Non-Proprietary

CALCULATION TITLE PAGE

CALCULATION NUMBER: PSAT 05656A.04

CALCULATION TITLE: Calculation of TMI-1 Engineered Safety Feature Component Leakage Iodine Release

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Purpose

The purpose of this calculation is to calculate the iodine released to the environment due to engineered safety feature (ESF) component leakage into an ESF component room in the auxiliary building, subsequent evolution of the iodine from the leakage pool, and circulation of the building air from the ESF component room to the environment.

Methodology

The overall approach is to apply the Reference [1] Standard Review Plan (SRP) guidance that if the calculated flash fraction is less than 10% or if the water is less than 212 F, then an amount of iodine smaller than 10% of the iodine in the leakage may be used if justified based upon actual sump pH history and ventilation rates. The steps in the calculation are as follows:

- Evaluate the elemental iodine concentration in the ESF liquid. This is a function of the core inventory of iodine, the iodine release from the core during the DBA LOCA (this iodine is assumed to go into solution in the RCS and reactor building sump liquid which is in turn recirculated through the auxiliary building as ESF liquid), the total ESF liquid mass (i.e., reactor coolant, core flood tanks (CFTs), NaOH tank, and borated water storage tank (BWST)), liquid density, and the ESF liquid pH.
- Evaluate the iodine concentration in the ESF room gas phase. It is assumed that the liquid phase – gas phase partitioning of iodine is always at equilibrium condition which is a function of liquid temperature as discussed below under assumptions.
- Using the volumetric flow of gas from the ESF gas space to the environment, calculate iodine release to the environment.

Assumptions

Assumption 1: The flashing fraction is always less than 10% and the flash release is negligible compared to the calculated release.

Justification: The peak ESF liquid temperature is about 407 K, or 273 F. Using a constant enthalpy method per reference [1],

$$mh = m_g h_g + m_l h_l$$

where m is total mass (liquid), h is the initial liquid enthalpy, m_g is flashed mass, h_g is gas enthalpy, m_l is unflashed liquid mass, and h_l is unflashed liquid enthalpy. Thus, the flashing fraction, which is the flashed mass divided by the total mass, is

$$ff = m_g / m = (mh - m_l h_l) / mh_g$$

Using initial liquid temperature of 273 F and final temperature of 212 F (corresponding to the saturation temperature at atmospheric pressure which is the final pressure of the flashed mixture), using the steam tables, and setting m = 1 so that the flashing fraction is just m_g, we obtain

$$ff = (242 - (1 - ff)180)/1150$$
$$ff(1150 - 180) = 242 - 180$$
$$ff = 0.064 = 6.4\%$$

Since the ESF liquid temperature continuously decreases from 407 K, the flashing fraction is always < 10%.

The flash release is the iodine released to the gas phase during the flash. It can be estimated as the product of:

- The fraction of total iodine in the liquid which is elemental
- The fraction of this elemental iodine which partitions to the gas phase
- The ratio of flashed steam volume to liquid volume
- The fraction of liquid which flashed.

As is calculated below in the Attachment 1 spreadsheet, the fraction of total iodine in the liquid which is elemental is roughly 1E-7 (due to the high pH). The steam from the flashed liquid has a volume of the order of 1000 times the liquid. The partition coefficient is of the order of unity at the peak ESF liquid temperature, and of the order of 0.1 or lower after 24 hours. The flashing fraction is of the order of 0.1 at the beginning of the accident and quickly approaches zero after a few hours. The flashing release can then be approximated as

$$(1E\text{-}7)(1000)(1)(0.1) \approx 1E\text{-}5$$

at the beginning of the accident, and after a few hours is much lower. As will be seen from the calculation result, the release over 30 days is of the order of 1E-3. Thus the flashing release is negligible.

Assumption 2: The iodine partitioning between the liquid and bulk gas is based on equilibrium conditions. That is, a fraction of the I_2 in the liquid is assumed to partition instantaneously to the bulk gas phase. This fraction depends only on the temperature of the liquid and does not consider transport of the I_2 within the liquid to the liquid – gas interface, nor transport of the I_2 across the gas boundary layer between the liquid surface and the bulk gas phase.

