Tritium Dose Pathway Comparison – Regulatory Guide 1.109 and Beyond

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Presented at the 15th Annual RETS-REMP Workshop
Wilmington, NC / 27-29 June 2005
Need For Investigation

- At 2003 RETS-REMP Workshop, I reported that tritium released via airborne pathways yielded an equivalent dose 100 to 1,000 times higher than releases via liquid pathways.
- Several other licensees that have performed such a comparison have obtained similar results.
- Choice of release pathway can be an important factor in overall tritium management strategy.
- Inquiring minds want to know...Why does airborne pathway yield higher dose?
Basis for Comparison

- Effluent dose pathway models were based on Regulatory Guide 1.109...
  - “Calculation of Annual Doses from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I”
- RG-1.109 provides standard equations for calculating media concentrations to estimate annual intake of radionuclides
- Perform comparison of RG-1.109 models for liquid and airborne effluent pathways
Concentration in Water – Liquid Effluent Pathway

- Regulatory Guide 1.109 Equation A-1
- \( C_w = 1100 \times (M_p / F) \times Q \times \exp (-\lambda t) \)
  - \( C_w \) = tritium concentration in water, pCi/L
  - 1100 = convert Ci/yr and ft\(^3\)/sec to pCi/L
  - \( M_p \) = mixing ratio (reciprocal of dilution factor)
  - \( F \) = flow rate in effluent stream (waste+dilution), ft\(^3\)/sec
  - \( Q \) = annual tritium release rate, Ci/yr
  - \( \lambda \) = tritium decay constant, 6.44E-6 hr\(^{-1}\)
  - \( t \) = transit time field to table, = 24 hours
Concentration in Vegetation – Liquid Effluent Pathway

- Regulatory Guide 1.109 Equation A-10
- \( C_v = C_w \)
  - \( C_v \) = tritium concentration in vegetation, pCi/kg
  - \( C_w \) = tritium concentration in water, pCi/L
Concentration in Air – Airborne Effluent Pathway

- **Regulatory Guide 1.109 Equation C-3**
- $x_i = 3.17E4 \times Q \times \frac{x}{Q}$
  - $x_i =$ tritium concentration in air, pCi/m$^3$
  - $3.17E4 = 1E12$ pCi/Ci / $3.15E7$ sec/yr
  - $Q =$ annual tritium release rate, Ci/yr
  - $\frac{x}{Q} =$ atmospheric dispersion factor, sec/m$^3$
Concentration in Vegetation – Airborne Effluent Pathway

- Regulatory Guide 1.109 Equation C-9
- $C_v = 3.17 \times 10^7 \times Q \times \frac{x}{Q} \times 0.75 \times (0.5/H)$
  - $C_v$ = tritium concentration in vegetation, pCi/kg
  - $3.17 \times 10^7 = 1 \times 10^{12}$ pCi/Ci $\times 1 \times 10^3$ g/kg $/$ $3.15 \times 10^7$ sec/yr
  - $Q$ = annual tritium release rate, Ci/yr
  - $x/Q$ = atmospheric dispersion factor, sec/m$^3$
  - $0.75$ = fraction of total plant mass that is water
  - $0.5$ = ratio of tritium in plant water to atmospheric water
  - $H$ = absolute humidity, g/m$^3$... 3 to 9 g H$\text{}_2\text{O}$/m$^3$ air
Intake Pathway Differences

- No inhalation pathway for waterborne releases
  - Airborne tritium from cooling pond evaporation?
- No drinking ingestion pathway for airborne releases
  - Rainout of atmospheric tritium into surface water?
- Waterborne equations assume a plant is 100% water, in 100% equilibrium with irrigation tritium concentration... 100% from irrigation
- Airborne equations assume a plant is 75% water, and 50% of plant water arises from atmospheric water... 50% remainder from irrigation
Pathway Comparisons

- Assume 1.0 Curie of tritium released
- Liquid effluent release
  - 200,000 gpm circulating water flow, equals \( \sim 4 \times 10^{11} \) Liters/yr dilution flow
  - Mixing Ratio = 0.2
- Airborne effluent release
  - Elevated \( x/Q = 1.0 \times 10^{-6} \) sec/m\(^3\)
  - Ground-level \( x/Q = 9.4 \times 10^{-6} \) sec/m\(^3\)
## Pathway Concentrations

