Advanced Variance Reduction Strategies for Optimizing Mesh Tallies in MAVRIC

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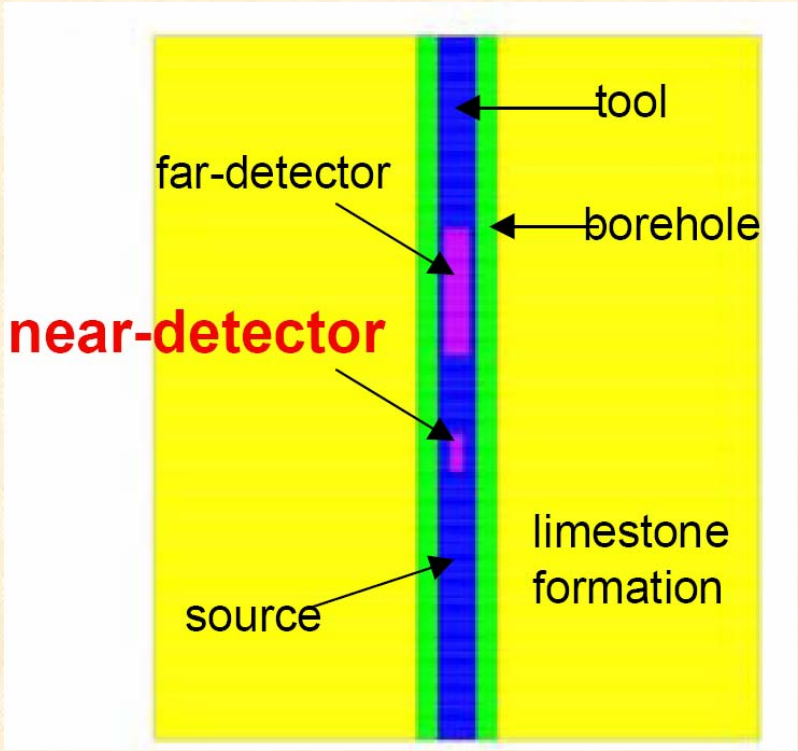
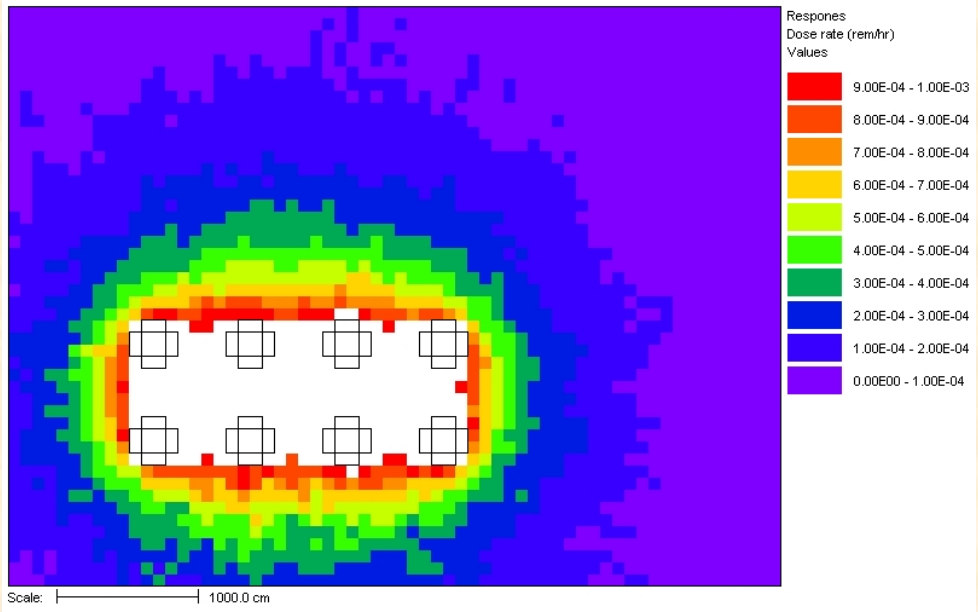
Problem