Justification: Elemental iodine will transport across the liquid – gas interface (i.e., partition) at a rate depending upon its actual vapor pressure in the gas vs. its saturation vapor pressure. For lower temperatures, the saturation vapor pressure will be lower and the partitioning will be lower. Similarly, as temperature increases, the saturation vapor pressure increases and the partitioning increases. At equilibrium, the actual vapor pressure equals the saturation vapor pressure. Equilibrium conditions have been assumed to simplify the calculation. This assumption is very conservative since it neglects any transient effects and it neglects the resistance to gas transport across the gas boundary layer. This boundary layer effect is considered in the Appendix A calculation.

Assumption 3: The ESF component leakage remains at the reactor building (RB) sump liquid temperature.

Justification: ESF liquid is reactor building (RB) sump liquid which is recirculating through three systems in the auxiliary building (makeup, decay heat removal, and RB spray). ESF component leakage is ESF liquid which leaks (e.g., pump seal, valve stem) into the auxiliary building room in which the component is located. The ESF component leakage is assumed to remain at the RB sump liquid temperature. In fact there will be heat transfer from the leaked liquid to the auxiliary building room wall surfaces and structures, as well as evaporative heat transfer. This will lower the liquid temperature significantly. For example, referring to reference [2], items {3.2} and {4.1}, at 24.5 hours a mass, M, of roughly (30)(24) + (30)(50) = 2200 gal, which is about 18,000 lbm or 300 ft^3, of leakage has occurred. If this leakage pools in a room of floor area 300 ft^2, the thickness of the pool is

$$\begin{aligned} th &= \text{Volume/Area} \\ &\approx 1 \text{ ft} \end{aligned}$$

The heat transfer from the liquid to the floor surface may be estimated using the liquid temperature at 24 hours (163 F) and an assumed floor temperature of 100 F, and a thermal conductivity of water of 0.4 BTU/hr/ft/F:

$$\begin{aligned} q\ (\text{BTU/hr}) &= (0.4)(300)(63/1) \\ &\approx 7500 \text{ BTU/hr} \end{aligned}$$

Taking c_p of water as 1 BTU/lbm/F, we can estimate the time required to decrease the liquid temperature by 5F as

$$\begin{aligned} T\ (5F\ \text{decr}) &= 5Mc_p/q \\ &= (5)(16000)(1)/7500 \\ &\approx 10 \text{ hrs} \end{aligned}$$

This is about the same rate at which the RB sump liquid cooling is occurring at 24+ hours (see reference [2], item {3.2}). Neglecting this heat transfer is conservative since the amount of iodine partitioned from the liquid to the gas phase increases with increasing temperature.

Assumption 4: The entire auxiliary building is to be used as a single, well-mixed volume for ESF leakage iodine exchange with the environment (volume = 1,285,474 ft^3 per reference [2], item {5.4}).

Justification: Use of a single, well-mixed volume is conservative. In fact, the ECCS leakage will be to a room in the auxiliary building basement which has a restricted opening to the remainder of the auxiliary building. Modeling these separate volumes (i.e., two or more volumes in series) would slow the exchange with the environment relative to the single, well-mixed case. The entire auxiliary building volume has been assumed to exchange with the environment. This also is conservative since this maximizes the volumetric flow (and thus the fission product flow) out of the building for a given exchange rate.

Assumption 5: A volumetric exchange rate of 2 per hour will be used per reference [2], item {5.5}.

Justification: This exchange rate is conservative. For example, per reference [5], natural circulation air changes for average residential construction under average weather conditions vary over a range of 0.5 to 2 per hour.

References

Reference 1: NUREG-0800, NRC Standard Review Plan, Section 15.6.5, Appendix B, "Radiological Consequences of a Design Basis Loss of Coolant Accident: Leakage from Engineered Safety Features Components Outside Containment"

Reference 2: PSAT 05656A.03, "Plant-Specific Design Input for Calculation of TMI-1 ESF Component Leakage Iodine Release", Revision 0

Reference 3: R. Sher and J. Jokiniemi, "NAUAHYGROS 1.0: A Code for Calculating the Behavior of Aerosols in Nuclear Plant Containments Following a Severe Accident," EPRI Report TR-102775, July, 1993.

Reference 4: NUREG/CR-5950, "Iodine Evolution and pH Control", November 1992

Reference 5: ASHRAE Fundamentals Handbook, 1981, Chapter 22, Table 2.

