Modeling Radiation Transport Using MCNP6 and Abaqus/CAE

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What is MCNP?

- **Monte Carlo N-Particle transport code**
  - Simulates neutron, photon, charged particle transport
  - Basis is random sampling
  - MCNP first released in 1977, available to world in 1983
- Applications: radiation shielding, medical physics, criticality safety, reactor design
How does MCNP work?

- **User specifies:**
  - Source
    - Type, energy, direction
  - Geometry
    - Planes, spheres, cylinders, boxes
  - Materials
  - Tallies
    - Number of particles, energy deposition, flux

- **Random Walk**
  - Based on nuclear data
Where does Abaqus/CAE come in?

• Building complex geometries with legacy constructive solid geometry (CSG) is difficult, time-consuming, and error-prone

• Solution: Hybrid geometry
  • New capability in MCNP6
  • Unstructured mesh (UM) created with Abaqus/CAE is embedded into CSG
  • Can use 1st and 2nd order hex, tet, and wedge elements
  • Gaps and overlaps allowed
Lead Sheet

- Source is plane wave of 1 MeV photons directed through 1 cm thickness of lead sheet
- Hand Calculation
  - Attenuation Equation:
    \[ \Phi = \Phi_0 e^{-\Sigma x} \]
    - Flux at distance \( x \)
    - Incident flux
    - Distance
    - Macroscopic cross section
- CSG
- Unstructured mesh – Abaqus/CAE
Lead Sheet: Comparison of Flux Results

Side view of photon flux in lead sheet from MCNP’s plotter.

3D view of photon flux in lead sheet from Abaqus/CAE.
Lead Sheet: Comparison of Flux Results

- Good agreement between hand calculation, CSG, Abaqus/CAE UM

Photon energy > 995 keV

Flux [photons/(cm² s)]

Distance (cm)
Photon Irradiation of Material Sample

- Experiment at LANL’s Ion Beam Materials Laboratory
- Proton beam irradiates metal target producing 55 keV photons
- Photons penetrate bottom plate of can and interact with sample
- How much is lost through bottom plate?
IBML Experiment: Comparison of Flux Results

Photon Flux
[photons/(cm² sec)]

MCNP’s Plotter

Side view (left) of can bottom. View of bottom of plate, side closest to beam (right).

Abaqus/CAE

3D view of photon flux results calculated by MCNP6 in can bottom. Quarter cut-out for viewing.
IBML Experiment: Comparison of Flux Results

Flux [photons/(cm\(^2\) sec)]

- Source of photons (metal target)
- CSG
- Abaqus/CAE UM

Distance along beam axis (cm)

Surface of can bottom closest to beam

Surface of can bottom closest to sample
Steel Bar Contaminated with Cobalt-60

- Co-60 sources can be mixed in with scrap metal and melted in steel mills, contaminating the entire batch of steel
  - Radioactivity detected in elevator buttons, 2008
- Scenario of contaminated steel bar on concrete floor with lead wall for shielding

Top view depicting contaminated steel scenario.
Contaminated Steel: Comparison of Flux Results

Photon Flux
[photons/(cm² sec)]

MCNP’s Plotter

Abaqus/CAE
Contaminated Steel: Comparison of Flux Results

- **Co-60**
  - Contaminated Steel
  - Lead Wall

Flux [photons/(cm² disintegration)]

Distance from center of floor (cm)
Contaminated Steel: Visualize Separate Parts in Abaqus/CAE

- Air
- Concrete Floor
- Lead Wall
- Co-60 Contaminated Steel

Photon Flux
[photons/(cm² sec)]
Contaminated Steel: Dose Rate in Room
Contaminated Steel: Dose Rate in Room

0.4 Ci Source

Dose rate (mrem/hr)

Distance from center of source (cm)

X axis (y=0)
Y axis (x=0)
Diagonal (y=x)

Very High Radiation Area
High Radiation Area
Radiation Area

Operated by Los Alamos National Security, LLC for the U.S. Department of Energy’s NNSA
Experiment Package in ACRR

- Irradiation of experiment package in Sandia National Laboratory’s research reactor, ACRR
- Aluminum can that holds two polymer coupons
- Orphan Abaqus/CAE mesh model of can, CSG model of ACRR

CSG model of ACRR with can. Side planar view (left), top planar view (right).

Orphan mesh model of experiment can. Half of can cut away for viewing.
## ACRR Experiment: Comparison of Results

<table>
<thead>
<tr>
<th>Geometry Description</th>
<th>Energy Deposition $J / (g \text{ MJ of reactor energy})$</th>
<th>Statistical Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSG</td>
<td>0.6836</td>
<td>0.0081</td>
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<tr>
<td>Abaqus/CAE UM</td>
<td>0.6836</td>
<td>0.0084</td>
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</table>
## MCNP6 Computer Run Time Comparisons

<table>
<thead>
<tr>
<th>Model</th>
<th>Type of Elements</th>
<th>Number of Elements</th>
<th>CPU Time (min)</th>
<th>Memory (GB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Sheet CSG</td>
<td>N/A</td>
<td>N/A</td>
<td>59.92</td>
<td>0.1</td>
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<tr>
<td>Lead Sheet UM</td>
<td>1st Order Hex</td>
<td>9226</td>
<td>229.53</td>
<td>0.1</td>
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<tr>
<td>Contaminated Steel CSG</td>
<td>N/A</td>
<td>N/A</td>
<td>40.01</td>
<td>0.1</td>
</tr>
<tr>
<td>Contaminated Steel UM</td>
<td>1st Order Tet</td>
<td>214 402</td>
<td>551.77</td>
<td>0.3</td>
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<tr>
<td>IBML Exp. CSG</td>
<td>N/A</td>
<td>N/A</td>
<td>45.94</td>
<td>0.1</td>
</tr>
<tr>
<td>IBML Exp. UM</td>
<td>1st Order Hex</td>
<td>112 064</td>
<td>224.75</td>
<td>0.3</td>
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<tr>
<td>ACRR Exp. CSG</td>
<td>N/A</td>
<td>N/A</td>
<td>4289.01</td>
<td>0.2</td>
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<tr>
<td>ACRR Exp. UM</td>
<td>1st Order Hex</td>
<td>81 586</td>
<td>5449.62</td>
<td>0.4</td>
</tr>
</tbody>
</table>

- First three models (green) run on 2.76 GHz Intel Xeon Processor; Last model (blue) run on 2.2 GHz Quad-Core AMD Opteron™ Processor
- Runtime depends on model and material complexity
- CSG tracking over fewer surfaces, by many orders of magnitude
Conclusions

• Results from MCNP6 calculations that use unstructured mesh geometries generated by Abaqus/CAE have shown to agree well with the results from the calculations that use CSG

• Benefits of using Abaqus/CAE unstructured mesh:
  • Easier to build complex geometries
  • Visualize results in 3D
    • View individual parts, cut away sections for viewing
  • Multi-physics

• Future work will include incorporating MCNP6 mesh results in an .odb as a source term in Abaqus/CAE