<table>
<thead>
<tr>
<th>Media</th>
<th>Fresh Water</th>
<th>Salt Water</th>
<th>Elevated</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water pCi/ L</td>
<td>5.0E-1</td>
<td>5.0E-1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Air pCi/ m³</td>
<td>--</td>
<td>--</td>
<td>3.2E-2</td>
<td>3.0E-1</td>
</tr>
<tr>
<td>Crops pCi/ kg</td>
<td>5.0E-1</td>
<td>--</td>
<td>2.1E+0</td>
<td>2.0E+1</td>
</tr>
<tr>
<td>Milk pCi/ L</td>
<td>2.5E-1</td>
<td>--</td>
<td>8.4E-2</td>
<td>2.2E-1</td>
</tr>
<tr>
<td>Meat pCi/ kg</td>
<td>3.0E-1</td>
<td>--</td>
<td>1.0E-1</td>
<td>3.0E-1</td>
</tr>
<tr>
<td>Fish pCi/ kg</td>
<td>4.5E-1</td>
<td>4.5E-1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Shellfish pCi/ kg</td>
<td>4.5E-1</td>
<td>4.5E-1</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
## Usage Factors - Child

<table>
<thead>
<tr>
<th>Media</th>
<th>Fresh Water</th>
<th>Salt Water</th>
<th>Elevated</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water L/ yr</td>
<td>510</td>
<td>Zero</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Air m³/ yr</td>
<td>--</td>
<td>--</td>
<td>3700</td>
<td>3700</td>
</tr>
<tr>
<td>Crops kg/ yr</td>
<td>546</td>
<td>--</td>
<td>546</td>
<td>546</td>
</tr>
<tr>
<td>Milk L/ yr</td>
<td>330</td>
<td>--</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>Meat kg/ yr</td>
<td>41</td>
<td>--</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td>Fish kg/ yr</td>
<td>7</td>
<td>7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Shellfish kg/ yr</td>
<td>3</td>
<td>3</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
# Pathway Dose – Child, mrem/yr

<table>
<thead>
<tr>
<th>Media</th>
<th>Fresh Water</th>
<th>Salt Water</th>
<th>Elevated</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Ingest.</td>
<td>5.2E-5</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Breathing</td>
<td>--</td>
<td>--</td>
<td>3.6E-5</td>
<td>3.3E-4</td>
</tr>
<tr>
<td>Crops</td>
<td>5.6E-5</td>
<td>--</td>
<td>1.8E-4</td>
<td>1.7E-3</td>
</tr>
<tr>
<td>Milk</td>
<td>1.7E-5</td>
<td>--</td>
<td>5.6E-6</td>
<td>1.7E-5</td>
</tr>
<tr>
<td>Meat</td>
<td>2.5E-6</td>
<td>--</td>
<td>8.4E-7</td>
<td>2.5E-6</td>
</tr>
<tr>
<td>Fish</td>
<td>6.3E-7</td>
<td>6.3E-7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Shellfish</td>
<td>2.8E-7</td>
<td>2.8E-7</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Total</td>
<td>1.3E-4</td>
<td>9.0E-7</td>
<td>2.2E-4</td>
<td>2.1E-3</td>
</tr>
</tbody>
</table>
“Dilution Factor” -- Liquid

- 1.0 Ci discharged in 1000 gal.
  - equals concentration of $2.6E-1 \text{ uCi/mL}$
- Dilution flow = 200,000 gpm
  - equals 450 ft³/sec, or 4E+11 L/yr
- Mixing ratio = 0.2
- Concentration in field = 4.9E-1 pCi/L
  - equals $4.9E-10 \text{ uCi/mL}$
- “Dilution Factor” = $2.6E-1 / 4.9E-10$
  - equals 5.3E+8
“Dilution Factor” -- Airborne

- 1.0 Ci discharged at 100,000 cfm
  - equals 3.2E-8 Ci/sec release rate
  - equals concentration of 6.7E-10 uCi/cc
- \( \chi/Q \) (ground-level release) = 1E-5 sec/m\(^3\)
- Concentration in field = 3.2E-13 Ci/m\(^3\)
  - equals 3.2E-13 uCi/cc
- “Dilution Factor” = 6.7E-10 / 3.2E-13
  - equals 2.1E+3
“Dilution Factor” Comparison

- Liquid Effluent “Dilution Factor”...
  \[5.3\times10^8\]
- Airborne Effluent “Dilution Factor”...
  \[2.1\times10^3\]
- RG-1.109 modeling assumptions mean that liquid effluents appear to be diluted by an additional five orders of magnitude when compared to airborne effluents!!
“Dilution Factor” – Water Vapor

1.0 Ci discharged at 100,000 cfm
- concentration of 6.7E-10 uCi/cc air
- air at 90°F, 40%RH = 1.4E-5 g H₂O/cc air
- 6.7E-10 / 1.4E-5 = 4.8E-5 uCi/mL H₂O

Concentration in field = 3.2E-13 uCi/cc air
- Absolute humidity = 5.6E-6 g H₂O/cc air
- 3.2E-13 / 5.6E-6 = 5.7E-8 uCi/mL H₂O

“Dilution Factor” = 4.8E-5 / 5.7E-8
- equals 8.4E+2... within factor of 3 of airborne DF
“Dilution Factor” – Water Vapor

- Airborne Effluent “Dilution Factor”...
  \[ 2.1 \times 10^3 \]
  - \( x/Q \) accounts for volumetric dilution between release point and receptor

- Water Vapor “Dilution Factor”...
  \[ 8.4 \times 10^2 \]
  - What about all of the natural water vapor in air?