Reference 6: PSAT 05656A.02, "Implementing Procedure for Design Control for Calculation of TMI-1 Engineered Safety Feature component Leakage Iodine Release"

Calculation

Per reference [6], the calculational approach is to evaluate the iodine release based upon actual sump pH history and ventilation rates. This is consistent with the SRP [1] guidance, based upon assumption (1) that flashing fraction is less than 10%.

I_2 Concentration in Liquid

This is the first of three calculational sections. This calculational section determines the concentration of elemental iodine in the ESF liquid.

The total iodine concentration in the ESF liquid is

$$[I^-] = (I_c)(frel)/V_{ESF}/130$$

where $[I^-]$ = total iodine concentration in kgmol/m^3 in the ESF liquid
I_c = total core inventory of iodine in kg
frel = iodine release fraction from core to containment (= 0.5 per reference [1])
V_{ESF} = the volume of liquid (m^3) in which I^- is dissolved

From reference [2], items {2.1} and {3.1}, I_c = 21.4 kg which is 21.4/130 kgmol and total liquid mass m = 3.357E6 lbm (sum of RCS, BWST, NaOH tank, and CFT). From reference [3] the density of liquid water may be expressed as

$$\rho_{water} = \frac{(4.6137)(0.018016)(1000)}{0.26214^{(1+(1-T/647.29)^{0.23072})}}$$

Noting that $V_{ESF} = m/\rho_{water}$ we have

$$[I^-] = (21.4)(0.5)/130/(m/\rho_{water}) \text{ kgmol/m}^3 \qquad \text{Equation 1}$$

Now using equation [12] from reference [4], the elemental iodine concentration in the liquid may be calculated

Equations 1 and 1a are used to obtain $[I^-]$ and $[I_2]$aq as a function of temperature (see Attachment 1 spreadsheet, discussed further below). One exception is for 0 to 29.1 minutes during which time recirculation has not yet been initiated (per reference [2], item {4.3}) and $[I^-]$ and $[I_2]$aq are zero.

I_2 Concentration in Bulk Gas

Per assumption (2), the iodine partitioning between the liquid and bulk gas is based on equilibrium conditions.

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I_2 Release from Gas Space

The I_2 release from the auxiliary building to the environment is equal to the product of the volumetric gas flow from the auxiliary building to the environment in m^3 per hour and $[I_2]g$. Per assumption (4) the entire auxiliary building is to be considered in the ESF leakage iodine release problem (volume V = 1,285,474 ft^3). Per assumption (5) volumetric gas flow to the environment is based on an exchange rate, $\dot{V}/V$, of 2 volumes per hour where $\dot{V}$ is volumetric flow m^3 per hour. (Attachment 1 also includes sensitivity calculations for exchange rates of 1, 3, and 5 per hour.)

Results

The results of this calculation are presented in Tables 1 and 2. (Tables 1 and 2 are taken from the Attachment 1 spreadsheet. Table 1 is taken from column 12 of page 2 of the spreadsheet, and Table 2 is taken from the release fractions over Chi/Q intervals [lower left hand subtable on page 2 of the spreadsheet]. There are 4 pages in Attachment 1, one page for each exchange rate with exchange rate 2 per hour being the base case reported in Tables 1 and 2.)

The results are in units of fraction of total iodine leaking into the ESF component room(s) (i.e., fraction of the total dissolved iodine in the 30 gal per hour). As is evident from Table 1, in the first 29.1 minutes (1746 seconds) the release is zero since recirculation has not yet started. Early in the accident the release is several percent of the total iodine in the leakage. The fraction decreases with time and is less than 1% percent after a day. This decrease is due mainly to decreasing temperature as the ESF liquid is cooled (and thus the amount of iodine partitioning from the liquid decreases per equations 2 and 3).

For input to the dose calculation, the $Frac_i$ quantities in Table 1 (from equation 5) have been time-weighted to produce a fractional release of total incoming iodine for time intervals corresponding to the chi/Q intervals. This is presented in Table 2.

Conclusions

The conclusion from this calculation is that the iodine release from ESF leakage for TMI-1 is under 3% of the total incoming iodine in the leakage, for exchange rate of 2 per hour, for all of the Chi/Q intervals.

