ATTACHMENT 1 - SAMPLE CASE RESULTS

Containment Cable Inventory = 100,000 lbs

Time (hr)	[H]	Sump Int Dose		GNT Int Dose		Total [H]	[C-OH]	Total [OH-] x	Final [H+]	pH
		(M/Rad)	[HNO3]	Gamma (M/Rad)	beta (M/Rad)					
0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.00000E-06	0.00000E+00	1.00000E-06	6.000
0.05361	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.00000E-06	0.00000E+00	0.00000E-06	6.000
0.1	1.8989E-08	1.2899E-02	9.4158E-08	4.5028E-02	1.2597E-07	1.32571E-05	4.38167E-05	1.32245E-05	3.25815E-09	8.487
0.1	1.8989E-08	6.3735E-02	4.6527E-07	4.8424E-01	2.3648E+00	1.1132E-06	3.30000E-05	3.30010E-05	2.72095E-05	9.481
0.53361	1.4286E-07	1.0800E-01	8.0000E-01	8.0000E-01	4.0347E+00	1.9039E-05	4.05728E-05	7.31898E-05	4.05713E-05	9.840
1	8.5714E-07	1.8489E-01	1.3482E-06	1.4488E+00	7.1405E+00	3.3741E-06	6.56334E-05	1.59339E-04	6.56339E-05	6.54299E-11
2	8.5714E-07	1.8697E-01	1.3649E-06	1.4685E+00	7.2381E+00	3.4202E-06	6.64223E-05	1.62286E-04	6.64474E-05	6.42532E-11
2.03361	8.5714E-07	1.8697E-01	1.3649E-06	1.4685E+00	7.2381E+00	3.4202E-06	6.64480E-05	1.62286E-04	6.64474E-05	6.49557E-11
3	8.5714E-07	2.4723E-01	1.8048E-06	1.9775E+00	9.9205E+00	5.8825E-06	9.94750E-05	1.62286E-04	1.62296E-04	6.56397E-11
4	8.5714E-07	3.0708E-01	2.1979E-06	2.4041E+00	1.2510E+01	5.8825E-06	9.94750E-05	1.62286E-04	1.62296E-04	6.62860E-11
5	8.5714E-07	3.4882E-01	2.5464E-06	2.7429E+00	1.8553E+01	8.6605E-06	1.33789E-05	1.62286E-04	1.62296E-04	6.71510E-11
6	8.5714E-07	3.9195E-01	2.8612E-06	3.0064E+00	2.1470E+01	9.9837E-06	1.49903E-05	1.62286E-04	1.62296E-04	6.78961E-11
7	8.5714E-07	4.3143E-01	3.1495E-06	3.2051E+00	2.1470E+01	9.9837E-06	1.49903E-05	1.62286E-04	1.62296E-04	6.85697E-11
8	8.5714E-07	4.6795E-01	3.4160E-06	3.3886E+00	2.4089E+01	1.1165E-05	1.64391E-05	1.62286E-04	1.62296E-04	6.91830E-11
9	8.5714E-07	5.0197E-01	3.6644E-06	3.4445E+00	2.8614E+01	1.3197E-05	1.89511E-05	1.62286E-04	1.62296E-04	6.97619E-11
10	8.5714E-07	5.3387E-01	3.8973E-06	3.5003E+00	3.2267E+01	1.4098E-05	2.00723E-05	1.62286E-04	1.62296E-04	7.03119E-11
11	8.5714E-07	5.6394E-01	4.1168E-06	3.5649E+00	3.0595E+01	1.4098E-05	2.00723E-05	1.62286E-04	1.62296E-04	7.08300E-11
12	8.5714E-07	5.9240E-01	4.3245E-06	3.7933E+00	3.2427E+01	1.4331E-05	2.11272E-05	1.62286E-04	1.62296E-04	7.13205E-11
13	8.5714E-07	6.1943E-01	4.5218E-06	4.0357E+00	3.5720E+01	1.6427E-05	2.39519E-05	1.62286E-04	1.62296E-04	7.22314E-11
