INTERNAL DOSIMETRY
AT NUCLEAR POWER PLANTS

Fission and Activation Products
Actinides
Case Studies
Learning Objectives

• Identify radionuclides of concern at nuclear power plants
• Identify appropriate bioassay methods
• Analyze two case studies
Exposure Conditions

• Usually external dose is more of issue than internal dose
• Activation products such as Co-60 exist in corrosion around pipe seals and similar locations
• Tritium always around, especially at BWRs
• Fission products mostly contained in fuel rods, except for cases of fuel failure and “tramp” U
• Failed fuel releases volatile nuclides such as Cs-137 and I-131
• “Control β-γ and you control α”...usually
Fission and Activation Products

• Beta-gamma emitters: Cs-137, Co-60, etc.
  In general, in-vivo bioassay is excellent
typical MDA is <0.1% ALI

• Iodines:
  External thyroid counting fairly easy for
gamma-emitters; because of high thyroid
doses, air monitoring important

• Tritium:
  Sensitive bioassay (MDA→ CEDE <1 mrem) air
sampling difficult; low dose/unit intake
Co-60

Strong gamma-emitter (1.17, 1.33 MeV, each 100%), 5.7 yr half-life

Easy to detect, MDA for WBC = 0.1 kBq

DCF

\[
\begin{align*}
W_{\text{inh}} &= 9 \times 10^{-9} \text{ Sv/Bq} \quad (33 \text{ mrem/μCi}) \\
Y_{\text{inh}} &= 6 \times 10^{-8} \text{ Sv/Bq} \quad (0.2 \text{ rem/μCi}) \\
W_{\text{ing}} &= 3 \times 10^{-9} \text{ Sv/Bq} \quad (11 \text{ mrem/μCi}) \\
Y_{\text{ing}} &= 7 \times 10^{-9} \text{ Sv/Bq} \quad (26 \text{ mrem/μCi})
\end{align*}
\]

ALI

\[
\begin{align*}
W_{\text{inh}} &= 6 \times 10^6 \text{ Bq} \quad (200 \text{ μCi}) \\
Y_{\text{inh}} &= 1 \times 10^6 \text{ Bq} \quad (30 \text{ μCi}) \\
W_{\text{ing}} &= 2 \times 10^7 \text{ Bq} \quad (500 \text{ μCi}) \\
Y_{\text{ing}} &= 7 \times 10^6 \text{ Bq} \quad (200 \text{ μCi})
\end{align*}
\]
Co-60 con’t

• Can exist as either Class W or Class Y material
• If process knowledge is inadequate, can distinguish by sequential whole-body counting over a few weeks.
• Because so easy to detect via WBC, frequently serves as a marker for other, harder to detect radionuclides, such as actinides
• Radionuclide ratios determined from analysis of air filters or smears
Tritium

- A ubiquitous contaminant; HTO or T$_2$O is dosimetrically more significant than T$_2$ gas because of rapid uptake and exchange with body water; tritiated organic compounds are frequently used in biological research.

- Reference man body water = 43 L, daily water intake is 3.0 L, so biological time constant = 3/43 = 0.0698; Biological half-life T(b) = 0.693/0.0698 = 10 d

- HTO absorbed directly through skin; dose coefficient for inhalation includes this pathway (0.33 intake by skin)
Tritium Dosimetry

• All soft tissue (65 kg) is considered to be uniformly irradiated.
• DCF is $2 \times 10^{-11}$ Sv/Bq (0.006 mrem/µCi)
• MDA for BLS urinalysis = 2000 dpm/L
• Rule of thumb: 1 µCi/L in urine = 100 mrem for samples soon after acute intake
• Treatment is by forcing fluids (water works, but beer is preferred, because alcohol inhibits pituitary secretion of anti-diuretic hormone, which inhibits kidney re-absorption of water)
## DOSE IMPLICATIONS OF TRITIUM IN URINE

(1000 dpm/L at 1 day after end of Chronic Exposure of t days duration, or at t days after an Acute Exposure)

<table>
<thead>
<tr>
<th>Days since Acute Exposure or Days of Chronic Exposure (t)</th>
<th>ACUTE INHALATION</th>
<th>CHRONIC INHALATION</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Intake (dpm)</td>
<td>CEDE (mrem)</td>
</tr>
<tr>
<td>1</td>
<td>44 500</td>
<td>0.00126</td>
</tr>
<tr>
<td>2</td>
<td>47 700</td>
<td>0.00135</td>
</tr>
<tr>
<td>3</td>
<td>51 100</td>
<td>0.00145</td>
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<tr>
<td>4</td>
<td>54 800</td>
<td>0.00155</td>
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<td>5</td>
<td>58 700</td>
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<tr>
<td>6</td>
<td>63 000</td>
<td>0.00178</td>
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<td>67 200</td>
<td>0.00191</td>
</tr>
<tr>
<td>8</td>
<td>72 600</td>
<td>0.00205</td>
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<td>10</td>
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<td>0.00236</td>
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<tr>
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<td>110 000</td>
<td>0.00311</td>
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<td>21</td>
<td>179 000</td>
<td>0.00506</td>
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<td>472 000</td>
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<td>768 000</td>
<td>0.0218</td>
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<tr>
<td>49</td>
<td>1 250 000</td>
<td>0.0354</td>
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<tr>
<td>56</td>
<td>2 030 000</td>
<td>0.0575</td>
</tr>
<tr>
<td>60</td>
<td>2 680 000</td>
<td>0.0760</td>
</tr>
<tr>
<td>365</td>
<td></td>
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</tr>
</tbody>
</table>
Cs- 137