- **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**
- **Mesh tallies are used to get answers everywhere**
  - **Wide range in relative uncertainties between voxels**

Goal

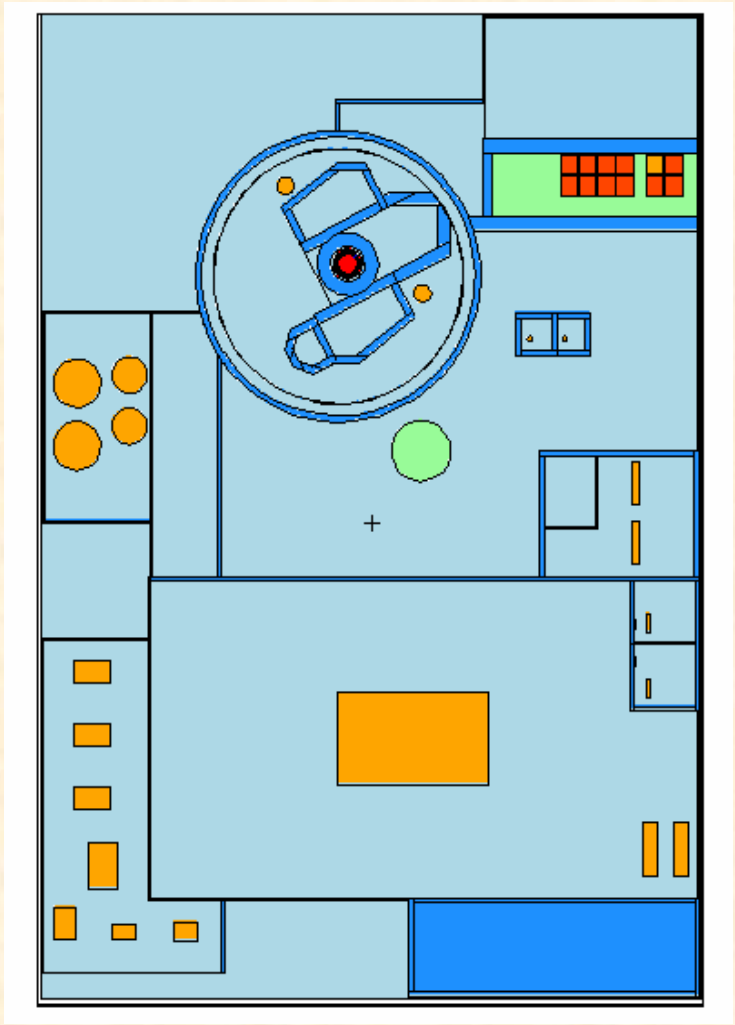
- **Compute a mesh tally over a large area with roughly equal relative uncertainties in each voxel**
- **Tune the MC calculation for the simultaneous optimization of several tallies**