14	8.5714E-07	6.4519E-01	4.7099E-06	4.0357E+00	3.7213E+01	1.7055E-05	2.59442E-05	1.62286E-04	1.62296E-04	7.22314E-11
15	8.5714E-07	6.6981E-01	4.8896E-06	4.1431E+00	3.9713E+01	1.7744E-05	2.46627E-05	1.62286E-04	1.62296E-04	7.26569E-11
16	8.5714E-07	6.9339E-01	5.0617E-06	4.2430E+00	3.8619E+01	1.8348E-05	2.54318E-05	1.62286E-04	1.62296E-04	7.30653E-11
17	8.5714E-07	7.1602E-01	5.2899E-06	4.3364E+00	3.9950E+01	1.8921E-05	2.61637E-05	1.62286E-04	1.62296E-04	7.34831E-11
18	8.5714E-07	7.3779E-01	5.5389E-06	4.4241E+00	4.1213E+01	1.9466E-05	2.68620E-05	1.62286E-04	1.62296E-04	7.38539E-11
19	8.5714E-07	7.5876E-01	5.5390E-06	4.5068E+00	4.2414E+01	1.9466E-05	2.68620E-05	1.62286E-04	1.62296E-04	7.42027E-11
20	8.5714E-07	7.7900E-01	5.6967E-06	4.5849E+00	4.3561E+01	1.9886E-05	2.75298E-05	1.62286E-04	1.62296E-04	7.45669E-11
21	8.5714E-07	7.9858E-01	5.8293E-06	4.6591E+00	4.4658E+01	2.0483E-05	2.81701E-05	1.62286E-04	1.62296E-04	7.49600E-11
22	8.5714E-07	8.1749E-01	5.9657E-06	4.7296E+00	4.5710E+01	2.0990E-05	2.87830E-05	1.62286E-04	1.62296E-04	7.53839E-11
23	8.5714E-07	8.3583E-01	6.1015E-06	4.7969E+00	4.6720E+01	2.1418E-05	2.93789E-05	1.62286E-04	1.62296E-04	7.58581E-11
24	8.5714E-07	8.5361E-01	6.2314E-06	4.8612E+00	4.7692E+01	2.1859E-05	2.99473E-05	1.62286E-04	1.62296E-04	7.63434E-11
30	8.5714E-07	9.5043E+00	7.9109E-06	5.1970E+00	5.2874E+01	2.4207E-05	3.30022E-05	1.62286E-04	1.62296E-04	7.98800E-11
40	8.5714E-07	1.0837E+00	6.9381E-06	5.1970E+00	5.9794E+01	2.7340E-05	3.71085E-05	1.62286E-04	1.62296E-04	8.20610E-11
50	8.5714E-07	1.1930E+00	8.7089E-06	5.9672E+00	6.5383E+01	3.2010E-05	4.04353E-05	1.62286E-04	1.62296E-04	8.40030E-11
60	8.5714E-07	1.2857E+00	9.3858E-06	6.2460E+00	7.0116E+01	3.2010E-05	4.32528E-05	1.62286E-04	1.62296E-04	8.57730E-11
70	8.5714E-07	1.3652E+00	9.9733E-06	6.4846E+00	7.4249E+01	3.3879E-05	4.57090E-05	1.62286E-04	1.62296E-04	8.74113E-11
80	8.5714E-07	1.4372E+00	1.0492E-05	6.6938E+00	7.7935E+01	3.5545E-05	4.78941E-05	1.62286E-04	1.62296E-04	8.87417E-11
90	8.5714E-07	1.5007E+00	1.0959E-05	6.8807E+00	8.1278E+01	3.7055E-05	4.98676E-05	1.62286E-04	1.62296E-04	8.9960E-11
100	8.5714E-07	1.5581E+00	1.1374E-05	7.0499E+00	8.4342E+01	3.8440E-05	5.16707E-05	1.62286E-04	1.62296E-04	9.03944E-11
150	8.5714E-07	1.7816E+00	1.3005E-05	7.7221E+00	9.6937E+01	4.4098E-05	5.88608E-05	1.62286E-04	1.62296E-04	9.67724E-11
200	8.5714E-07	1.9400E+00	1.4162E-05	8.2228E+00	1.0657E+02	4.8474E-05	6.44876E-05	1.62286E-04	1.62296E-04	1.02248E-10