Table 1 Fraction of Incoming Iodine Released

Time Interval (sec)			Frac (Fraction of Incoming Iodine)
75	to	720	N/A
720	to	1746	N/A
1746	to	3300	4.69E-02
3300	to	7200	3.52E-02
7200	to	28800	2.15E-02
28800	to	86400	1.39E-02
86400	to	88200	2.04E-04
88200	to	172800	9.54E-03
172800	to	345600	8.21E-03
345600	to	500000	7.38E-03
500000	to	2.59E+06	5.46E-03

Table 2 Fraction of Incoming Iodine Released During Chi/Q Periods

Time Period	Fraction of Incoming Iodine
0 to 2 hr	2.92E-02
2 to 8 hr	2.15E-02
8 to 24 hr	1.39E-02
24 hr to 24.5 hr	2.04E-04
1 to 4 days	8.65E-03
4 to 30 days	5.59E-03

APPENDIX A

APPENDIX TITLE: ESF Component Leakage Iodine Release with Reduced pH and Liquid – Gas Boundary Layer Effect

CALCULATION TITLE: Calculation of TMI-1 Engineered Safety Feature Component Leakage Iodine Release

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Purpose

The purpose of this appendix is to calculate the effect of reduced pH and the effect of the liquid – gas boundary layer on the main calculation result for ESF component leakage iodine release to the environment. This calculation is being performed to assess the sensitivity of the main calculation result to pH. Reduced pH will increase the iodine release. For simplicity, the boundary layer effect was not considered in the main calculation. It is, however, considered here since the effect is significant and since methods exist to address the effect.

Methodology

The overall approach is to apply the Reference [1] Standard Review Plan (SRP) guidance similar to the main calculation. The differences are use of pH 7.5 and 7 (vs. pH 8 in the main calculation) and development and application of a model for the mass transfer of iodine across the boundary layer between the liquid surface and the bulk gas space in the auxiliary building. The steps in the calculation are as follows:

- As in the main calculation, evaluate the elemental iodine concentration in the ESF liquid.
- Evaluate the gaseous iodine concentration at the liquid edge of the gas boundary layer. This is accomplished in the same manner as the main calculation evaluation of the iodine concentration in the ESF room gas phase except here this concentration becomes a boundary condition for the transport of iodine across the gas boundary layer. As in the main calculation, it is assumed that the liquid phase – gas phase partitioning of iodine is always at equilibrium condition which is a function of liquid temperature.
- Evaluate the mass transport of iodine across the gas boundary layer . The iodine concentration gradient and the mass transfer coefficient must be considered here. This will allow determining the bulk gas iodine concentration, which is a function of the iodine mass flux across the gas boundary layer and a mass balance with the iodine removal due to the volumetric exchange of the bulk gas space with the environment.
- Using the volumetric flow of gas from the ESF gas space to the environment, calculate iodine release to the environment.

Assumptions

Assumption 1: The flashing fraction is always less than 10% and the flash release is negligible compared to the calculated release.

Justification: Same as in main calculation.

Assumption 2: The iodine partitioning between the liquid and the liquid edge of the gas boundary layer is based on equilibrium conditions.

Justification: Same principle as in main calculation, except it is applied only to the gas concentration at the liquid edge of the gas boundary layer.

Assumption 3: The ESF component leakage remains at the reactor building (RB) sump liquid temperature.

Justification: Same as in main calculation. This assumption is even more conservative here than in the main calculation since as evident from assumption (6) below, the area of the liquid layer has been maximized which will increase heat transfer from the liquid to room surfaces and thus increase the rate of liquid temperature decrease.

Assumption 4: The entire auxiliary building is to be used as a single, well-mixed volume for ESF leakage iodine exchange with the environment (volume = 1,285,474 ft^3 per reference [2], item {5.4}).

Justification: Same as in main calculation.

Assumption 5: The sump liquid (and thus the ESF liquid) pH is 7.5 and 7.

Justification: Two cases for sump pH were calculated to determine the sensitivity of the main calculation (pH 8) result to pH. Per reference [7], one of the cases was pH 7.

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Assumption 9: A volumetric exchange rate of 2 per hour will be used.

Justification: Same as in main calculation.

