Simultaneous Optimization of Tallies in Difficult Shielding Problems

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Problem

• Analog Monte Carlo tallies tend to have uncertainties inversely proportional to flux
  – Low flux areas hardest to converge
  – Computation time is controlled by worst uncertainty

• Biasing (typically weight windows) helps move particles to areas of interest
  – Spend more time on “important” particles
  – Sacrifice results in “unimportant” areas
  – Different biasing for different tallies
Mesh Tallies

- Monte Carlo is used to calculate many tallies
  - Mesh tally - answers everywhere
  - Wide range in relative uncertainties tallies

- Many applications need mesh tallies
  - Dose rate maps
  - Activation of surrounding materials
  - Burn up of fuel pins in reactors
Example – Gamma-ray litho-density log

- **Problem Description from**


- **Source:** Cs-137, 2.7 Ci

- **Detectors:** NaI
  - Near: 2x2 at 20 cm
  - Far: 4x4 at 40 cm

- **Borehole:** 20 cm diam

- **Tool:** 10 cm diam
Analog Calculation

**Total Photon Flux**
- Near: $1.12 \times 10^3$ (±25%)
- Far: $7.98 \times 10^1$ (±53%)

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo</td>
<td>1200</td>
</tr>
</tbody>
</table>
How To Improve Uncertainties

- Weight windows/biased source with CADIS
  - Calculate adjoint fluxes from an adjoint source at one of the detector locations
    \[ q^+(\vec{r}, E) = \sigma_d(\vec{r}, E) \]
  - Estimate of response
    \[ R = \int \int \phi^+(\vec{r}, E) q(\vec{r}, E) \, d\vec{r} \, dE \]
  - Create importance map
    \[ w(\vec{r}, E) = \frac{R}{\phi^+(\vec{r}, E)} \]
  - and consistent biased source
    \[ \hat{q}(\vec{r}, E) = \frac{1}{R} q(\vec{r}, E) \phi^+(\vec{r}, E) \]
    \[ w_0(\vec{r}, E) = \frac{R}{\phi^+(\vec{r}, E)} \]
  - Run the forward Monte Carlo
How To Improve Uncertainties

- CADIS works
  - Improves the FOM for that detector
  - At the expense of tracking particles deep into the formation
  - At the expense of the other detector

- Try adjoint source in both detectors
  - Need more adjoint source at far detector
Forward-Weighted CADIS

- To get both detectors with same relative uncertainties, the amount of adjoint source in each detector location needs to be inversely proportional to the expected response.

<table>
<thead>
<tr>
<th>For the calculation of:</th>
<th>Use adjoint source:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi(\vec{r}, E)$</td>
<td>$q^+(\vec{r}, E) = \frac{1}{\phi(\vec{r}, E)}$</td>
</tr>
<tr>
<td>$\int \phi(\vec{r}, E) dE$</td>
<td>$q^+(\vec{r}) = \frac{1}{\int \phi(\vec{r}, E) dE}$</td>
</tr>
<tr>
<td>$\int \phi(\vec{r}, E) \sigma_d(\vec{r}, E) dE$</td>
<td>$q^+(\vec{r}, E) = \frac{\sigma_d(\vec{r}, E)}{\int \phi(\vec{r}, E) \sigma_d(\vec{r}, E) dE}$</td>
</tr>
</tbody>
</table>
Forward-Weighted CADIS

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward DO</td>
<td>11</td>
</tr>
<tr>
<td>Adjoint DO</td>
<td>29</td>
</tr>
<tr>
<td>Monte Carlo</td>
<td>120</td>
</tr>
</tbody>
</table>

Total Photon Flux
Near $1.41 \times 10^3 (\pm 1.1\%)$
Far $3.71 \times 10^1 (\pm 1.3\%)$
FW-CADIS for Mesh Tally

- Mesh tally is just a large set of tallies where we want roughly uniform relative uncertainties

- Adjoint source: the response function divided by the expected forward response in each cell of the mesh tally volume
SCALE Sequence: MAVRIC

---PARM=check---

---PARM=forward---

---PARM=denovo---

---PARM=impmap---

Input

BONAMI / NITAWL or BONAMI / CENTRM / PMC

Resonance cross-section processing

DO forward cross sections
Optional: first-collision source calculation
3-D discrete ordinates calculation

DO adjoint cross sections
Optional: first-collision source calculation
3-D discrete ordinates calculation

Optional: importance map and biased source

3-D Monte Carlo

ICE Denovo

ICE Denovo

CADIS stuff

Monaco

End

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Dose Rates Near A Cask Array