300	8.5714E-07	2.1571E+00	1.5747E-05	8.9683E+00	1.2195E+02	5.5235E-05	7.28392E-05	1.62286E-04	1.62296E-04	1.11788E-10
400	8.5714E-07	2.3028E+00	1.6817E-05	9.5294E+00	1.3327E+02	6.0512E-05	7.91736E-05	1.62286E-04	1.62296E-04	1.20313E-10
500	8.5714E-07	2.4098E+00	1.7585E-05	9.9894E+00	1.4303E+02	6.4911E-05	8.43536E-05	1.62286E-04	1.62296E-04	1.28300E-10
600	8.5714E-07	2.4801E+00	1.8177E-05	1.0371E+01	1.5149E+02	6.8722E-05	8.87563E-05	1.62286E-04	1.62296E-04	1.35891E-10
700	8.5714E-07	2.5542E+00	1.8646E-05	1.0708E+01	1.5901E+02	7.2105E-05	9.26077E-05	1.62286E-04	1.62296E-04	1.43499E-10
720	8.5714E-07	2.5654E+00	1.8729E-05	1.0771E+01	1.6042E+02	7.2140E-05	9.33247E-05	1.62286E-04	1.62296E-04	1.44889E-10

**Containment Cable Inventory = 200,000 lbs**

Time (hr)	Sump Int Dose			CMT Int Dose			Total [H+]	[CsOH]	Total [OH-]	x	Final [H+]	pH	
	[HI]	(MRad)	[HNO3]	Gamma (MRad)	Beta (MRad)	[HCl]							
0	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E-06	0.0000E+00	1.0000E-08	0.0000E+00	1.0000E-06	6.000
0.03361	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	1.0000E-06	0.0000E+00	1.0000E-08	0.0000E+00	1.0000E-06	6.000
0.1	1.8968E-08	1.2898E-02	9.4158E-08	8.9991E-02	4.5028E-01	4.2516E-07	1.53829E-06	4.38167E-06	4.39167E-06	1.53479E-06	3.50033E-09	8.456	9.465
0.53361	1.4286E-07	6.3735E-02	4.6527E-07	4.4942E-01	2.3648E+00	2.2263E-06	3.83444E-06	3.30000E-05	3.30100E-05	3.83410E-06	3.42749E-10	9.465	9.829
1	3.6495E-07	1.0800E-01	7.8839E-07	8.0000E-01	4.0347E+00	3.8079E-06	5.96122E-06	7.31983E-05	7.32083E-05	5.96107E-06	1.48705E-10	9.829	10.175
2	8.4114E-07	1.8468E-01	1.3482E-06	1.4488E+00	7.1405E+00	6.7483E-06	9.93759E-06	1.59389E-04	1.59399E-04	9.93752E-06	6.69070E-11	10.175	10.183
2.03361	8.5714E-07	1.8697E-01	1.3649E-06	1.4685E+00	7.2381E+00	6.8405E-06	1.00625E-05	1.62286E-04	1.62296E-04	1.00624E-05	6.56886E-11	10.183	10.174
3	8.5714E-07	2.4723E-01	1.8048E-06	1.9775E+00	9.9206E+00	9.3658E-06	1.30277E-05	1.62286E-04	1.62296E-04	1.30276E-05	6.69936E-11	10.174	10.166
4	8.5714E-07	3.0108E-01	2.1979E-06	2.4041E+00	1.2510E+01	1.1785E-05	1.58400E-05	1.62286E-04	1.62296E-04	1.58399E-05	6.82800E-11	10.166	10.158
5	8.5714E-07	3.4882E-01	2.5464E-06	2.7429E+00	1.4966E+01	1.4062E-05	1.84651E-05	1.62286E-04	1.62296E-04	1.84651E-05	6.95262E-11	10.158	10.147
6	8.5714E-07	3.9195E-01	2.8612E-06	3.0064E+00	1.8553E+01	1.7321E-05	2.20394E-05	1.62286E-04	1.62296E-04	2.20394E-05	7.12980E-11	10.147	10.138