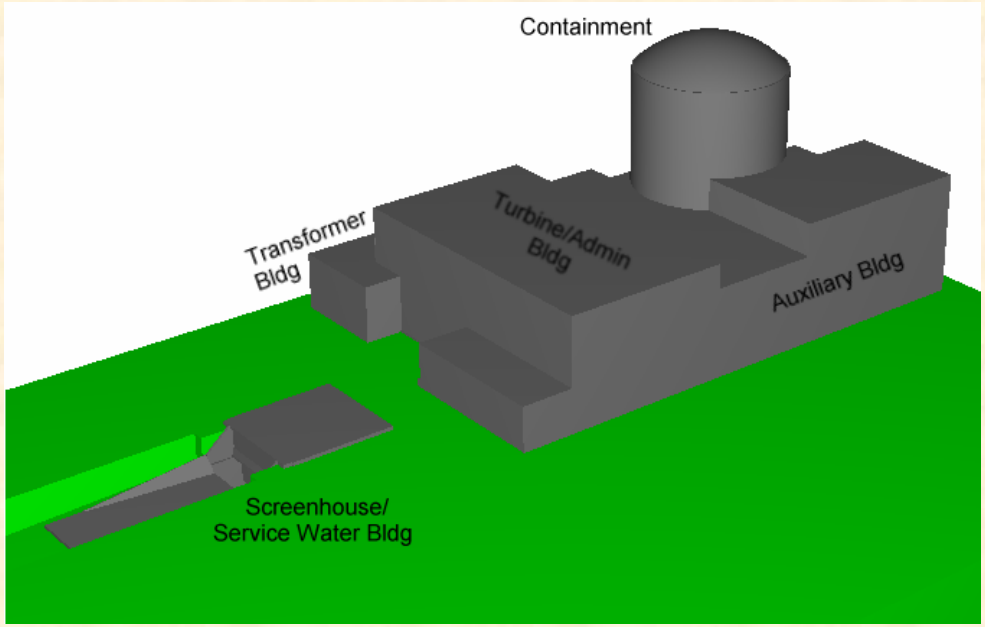


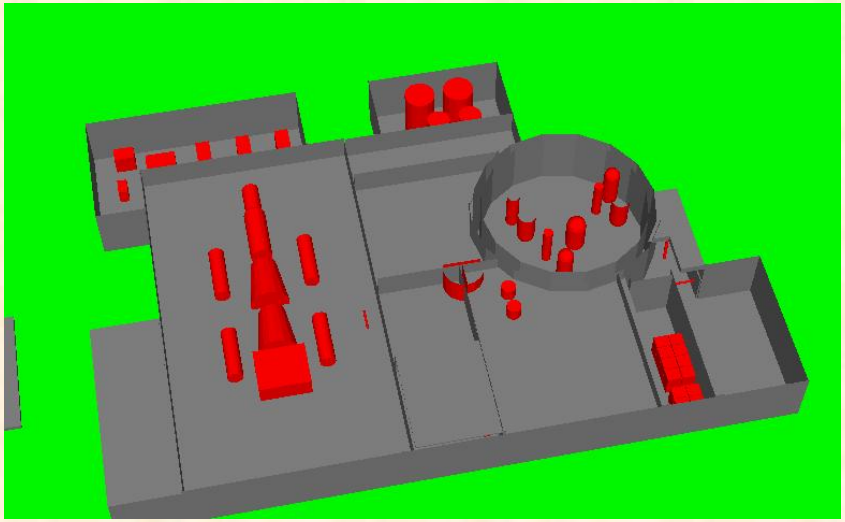


Example Application: PWR dose rates

Large scales, massive shielding
Difficult to calculate dose rates







Advanced Variance Reduction

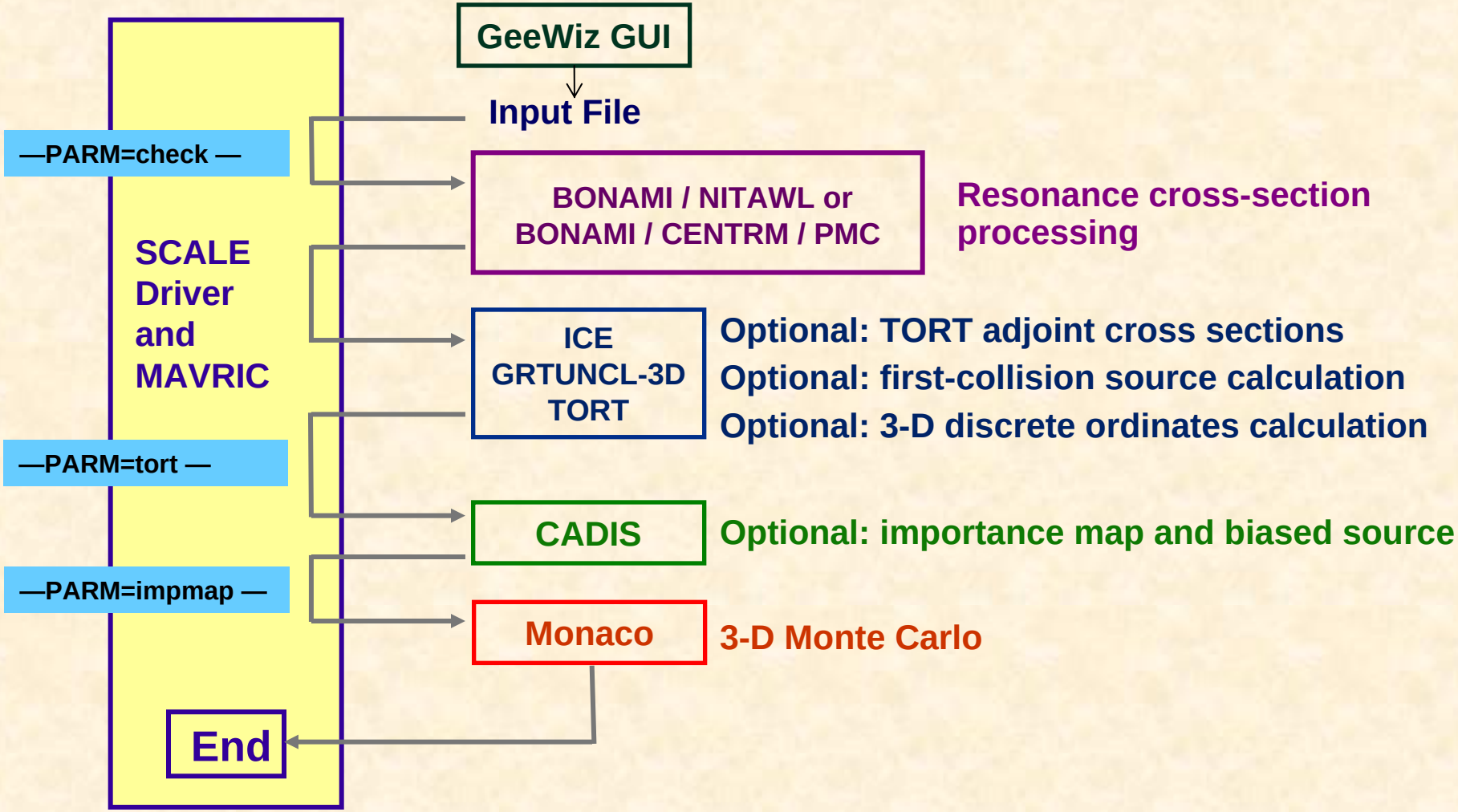
- **MC weight windows inversely proportional to the adjoint flux determined by discrete ordinates**
  - **SAS4, AVATAR, ADVANTG, MCNP5/PARTISN, MAVRIC**
  - **CADIS (Wagner): WW and biased source**
  - **Focus on one specific response at one location**
- **Global variance reduction – Cooper & Larsen**
  - **Construct MC weight windows proportional to the forward flux determined by discrete ordinates**
  - **Focus on getting equal uncertainties in MC flux everywhere – space and energy**
- **Weight windows are based on an *approximate* adjoint or forward DO solution**

SCALE 6

- **Monaco – 3D, multi-group, fixed source MC**
  - **Based on MORSE/KENO physics**
  - **Same cross sections and geometry as KENO-VI**
  - **Variety of sources and tallies**
- **MAVRIC – Automated sequence for CADIS**
  - **SCALE cross section processing**
  - **GTRUNCL3D and TORT**
    - **Computes the adjoint flux for a given response**
  - **Use CADIS methodology to compute:**
    - **Importance map (weight windows for splitting/roulette)**
    - **Biased source distribution**
  - **Monaco for Monte Carlo calculation**

SCALE 6 Sequence: MAVRIC

Monaco with Automated Variance Reduction using Importance Calculations



CADIS Methodology

Consistent Adjoint Driven Importance Sampling

Biased source and importance map work together

Ali Haghighat and John C. Wagner, "Monte Carlo Variance Reduction with Deterministic Importance Functions," *Progress in Nuclear Energy*, 42(1), 25-53, (2003).