Independent Spent Fuel Storage Installation

Dose rate limit at boundary of controlled area is 25 mrem/yr
Spent Fuel Cask

- **Source:** Mid-sized PWR
  - Burned: 55,000 MWd/MtU
  - Cooling: 10 years
  - Cask holds 1/6th core
  - $4.7353 \times 10^{16}$ gammas/second

### Fresh Fuel (kilograms)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium (4.2%)</td>
<td>Others</td>
</tr>
<tr>
<td>U-235</td>
<td>1936.2</td>
</tr>
<tr>
<td>U-238</td>
<td>44163.8</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
</tr>
<tr>
<td>N</td>
<td>3</td>
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<tr>
<td>O</td>
<td>6209</td>
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<tr>
<td>Al</td>
<td>5</td>
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<tr>
<td>Si</td>
<td>7</td>
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<tr>
<td>P</td>
<td>14</td>
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<tr>
<td>Ti</td>
<td>5</td>
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<tr>
<td>Cr</td>
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<td>Fe</td>
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<tr>
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<td>3</td>
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<tr>
<td>Ni</td>
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<tr>
<td>Zr</td>
<td>10071</td>
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<tr>
<td>Nb</td>
<td>33</td>
</tr>
<tr>
<td>Mo</td>
<td>18</td>
</tr>
<tr>
<td>Sn</td>
<td>165</td>
</tr>
</tbody>
</table>
Geometry Model

- **Simplified cask**
  - Homogenized, uniform source

- **Array of 2 x 4**
  - Concrete pad – 60 cm
  - 1 km$^2$ of soil, 5 m thick
  - Air up to 500 m
Analog Calculation

- 560 hours
- Relative uncertainty increases as dose rate decreases
- Difficult to judge where the 1.2×10^-5 rem/hr contour
Source Strength

\[ q(\vec{r}, E) \]
FW-CADIS

Estimate of forward flux

$$\phi(\vec{r}, E)$$
Estimate of dose rate

\[ \int \phi(\vec{r}, E) \sigma_d(\vec{r}, E) \, dE \]
Adjoint source strength

\[ q^+(\vec{r}, E) = \frac{\sigma_d(\vec{r}, E)}{\int \phi(\vec{r}, E) \sigma_d(\vec{r}, E) dE} \]
FW-CADIS

Adjoint flux for 1 MeV photons

$$\phi^+ (\vec{r}, E) \quad R = \iiint \phi^+ (\vec{r}, E) q(\vec{r}, E) d\vec{r} dE$$

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FW-CADIS

target weight windows for 1 MeV photons

\[ w(\vec{r}, E) = \frac{R}{\phi^+(\vec{r}, E)} \]
Biased source strength

\[ \hat{q}(\vec{r}, E) = \frac{1}{R} q(\vec{r}, E) \phi^+(\vec{r}, E) \]
Biased source strength

\[
\hat{q}(\vec{r}, E) = \frac{1}{R} q(\vec{r}, E) \phi^+(\vec{r}, E)
\]

\[
w_0(\vec{r}, E) = \frac{R}{\phi^+(\vec{r}, E)}
\]
**FW-CADIS**

**Dose rate (rem/hr)**

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward DO</td>
<td>17 min</td>
</tr>
<tr>
<td>Adjoint DO</td>
<td>21 min</td>
</tr>
<tr>
<td>Monte Carlo</td>
<td>108 hr</td>
</tr>
</tbody>
</table>

**Relative Uncertainty**

- 25 mrem/yr boundary
  - (1.2×10⁻⁵ rem/hr for 2000 hr/yr)

Located at \( r = 360 \) m
Are the Rel. Unc. more uniform?

PDF of relative uncertainties

CDF of relative uncertainties

78.4% of voxels have <=5% rel unc

96.6% of voxels have <=10% rel unc
Comparison to Analog

PDF for Analog

fraction of voxels

relative uncertainty

FW-CADIS (108 hours)

analog (560 hours)
**ICRS-11/RPSD 2008 Conference Logo**

- Eric Burgett (Georgia Tech)
- Neutron duct streaming
- Some artistic license taken

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**ICRS-11**
11th International Conference on Radiation Shielding

&

**RPSD-2008**
15th Topical Meeting of the Radiation Protection & Shielding Division of ANS

**Finding Your Way Through the Shielding Maze!**

- April 13-18, 2008 - Callaway Gardens, Pine Mountain, Georgia, USA
Summary

• FW-CADIS can be used to simultaneously optimize several tallies or a mesh tally – roughly uniform relative uncertainty

• MAVRIC provides automated use of powerful variance reduction techniques

• MAVRIC greatly simplifies the calculation of the controlled area boundary for a cask array

• **Bonus:** Can create conference logos with more uniform relative uncertainties
Discussion & Questions

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