7	8.5714E-07	4.3143E-01	3.1495E-06	3.2051E+00	2.1470E+01	1.9967E-05	2.49739E-05	1.62286E-04	1.62296E-04	2.49738E-05	7.28216E-11	10.138	10.129
8	8.5714E-07	4.6795E-01	3.4160E-06	3.3485E+00	2.4088E+01	2.2332E-05	2.76050E-05	1.62286E-04	1.62296E-04	2.76049E-05	7.42441E-11	10.129	10.122
9	8.5714E-07	5.0197E-01	3.6644E-06	3.4445E+00	2.6455E+01	2.4461E-05	2.99827E-05	1.62286E-04	1.62296E-04	2.99826E-05	7.55783E-11	10.122	10.114
10	8.5714E-07	5.3387E-01	3.8973E-06	3.5003E+00	2.8614E+01	2.6393E-05	3.21478E-05	1.62286E-04	1.62296E-04	3.21478E-05	7.68356E-11	10.114	10.108
11	8.5714E-07	5.6394E-01	4.1168E-06	3.6549E+00	3.0595E+01	2.8197E-05	3.41706E-05	1.62286E-04	1.62296E-04	3.41705E-05	7.80487E-11	10.108	10.101
12	8.5714E-07	5.9240E-01	4.3245E-06	3.7933E+00	3.2427E+01	2.9862E-05	3.60437E-05	1.62286E-04	1.62296E-04	3.60436E-05	7.92066E-11	10.101	10.095
13	8.5714E-07	6.1943E-01	4.5218E-06	3.9196E+00	3.4129E+01	3.1409E-05	3.77883E-05	1.62286E-04	1.62296E-04	3.77882E-05	8.03164E-11	10.095	10.089
14	8.5714E-07	6.4519E-01	4.7099E-06	4.0357E+00	3.5720E+01	3.2854E-05	3.94214E-05	1.62286E-04	1.62296E-04	3.94213E-05	8.13839E-11	10.089	10.084
15	8.5714E-07	6.6981E-01	4.8896E-06	4.1431E+00	3.7213E+01	3.4210E-05	4.09570E-05	1.62286E-04	1.62296E-04	4.09569E-05	8.24139E-11	10.084	10.079
16	8.5714E-07	6.9339E-01	5.0617E-06	4.2430E+00	3.8619E+01	3.5488E-05	4.24065E-05	1.62286E-04	1.62296E-04	4.24064E-05	8.34103E-11	10.079	10.074
17	8.5714E-07	7.1602E-01	5.2269E-06	4.3364E+00	3.9950E+01	3.6695E-05	4.37796E-05	1.62286E-04	1.62296E-04	4.37795E-05	8.43766E-11	10.074	10.069
18	8.5714E-07	7.3779E-01	5.3859E-06	4.4241E+00	4.1213E+01	3.7841E-05	4.50844E-05	1.62286E-04	1.62296E-04	4.50843E-05	8.53159E-11	10.069	10.064
19	8.5714E-07	7.5876E-01	5.5390E-06	4.5068E+00	4.2414E+01	3.8932E-05	4.63278E-05	1.62286E-04	1.62296E-04	4.63277E-05	8.62307E-11	10.064	10.060
20	8.5714E-07	7.7900E-01	5.6867E-06	4.5849E+00	4.3561E+01	3.9972E-05	4.75158E-05	1.62286E-04	1.62296E-04	4.75157E-05	8.71232E-11	10.060	10.056
21	8.5714E-07	7.9856E-01	5.8295E-06	4.6591E+00	4.4658E+01	4.0967E-05	4.86535E-05	1.62286E-04	1.62296E-04	4.86534E-05	8.79954E-11	10.056	10.051
22	8.5714E-07	8.1749E-01	5.9677E-06	4.7296E+00	4.5710E+01	4.1920E-05	4.97453E-05	1.62286E-04	1.62296E-04	4.97452E-05	8.88490E-11	10.051	10.047
23	8.5714E-07	8.3583E-01	6.1015E-06	4.7969E+00	4.6720E+01	4.2836E-05	5.07950E-05	1.62286E-04	1.62296E-04	5.07949E-05	8.96855E-11	10.047	10.043