- **Solve the adjoint problem using the detector response function as the adjoint source.**

$$q^{+}(\vec{r},E)=\sigma_{d}(\vec{r},E)$$

- **Weight windows are inversely proportional to the adjoint flux (measure of importance of the particles to the response).**

$$w(\vec{r},E)=\frac{c}{\phi^{+}(\vec{r},E)}$$

CADIS Methodology

- **We want source particles born with a weight matching the weight windows**

$$w_0(\vec{r},E) \equiv \frac{q(\vec{r},E)}{\hat{q}(\vec{r},E)}$$

- **So the biased source needs to be**

$$\hat{q}(\vec{r},E) = \frac{q(\vec{r},E)}{w(\vec{r},E)} = \frac{1}{c} q(\vec{r},E)\,\phi^{+}(\vec{r},E)$$

- **Since the biased source is a pdf, solve for *c***

$$c = \iint q(\vec{r},E)\,\phi^{+}(\vec{r},E)\,d\vec{r}\,dE$$

- **Summary: define adjoint source, find adjoint flux, find *c*, construct weight windows and biased src**

Cooper's Method for Global Var. Red.

- **The physical particle density, $n(\vec{r})$, is related to the Monte Carlo particle density, $m(\vec{r})$, by the average weight $\overline{w}(\vec{r})$.**

$$n(\vec{r}) = \overline{w}(\vec{r})\, m(\vec{r})$$

- **For uniform relative uncertainties, make $m(\vec{r})$ constant. So, the weight windows need to be proportional to the physical particle density, $n(\vec{r})$, or the estimate of forward flux $\phi(\vec{r})$**

$$w(\vec{r}) = \frac{\phi(\vec{r})}{\max(\phi(\vec{r}))}$$

MAVRIC: Extended Cooper's Method

- **Function of space and energy**
- **Add a consistent biased source**
- **Weight windows proportional to flux estimate**

$$w(\vec{r},E)=c\phi(\vec{r},E)$$

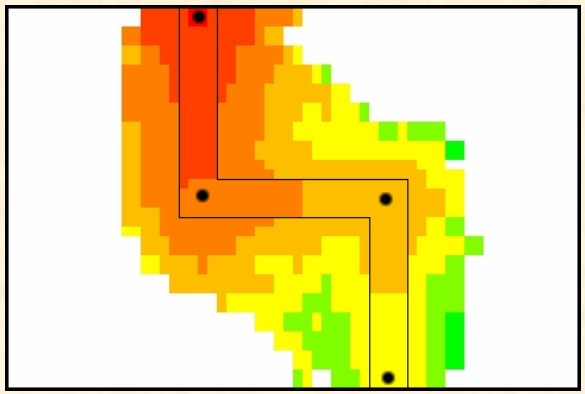
- **Source particles born with matching weight, so the biased source is**

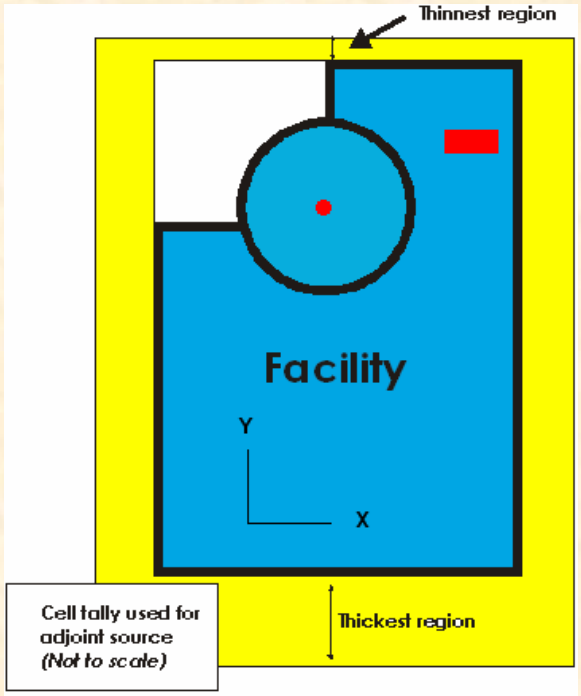
$$\hat{q}(\vec{r},E)=\frac{q(\vec{r},E)}{w(\vec{r},E)}=\frac{q(\vec{r},E)}{c\phi(\vec{r},E)}$$