- Important because of long physical half-life and biological accumulation.
- Uptake is 100%; two retention components:
  - 10% with 2-d biological half-life and 90% with 110 d.
- $\text{DCF} = 8.6 \times 10^{-9} \text{ Sv/Bq (0.03 rem/µCi)}$ inhal.
  $\quad = 1.4 \times 10^{-8} \text{ Sv/Bq (0.05 rem/µCi)}$ ingest.
- $\text{ALI} = 6 \text{ MBq inhalation, 4 MBq ingestion}$
- $\text{MDA for 30 min WBC} = 40 \text{ Bq (~ 1 nCi)}$
Cs-137 (con’t)

- Cs is a potassium analogue, so is uniformly distributed throughout body (mostly muscle).
- Body burden from global fallout is about 0.3 Bq Cs-137 per g K, or 40 Bq average.
- Excretion of Cs can be enhanced by giving “prussian blue” (ferric ferricyanate), 1-3 g three times a day up to three weeks; inhibits reuptake from GI tract, so reduces biological half-life to 35 d and is well tolerated.
Iodines

• All ALI’s (except I-120m, I-128, I-134) are based on non-stochastic limit of 500 mSv CODE to thyroid ( $w_T = 0.03$)

• Volatile, so easily dispersed; treatment is usually blocking with stable KI (325 mg); unblocked thyroid deposition = 25%; KI administered within 1-2 minutes lowers to 2%, after 6 hr lowers to 10%, no effect more than 12 hr after intake; however, daily dose prevents re-uptake of circulating iodide

• MDA in thyroid for photon-emitting isotopes is less than 0.4 Bq
Actinide Dosimetry

- In general, actinides have long physical half-lives and also long biological half-lives; consequently, the CDE is actually delivered over a protracted time.
- Most are alpha emitters with little gamma, so low external hazard, high internal; low $f_1$’s.
- With the exception of uranium, actinides deposit in bone and liver; usually ALI is determined by non-stochastic limit for bone surface following inhalation.
Assessing Intake Mode from Sequential Whole-Body Counts

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R. L. Nimitz, USNRC, King of Prussia, PA
R. Pedersen, USNRC, Rockville, MD
Exposure Circumstances

• Two workers removing debris from a fuel transfer canal during a refueling outage
• No respiratory protection or air sampling provided
• Workers found to have facial contamination on exit, and referred for whole-body counts
• Incident is described in NRC information notice number 97-36
Worker 1 WBC Data

\[ \text{ALI (Y)} = 1 \times 10^6 \text{ Bq} \]
Need for Careful Assessment

• Plant had a history of fuel failure
• Analysis of debris samples showed high $\alpha/\beta$ activity ratios and various TRU, including $^{238}\text{Pu}$, $^{239,240}\text{Pu}$, $^{241}\text{Am}$, and $^{244}\text{Cm}$
• Initial calculation of CDE to bone surfaces exceeded 1 Sv
• Results from fecal samples for TRU were highly variable
Worker 1: Fits to WBC Data

$^{60}\text{Co}$, Bq

Days post intake

- black squares: actual
- blue triangles: Class Y
- red circles: Class W
- red line: Ingestion

6/25/2012
Determining “Best Fit” to data

• Typically in bioassay data analysis, we assume an intake model, and use least squares to determine the best estimate of the intake

• We can also compare intake models, by comparing the sum of squared deviations between predicted and observed values of the bioassay data
Ingestion vs. Inhalation

• The first comparison of models involved assuming different fractions of inhalation vs. ingestion, e.g.:
  – 100% inhalation
  – 90% inhalation, 10% ingestion
  – 80% inhalation, 20% ingestion
  – etc., etc., etc.

• Using ICRP 30 models, 1 μ AMAD
Worker 1: Summed square deviations vs. ingestion fraction

% Ingestion

ICRP-30 model, 1 μ

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Worker 1: Best fit to WBC Data

$^{60}\text{Co}$, Bq

Days post intake

ICRP-30 model, 1 $\mu$

Actual

Fit 91\% Ing+9\% Y

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What About Particle Size?

• The combination of inhalation and ingestion could reflect a larger particle size, resulting in greater deposition in the upper respiratory tract, leading to mucociliary clearance and swallowing of inhaled material.