References

Reference 1: NUREG-0800, NRC Standard Review Plan, Section 15.6.5, Appendix B, "Radiological Consequences of a Design Basis Loss of Coolant Accident: Leakage from Engineered Safety Features Components Outside Containment"

Reference 2: PSAT 05656A.03, "Plant-Specific Design Input for Calculation of TMI-1 ESF Component Leakage Iodine Release", Revision 0

Reference 3: R. Sher and J. Jokiniemi, "NAUAHYGROS 1.0: A Code for Calculating the Behavior of Aerosols in Nuclear Plant Containments Following a Severe Accident," EPRI Report TR-102775, July, 1993.

Reference 7: PSAT 05656A.02, "Implementing Procedure for Design Control for Calculation of TMI-1 Engineered Safety Feature component Leakage Iodine Release"

Calculation

As in the main calculation and per reference [7], the calculational approach is to evaluate the iodine release based upon actual sump pH history and ventilation rates, with the additional step of consideration of the effect of the gas boundary layer at the pool surface. This is consistent with the SRP [1] guidance, based upon assumption (1) that flashing fraction is less than 10%.

I_2 Concentration in Liquid

This is the first of four calculational sections. This calculational section determines the concentration of elemental iodine in the ESF liquid.

The total iodine concentration in the ESF liquid is

$$[I^-] = (I_c)(frel)/V_{ESF}/130$$

where $[I^-]$ = total iodine concentration in kgmol/m^3 in the ESF liquid
I_c = total core inventory of iodine in kg
frel = iodine release fraction from core to containment (= 0.5 per reference [1])

V_{ESF} = the volume of liquid (m^3) in which I^- is dissolved

From reference [2], items {2.1} and {3.1}, I_c = 21.4 kg which is 21.4/130 kgmol and total liquid mass m = 3.357E6 lbm (sum of RCS, BWST, NaOH tank, and CFT). From reference [3] the density of liquid water may be expressed as

$$\rho_{water} = \frac{(4.6137)(0.018016)(1000)}{0.26214^{(1+(1-T/647.29)^{0.23072})}}$$

where T is degrees Kelvin. Noting that $V_{ESF} = m/\rho_{water}$ we have

$$[I^-] = (21.4)(0.5)/130/(m/\rho_{water}) \text{ kgmol/m}^3 \qquad \text{Equation 1}$$

I_2 Concentration at Liquid Edge of Gas Boundary Layer

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Gas Transport of Iodine Across Boundary Layer

The problem of iodine gas transport across the gas boundary layer at the liquid – gas interface is illustrated in Figure 1. $[I_2]$aq and $[I_2]g_i$ are known from equations 1 through 3. The object of this gas transport calculation is to solve for $[I_2]g_b$.

Figure 1 Illustration of Boundary Layer

The problem of mass transfer of the iodine gas across the gas boundary layer at the liquid –gas interface is treated by defining a mass transfer coefficient in a manner similar to that used for defining a heat transfer coefficient

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The solutions to equation 9 for steady state $[I_2]g_b$ and to equation 13 for transient $[I_2]g_b$ are provided in the Attachment 3 spreadsheets. The attachment consists of 9 spreadsheets, one for each of the 9 time intervals after 29.1 minutes (which in turn correspond to a given ESF leakage pool temperature – see Attachment 2 for time intervals and corresponding temperatures). For the first time interval with non-zero iodine concentration in the ESF leakage (i.e., the third time interval) in Attachment 3, the transient calculation has been carried out for 3600 seconds (pages 1 – 9 of Attachment 3). For the remaining 8 time intervals (intervals 4 to 11) in Attachment 3, the transient calculation is carried out only to 320 seconds to confirm that the transient behavior is similar to the first time interval. Except for the third Attachment 3 time interval, a time interval (i.e., spreadsheet) consists of 4 pages: page 1 is the steady state and transient (to 320 seconds) result for $[I_2]g_b$; page 2 includes case-specific and non-case specific inputs to the mass transfer calculation; page 3 is the calculation of the Sherwood Number; and page 4 is a calculation of $[I_2]g_l$. For the third Attachment 3 time interval, the spreadsheet is 12 pages: 9 pages for the transient $[I_2]g_b$ calculation (to 3600 seconds), and 1 page each for the inputs, Sherwood Number, and $[I_2]g_l$. Thus Attachment 3 is 44 pages.

It is noted that the boundary layer model in the spreadsheets is configured for a 2 volume bulk gas region, although the problem addressed here assumes a single, well-mixed volume per assumption (4).