- **Constant of proportionality**

$$c=\iint\frac{q(\vec{r},E)}{\phi(\vec{r},E)}d\vec{r}dE$$

Using CADIS to Optimize a Mesh Tally or Simultaneously Optimize Multiple Tallies

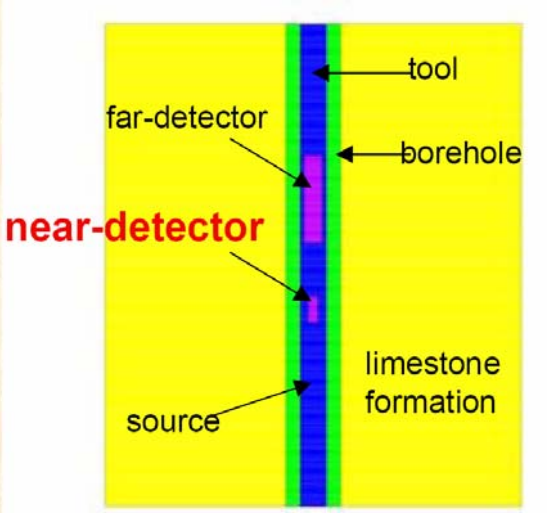




- **Use adjoint source at furthest tally**
  - **Particles are driven outward from source**
- **For multiple directions, put adjoint source all around the model – "Exterior Adjoint" method**
  - **Amount of adjoint weighted to balance directions**
- **Drawbacks**
  - **May miss low energy particles far from tally**
  - **How to determine weights?**

Using CADIS to Optimize a Mesh Tally or Simultaneously Optimize Multiple Tallies

- **Use multiple adjoint sources**
  - **Put adjoint source everywhere you want an answer (everywhere is equally 'important')**
  - **Experience says to weight the adjoint source strengths (less adjoint source close to true source)**
  - **Adjoint sources should be weighted inversely proportional to forward response**



- **Leads to: the Forward-Weighted CADIS Method**

Forward-Weighted CADIS

- **Perform a forward discrete ordinates calculation**
- **Estimate the response of interest *R(r,E)* everywhere**
- **Construct a volumetric adjoint source**
  - **Using the response function (as the energy component)**
  - **where the source strength is weighted by *1/R(r,E)***

- **Perform the adjoint discrete ordinates calculation**
- **Create the weight windows and biased source**
- **Perform the Monte Carlo calculation**

Forward-Weighted CADIS

- **How to weight the adjoint source – depends on what you want to optimize the MC for:**
- **For Total Dose**

$$q^{+}(\vec{r},E)=\frac{\sigma_d(\vec{r},E)}{\int\phi(\vec{r},E)\sigma_d(\vec{r},E)dE}$$