• Repeat least squares analysis for 100% inhalation vs. particle size.
Worker 1: Summed squared deviations vs. particle size (inhalation only)

Particle size, microns
Worker 1: Best fit to WBC data, inhalation only

ICRP-66 model

Time post intake, days

$^{60}\text{Co}$, Bq

Actual
Fit 20 micron

100000
10000
1000
100
0
6/25/2012
Dose Assessment

• If 1 μ particles, inhalation plus ingestion:
  $^{60}$Co intake = 1.4 kBq inh. + 14 kBq ing.
  CEDE = 4.4 mSv; CDE (BS) = 77 mSv

• If 20 μ particles, inhalation only:
  $^{60}$Co intake = 400 kBq
  CEDE = 3.4 mSv; CDE (BS) = 59 mSv

• Dose is almost entirely from TRU
Conclusions

• Accurate intake assessment is needed when TRU nuclides are involved
• More complete fecal sampling (especially at early times) would have helped
• Ease of detection of $^{60}$Co by WBC makes it useful as a marker radionuclide
• Only definitive way to characterize intake would be by particle size analysis
Alpha Emitter Intakes at NPPs

- Two reactors have been under major refurbishment for five years.
- Lay-up of the reactors was in place for many years before this (approximately ten years total).
- Significant decontamination efforts had been conducted prior to refurbishment to improve conditions for working:
  - H-3 source term had been reduced.
  - Beta gamma contamination levels were low.
  - Much work was conducted without respiratory protection.
- As contamination ages, ratios decrease and the alpha proportion becomes more significant dosimetrically.
- Unaware that Beta to Alpha ratios were now in the range of 7:1, vs. 10,000:1 during operation.
Refurbishment Work

• U2 feeder work completed successfully in fall 2009
  – No detection of any beta airborne activity
  – Low beta contamination levels
• Unit 1 commenced at the end of November 2009
  – Same controls used in Unit 2 were used in Unit 1
  – Airborne beta activity detected early
  – Additional controls were placed on work
  – Work tented to enclose activity
  – Further monitoring added
  – Detected alpha contamination
Dose Assessments

- Difficult to assess dose based on limited information
- Prioritized assessment process developed
- Dose estimates based on:
  - Vault access logs that documents all entries for all personnel
  - Air sample results (beta and alpha)
  - Conservative models to determine the hazard levels during work evolution
- All workers in vault assessed for possible exposures:
  - Before building tents for feeder work
  - After tents until the end of feeder work
 Significant Challenges

- Lack of familiarity with alpha - not an issue in operating plants so individual knowledge limited
- Large number of people to reach out to
- Large-volume Alpha bioassay analysis available but limited and results not quickly available
- Alpha bioassay analysis process is complicated, therefore dose results not quickly available
- New suppliers required for fecal analysis
- Alpha related work restrictions necessary to ensure sample purity
- Complicated issue to explain and lack of trust
- Several stakeholders
Interim actions

• Alpha monitoring controls were added to U1 and U2 vault for general access:
  – Personal alpha contamination monitors
  – Routine air sample counting for alpha
• Back to Work
  – Staged return to work process developed (all work was suspended for 2 months)
  – Return to work criteria and plan for work in both vaults were established
    – additional alpha contamination and airborne monitoring and controls included
  – Comprehensive alpha characterisation of systems and areas
• Protocols/procedures developed
  – Work planning criteria and work controls for alpha
  – Alpha monitoring and air sampling protocols
  – Alpha free release standards and protocols
  – Verification waste streams to consider alpha
  – Incident response for alpha, including dosimetry requirements
Summary of Improvements Made

• Improvements initially focused on restart, but now extended to all operating units and fuel handling:
  – New standards for alpha control
  – New RPPE
  – New procedures
  – New training
  – New alpha instrumentation
  – Enhanced air sampling program
  – New alpha dosimetry processes
  – Permits revised for alpha controls
  – Engaged external experts
Bioassay sampling statistics

• 556 people were in the vault during the work period in question
  – Initial estimates indicated up to 193 could require further bioassay testing
• 552 personnel were tested - at least one sample
  – 33 individuals provided multiple samples (average 4 each)
  – 9 individuals remain on ongoing sampling
  – Process of dosimetry has taken 12 months to complete
• Final results confirm initial estimates
Alpha Contamination Event Dose Histogram
(Updated to 29 November, 2010)

Maximum dose = 8.8 mSv
Dose limit = 50 mSv
Future Activities

• Extent of condition work expanded to identify any historical doses
  – Workers in restart from previous work
  – Workers in fuel handling
  – Workers from other facilities
• 1008 individuals will be sampled
  – To date 700 samples complete
• Work is ongoing to assess doses to all personnel
  – Approximately ten percent of those sampled indicated potential intakes
  – Challenge is sensitivity of fecal historically, lack of lower threshold urinalysis capability and volume of personnel
  – Working with industry to create new bioassay laboratory
  – Ongoing, routine dosimetry practices to be defined
Summary

- Significant radiological event with large number of workers exposed to alpha and large consequences for company
- Ongoing work to assess historical impact of alpha and continue to identify any other issues
- Major contributors were lack of understanding of characterization implications and reliance on old assumptions
- Extremely vital to have accurate technical basis, believe instruments when indicating an abnormal condition and challenge assumptions