Nine values of the steady state, turbulent boundary layer decontamination factor (DF) corresponding to the 9 time intervals (after 29.1 minutes) for Attachment 3 are recorded in column 11 of Attachment 2. Boundary layer DF is defined as the elemental iodine concentration in the bulk gas without the boundary layer effect divided by the elemental iodine concentration with this effect The turbulent value has been used since this gives a higher iodine diffusion. $[I_2]g_b$ is calculated in column 12 by dividing $[I_2]g_i$ by boundary layer DF.

I_2 Release from Gas Space

The I_2 release from the auxiliary building to the environment is equal to the product of the volumetric gas flow from the auxiliary building to the environment in m^3 and $[I_2]g_b$.

Results

The results of this calculation are presented in column 14 of the Attachment 2 spreadsheet. The results are in units of fraction of total iodine leaking into the ESF component room(s) (i.e., fraction of the total dissolved iodine in the 30 gal per hour). In addition, the $Frac_i$ quantities from equation 15 have been time-weighted to produce a fractional release of total incoming iodine for time intervals corresponding to the chi/Q intervals. This is calculated and presented in the lower left of the Attachment 2 spreadsheet.

As is evident from the time weighted Frac_i quantities, for pH 7.5 the release is under 2% for 0 to 2 hours, decreasing to a few tenths of a percent at 30 days. The decrease with time is due mainly to decreasing temperature as the ESF liquid is cooled (and thus the amount of iodine partitioning from the liquid decreases per equations 2 and 3). For pH 7, the release is an order of magnitude higher. It should be noted, however, that the conservatisms discussed below would lower the release well below this result.

The steady state boundary layer effect has been calculated at the top of Attachment 3 and expressed in terms of a decontamination factor (DF). This DF is the bulk gas iodine concentration without the boundary layer effect divided by the concentration with the boundary layer effect (i.e., $[I_2]g_l/[I_2]g_b$). As is evident from Attachment 3, the turbulent boundary layer results in a DF of about 20. The laminar boundary layer results in a DF larger by about a factor of 2.

The transient boundary layer effect may be understood by examining the first 9 pages of Attachment 3. It is seen that after 1 hour, $[I_2]g_b$ is about 90% of the steady state value. This suggests that neglecting transient behavior over the first hour or two is conservative. Further, the approach to steady state is fast enough relative to later time intervals (which are of the order of many hours to days) that neglecting transient effects will have negligible effect on the release. It may further be observed that in the approximately 5 second duration of droplet fall for the jetted leakage discussed in assumption (8), the transient gas concentration will be negligible.

It is noted that the results reported here are quite conservative, particularly with respect to two effects: (1) the area of the ESF leakage pool was overestimated by assuming that a liquid layer is maintained on all walls and equipment surfaces in the area in which the leakage occurs; this significantly increases the mass transport across the boundary layer; and (2) the ESF leakage temperature was estimated by assuming no heat transfer from the leaked liquid to the structures and surfaces in the area in which the leakage occurs. These effects were treated in this manner for simplicity, and could be reevaluated if necessary to provide a more realistic estimate of the boundary layer.

Conclusions

The conclusions from this calculation are as follows:

- For the case of pH 7.5 and considering the boundary layer effect, the iodine release from ESF leakage for TMI-1 varies over the range of between 0.5% and 1.5% early, decreasing to about 0.3% at 30 days. For pH 7, the iodine release varies over the range of between 7% and 14% early, decreasing to about 3% at 30 days
- The effect of the boundary layer on iodine release, as modeled here, is about a DF of 20.

Attachment 1 **XL Spreadsheet for TMI-1 ESF Leakage Fraction Released to Environment**

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Attachment 2 XL Spreadsheet for TMI-1 ESF Leakage Fraction Released to Environment (Boundary Layer)

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Attachment 3 XL Spreadsheet Calculation of Iodine Concentration in Bulk Gas with BL Effect, AB 305 Area

(Third time interval)

Solution Using Turbulent Mass Transfer Coefficient		**Solution Using Laminar Mass Transfer Coefficient**	
Steady state solution	[I2]gb= 9.1E-12 kgmol/m3	**Steady state solution**	[I2]gb= 4.6E-12 kgmol/m3
	Boundary layer DF= 20.21609		Boundary layer DF= 39.64093

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