- RG-1.109 modeling assumptions do not appear to account for “dilution” by natural water vapor in air! Is this reasonable?
Model in Recent Literature

- Uses “PUFF-PLUME” dispersion model... comparable to $\chi/Q$ dispersion? Not sure, but most likely it is.
- Provides equations for calculating ingestion doses from vegetables, milk, beef, fish, and water
- Alternative to RG-1.109?
Concentration in Vegetation

\[
C_T^V = \frac{\text{CONC} \times 0.75 \times 0.5}{H},
\]

where

- \( C_T^V \) = concentration in vegetation, Bq g\(^{-1}\);
- \( \text{CONC} \) = atmospheric concentration, Bq m\(^{-3}\);
- 0.75 = fraction of plant mass that is water (U.S. NRC 1977);
- 0.5 = concentration ratio of plant tritium to atmospheric tritium (Hamby and Bauer 1994); and
- \( H \) = absolute humidity at the time of the accident (SRS annual average of 11 g m\(^{-3}\) used if no other data available) (Hamby 1990\(^{\dagger}\)).

- Virtually identical to RG-1.109 equation
Dose – Leafy Vegetables

\[
\text{Dose}_{\text{leafy}} = \frac{\text{CONC} \times DCF \times 0.75 \times 0.54 \times CF \times I_t}{H} \int_{0}^{30} e^{-\lambda_{\text{W}}t} \, dt
\]

(4)

where

\[
\begin{align*}
CF &= \text{conversion factor (1,000 g kg}^{-1}) \text{; and} \\
\lambda_{\text{W}} &= \text{disappearance rate for tritium in vegetable water (1 d}^{-1}).
\end{align*}
\]

- Note allowance for tritium loss following harvest, with an integral half-life of 1 day in leafy vegetables.
Dose - Vegetables

\[ Dose_{\text{veg}} = \frac{CONC \times DCF \times CF \times 0.75 \times 0.54}{H} \left\{ \int_0^{30} e^{-\lambda_w t} \right\} \]

\[ \times \left[ I_{v-30} + \frac{I_{v-335}}{30 d} \times \int_{30}^{365} e^{-\lambda_{it}} \right] \]. \quad (5)

- Also allows for tritium removal (loss) mechanisms following harvest
Differences from RG-1.109

- Underlying approach very similar to RG-1.109, except...
- Allows for loss of tritium from vegetation following harvest
- Different usage factors:
  - Leafy: 21 kg/yr vs. 26 kg/yr
  - Vegetable: 129 kg/yr vs. 520 kg/yr
- Different Ingestion DCFs:
  - Based on ICRP-30 vs. ICRP-2
Tritium Dose Conversion Factors

- **RG-1.109 Ingestion** – mrem/pCi
  - Adult: 1.05E-7  Teen: 1.06E-7
  - Child: 2.03E-7  Infant: 3.08E-7

- **RG-1.109 Inhalation** – mrem/pCi
  - Adult: 1.58E-7  Teen: 1.59E-7
  - Child: 3.04E-7  Infant: 4.62E-7
  - Inhalation DCFs 50% higher than ingestion

- **ICRP-30** – 1.73E-11 Sv/Bq
  - Non age-specific
  - Ingestion & Inhalation DCFs equal: 6.40E-8 mrem/pCi
Summary

- Regulatory Guide 1.109 airborne models for tritium do yield higher dose than liquid models in most cases.
- Underlying model assumptions seem to yield higher degree of “dilution” for liquid effluents compared to airborne effluents.
- Airborne model does not seem to adequately describe additional “dilution” by natural water vapor in air.
Summary (continued)

- New models do not appear fundamentally different from RG-1.109, but may yield lower airborne doses due to differences in:
  - Usage factors
  - Dose Conversion Factors (ICRP-30)
  - Tritium losses following harvest
Measuring tritium in environmental samples

- Vegetation should act as a good indicator of tritium in the environment... why?
- Literature reports plants reach equilibrium with atmospheric water within 30 min.
- Literature also reports tritium+water turns over in plant with half life of 1 day.
- Water is easy to extract from plant for tritium analysis.
- May help shed light on how representative airborne tritium models are.
- In-field airborne tritium sampling??