24	8.5714E-07	8.5361E-01	6.2314E-06	4.8612E+00	4.7692E+01	4.3718E-05	5.18062E-05	1.62286E-04	1.62296E-04	5.18061E-05	9.05062E-11	10.043	10.022
30	8.5714E-07	9.5043E-01	6.9381E-06	5.1970E+00	5.2874E+01	4.8414E-05	5.72091E-05	1.62286E-04	1.62296E-04	5.72090E-05	9.51595E-11	10.022	9.991
40	8.5714E-07	1.0837E+00	7.9109E-06	5.6296E+00	5.9794E+01	5.4681E-05	6.44490E-05	1.62286E-04	1.62296E-04	6.44489E-05	1.02201E-10	9.991	9.964
50	8.5714E-07	1.1930E+00	8.7089E-06	5.9672E+00	6.5383E+01	5.9738E-05	7.03045E-05	1.62286E-04	1.62296E-04	7.03044E-05	1.08706E-10	9.964	9.940
60	8.5714E-07	1.2857E+00	9.3858E-06	6.2460E+00	7.0116E+01	6.4020E-05	7.52626E-05	1.62286E-04	1.62296E-04	7.52625E-05	1.14899E-10	9.940	9.918
70	8.5714E-07	1.3662E+00	9.9733E-06	6.4846E+00	7.4249E+01	6.7757E-05	7.95875E-05	1.62286E-04	1.62296E-04	7.95874E-05	1.20907E-10	9.918	9.897
80	8.5714E-07	1.4372E+00	1.0492E-05	6.6938E+00	7.7936E+01	7.1090E-05	8.34393E-05	1.62286E-04	1.62296E-04	8.34392E-05	1.26813E-10	9.897	9.877
90	8.5714E-07	1.5007E+00	1.0955E-05	6.8807E+00	8.1278E+01	7.4110E-05	8.69227E-05	1.62286E-04	1.62296E-04	8.69226E-05	1.32673E-10	9.877	9.858
100	8.5714E-07	1.5581E+00	1.1374E-05	7.0499E+00	8.4342E+01	7.6879E-05	9.01102E-05	1.62286E-04	1.62296E-04	9.01101E-05	1.38532E-10	9.858	9.773
150	8.5714E-07	1.7816E+00	1.3005E-05	7.7221E+00	9.6874E+01	8.8196E-05	1.03059E-04	1.62286E-04	1.62296E-04	1.03059E-04	1.68813E-10	9.773	9.693
200	8.5714E-07	1.9400E+00	1.4162E-05	8.2228E+00	1.0657E+02	9.6947E-05	1.12966E-04	1.62286E-04	1.62296E-04	1.12966E-04	2.02718E-10	9.693	9.534
300	8.5714E-07	2.1571E+00	1.5747E-05	8.9683E+00	1.2156E+02	1.1047E-04	1.28074E-04	1.62286E-04	1.62296E-04	1.28074E-04	2.92211E-10	9.534	9.354
400	8.5714E-07	2.3028E+00	1.6811E-05	9.5294E+00	1.3327E+02	1.2102E-04	1.39691E-04	1.62286E-04	1.62296E-04	1.39691E-04	4.42382E-10	9.354	9.115
500	8.5714E-07	2.4089E+00	1.7585E-05	9.9849E+00	1.4303E+02	1.2982E-04	1.49255E-04	1.62286E-04	1.62296E-04	1.49254E-04	6.73360E-10	9.115	8.683
600	8.5714E-07	2.4901E+00	1.8177E-05	1.0371E+01	1.5149E+02	1.3744E-04	1.57478E-04	1.62286E-04	1.62296E-04	1.57476E-04	2.07479E-09	8.683	6.616
700	8.5714E-07	2.5542E+00	1.8646E-05	1.0708E+01	1.5901E+02	1.4421E-04	1.64713E-04	1.62286E-04	1.62296E-04	1.62292E-04	2.42103E-06	6.616	5.423
720	8.5714E-07	2.5654E+00	1.8728E-05	1.0771E+01	1.6042E+02	1.4548E-04	1.66065E-04	1.62286E-04	1.62296E-04	1.62293E-04	3.77150E-06	5.423	