C-14 Background, Pathway, and Dose Calculation Analysis

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2013 RETS/REMP & GROUNDWATER PROTECTION WORKSHOPS

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Principle Investigators

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Background

Objective: Develop technical bases and guidance for enhanced accuracy and precision of carbon-14 dose estimates.

- Continuation of “C-14 Dose Calculation Methods at Nuclear Power Plants” EPRI Report 1024827
- Regulatory Guide 1.109 Revision 1 Issued 1977 Based on ICRP 2
  - Encompasses Many of the Limitations of the Time
  - Recommendations of the ICRP Have Changed substantially
  - Several Parameters in the Calculation of C-14 Dose Changed Since 1977
- The Understanding of C-14 in the Environment has Evolved Significantly in Recent Years
Approach

• Extensive Literature Search Conducted
  – C-14 Behavior in the Environment
• Assessment of Radiocarbon Dating Industry for Detection of C-14
  – Accelerator Mass Spectrometry (AMS)
• Case Studies at Nuclear Power Plants Using AMS
  – Two Sites
• Comparisons to Regulatory Guide 1.109
  – Several Improvement Opportunities and Updates
Radiocarbon Laboratories & Analysis

- Units & Terms Used by Radiocarbon Laboratories
  - Radiocarbon Age
  - Fraction or % Modern Carbon (pMC)
  - \( \Delta^{14}C \)
  - Specific Activity (Bq/kg C or pCi/kg C)
  - Reference Standards
- Conversion of % Modern Carbon to Concentration C-14 (pCi/kg Fresh Weight of Sample)
- Accuracy and Precision for AMS
Percent Modern Carbon in the Troposphere during and Following Weapons Testing
Illustration of Localized $^{14}$CO$_2$ Signatures ($\Delta 14C$)
Suess Effect, Trends in CO₂ Releases

Atmospheric CO₂ Recorded at Mauna Loa Observatory (Tans & R. Keeling 2013)
C-14 in the Environment

• Models of Carbon Distribution in the Environment
  – Specific Activity Models (Everything is in Equilibrium)
  – Compartment Models

• Transfer Mechanisms for Carbon in Plants
  – Less Than 2% of the Total Carbon in Plants is Provided through the Roots
  – More than 98% if the Total Carbon in Plants is Provided by Photosynthesis Fixing Carbon from the Air

• Photorespiration
  – High Temperature and Low Moisture
Example Compartment Model for Carbon in Plants

Conceptual Illustration of a Compartment Model for C-14 Atmospheric Releases (Derived from Takahashi, et.al. 2011)
Carbon Inventories

• Inventories*
  – Ocean Inventory 38,000 Pg C (P is $10^{15}$)
  – Atmospheric Inventory 730 Pg C
  – Terrestrial Inventory 2,200 Pg C

• Most Carbon Eventually Resides in the Oceans

*Matsumoto & R. M. Key 2004
Data Comparisons with Regulatory Guide 1.109

- **Comparison of Transfer Coefficients for $^{14}$C**
  - Canadian Standards Association
  - German Regulatory Authority
  - Others
    - Milk Generally Comparable (some less than 1.109)
    - Meat & Eggs Slightly Less
- **Annual Intake (Usage) of Various Food Stuffs**
  - Trends From US Department of Agriculture
Case Studies PWR 1

– Collard Greens (Late July to September 24, 2012)

<table>
<thead>
<tr>
<th>Sample Location &amp; Number</th>
<th>Location Description</th>
<th>Percent Modern Carbon (pMc)</th>
<th>Specific Activity (pCi/ kg of Carbon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>Indicator Garden</td>
<td>103.2±.3</td>
<td>6256</td>
</tr>
<tr>
<td>B-1</td>
<td>Control Garden</td>
<td>104.6±.3</td>
<td>6341</td>
</tr>
<tr>
<td>C-1</td>
<td>Indicator Garden</td>
<td>104.2±.3</td>
<td>6317</td>
</tr>
</tbody>
</table>

– No Detectable Contribution Attributed to the Station
<table>
<thead>
<tr>
<th>Date</th>
<th>Vegetation</th>
<th>Plant Mass that is Natural Carbon</th>
<th>Concentration</th>
<th>Attributed to Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/2011</td>
<td>Peppers</td>
<td>0.030</td>
<td>189.7</td>
<td>188.1</td>
</tr>
<tr>
<td>11/2011</td>
<td>Potatoes</td>
<td>0.103</td>
<td>656.9</td>
<td>643.0</td>
</tr>
<tr>
<td>9/2012</td>
<td>Potatoes</td>
<td>0.103</td>
<td>651.4</td>
<td>645.8</td>
</tr>
<tr>
<td>9/2012</td>
<td>Corn</td>
<td>0.120</td>
<td>755.6</td>
<td>749.2</td>
</tr>
<tr>
<td>9/2012</td>
<td>Potatoes</td>
<td>0.103</td>
<td>648.6</td>
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</tr>
</tbody>
</table>

- Concentration Units pCi/kg Fresh Sample
Case Studies (C-14 Ingestion Doses*)

• PWR 1
  – None Measurable

• PWR 2
  – Child Bone Dose From Fresh Produce
  – 2.9E-3 to 2.5E-2 mrem

*Using Equation 13 Regulatory Guide 1.109
Equation C-8 Regulatory Guide 1.109

\[ C_{14}^V(r, \Theta) = 3.17 \times 10^7 p Q_{14} \left[ \frac{X}{Q} \right] (r, \Theta)^{0.11/0.16} \]

- \( C_{14}^V(r, \Theta) \) is the concentration of carbon-14 in vegetation grown at location \((r, \Theta)\) in pCi/kg
- \( Q_{14} \) is the annual release rate of carbon-14 in Ci/yr, Note that “C-14 is assumed to be released in oxide form (CO or CO\textsubscript{2})”
- 0.11 is the total plant mass that is natural carbon, dimensionless
- 0.16 is equal to the concentration of natural carbon in the atmosphere (gC/m\textsuperscript{3}),
- 3.17\times10\textsuperscript{7} is equal to \((1.0\times10^{12} \text{ pCi/Ci})(1.0\times10^{3} \text{ g/kg})/(3.15\times10^{7} \text{ sec/yr})
- \( p \) is the fractional equilibrium ratio, dimensionless
Advances in Information & Technology

• Concentration of Natural Carbon in the Atmosphere
  – .16 gC/m³ in Regulatory Guide 1.109 (1977)
  – Currently .20 gC/m³ (2010)*
  – The CO₂ in the Atmosphere is on an Increasing Trend

• Total Plant Mass that is Natural Carbon
  – .11 in Regulatory Guide 1.109 (1977)
  – Based IAEA Report #472* A Sampling by Vegetation Types
    • Leafy and Non-Leafy Vegetables .030
    • Root Crops .046
    • Fruit .062
    • Tubers .103
    • Sweet Corn .120
    • Feed Corn .380
    • Cereals .390
    • Leguminous Vegetables (Seed) .410

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