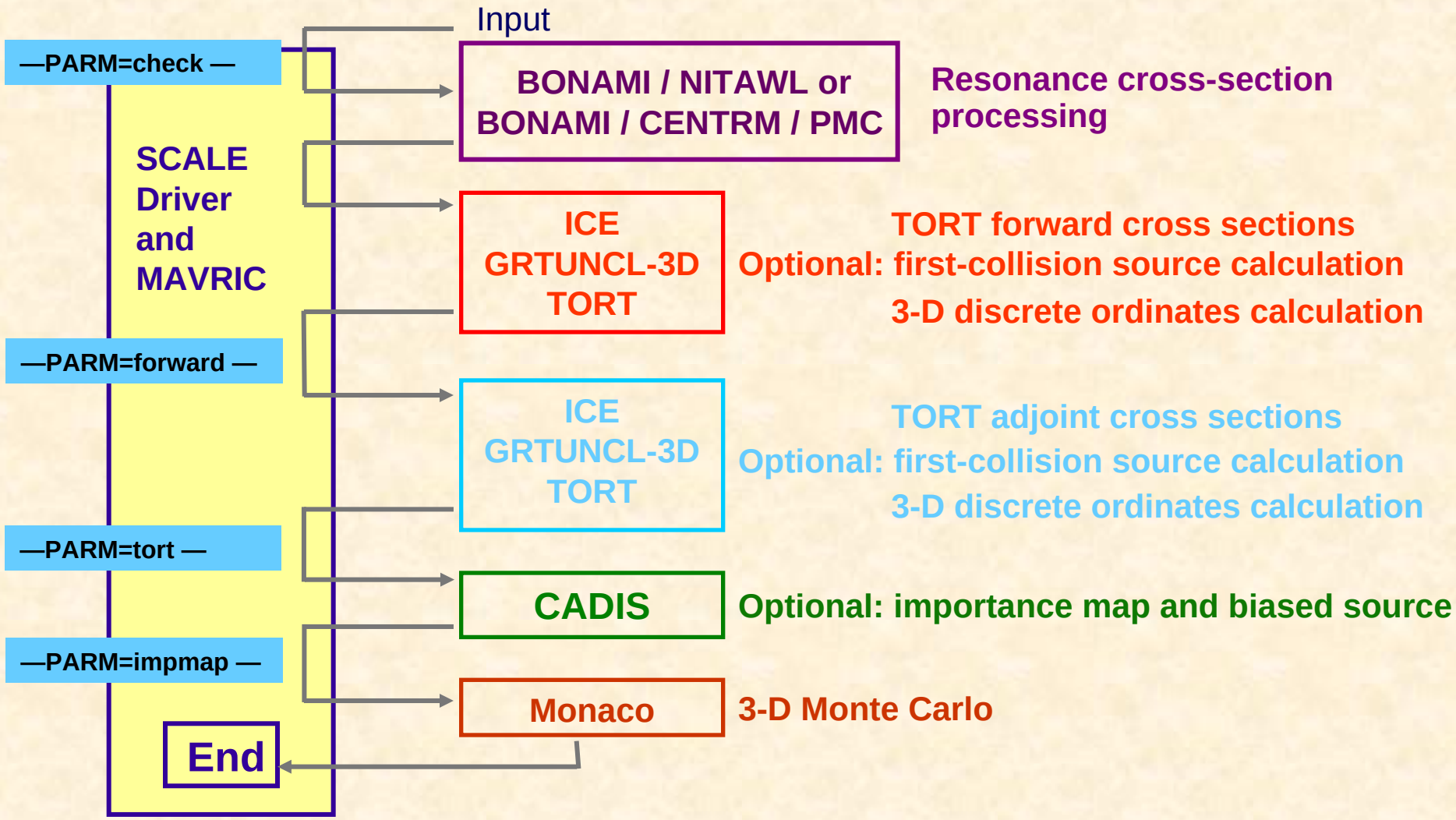
- **For Total Flux**

$$q^{+}(\vec{r},E)=\frac{1}{\int\phi(\vec{r},E)dE}$$

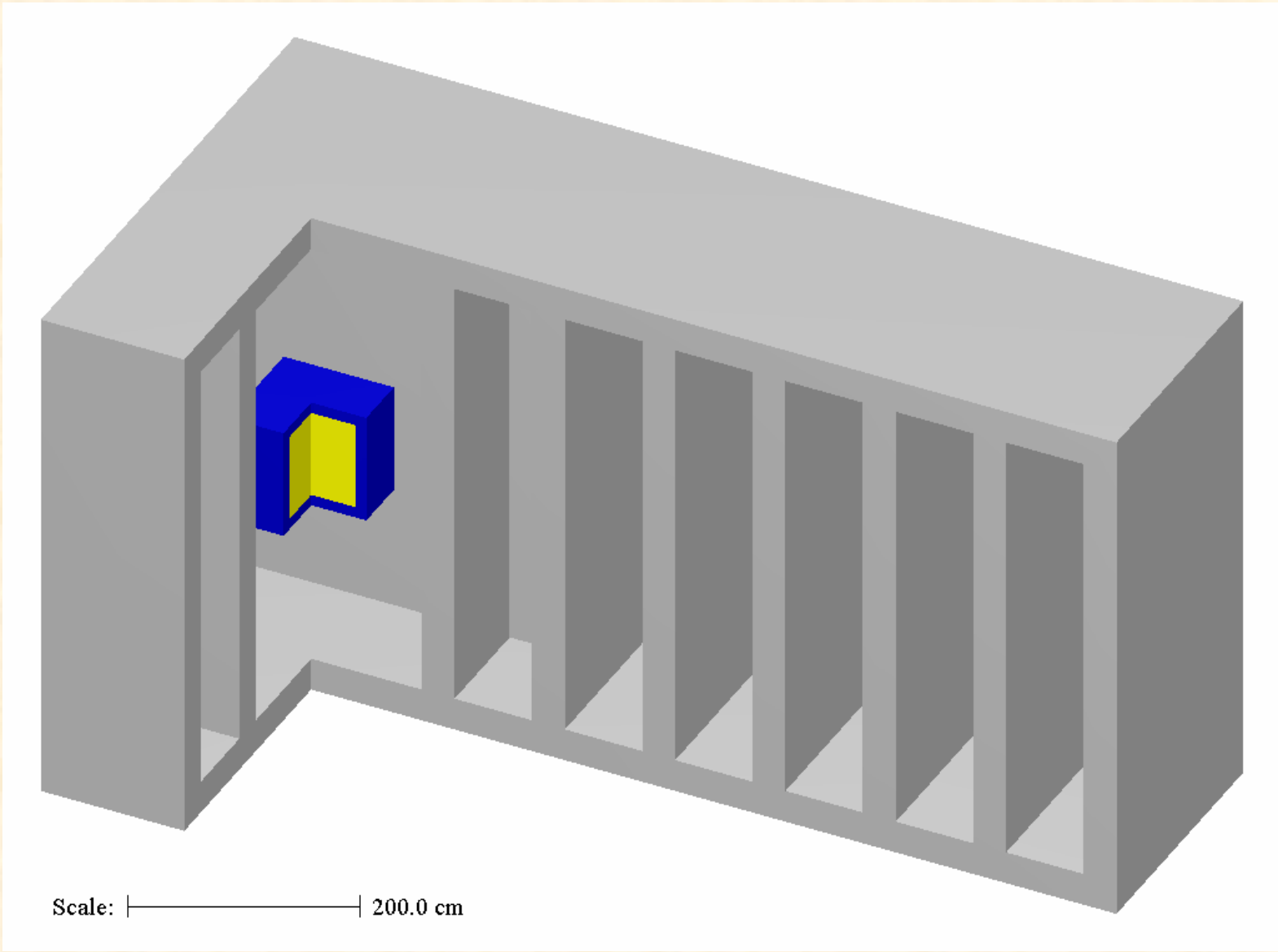
- **For Flux**

$$q^{+}(\vec{r},E)=\frac{1}{\phi(\vec{r},E)}$$

SCALE 6 Sequence: MAVRIC



Simple Problem: Find Dose Rates

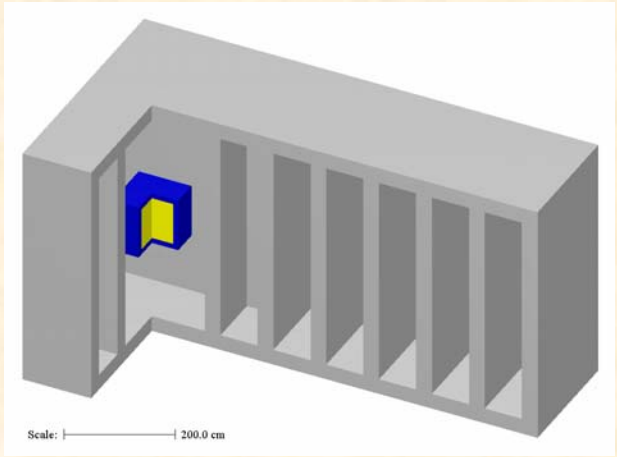


Six Methods: Dose Rate Mesh Tally

1. **Analog**
2. **Standard CADIS, adjoint source in one region**
3. **Uniformly distributed adjoint source everywhere**
4. **Exterior adjoint source, with guessed amounts**
5. **Cooper's Method, with source biasing**
6. **Forward-weighted CADIS**

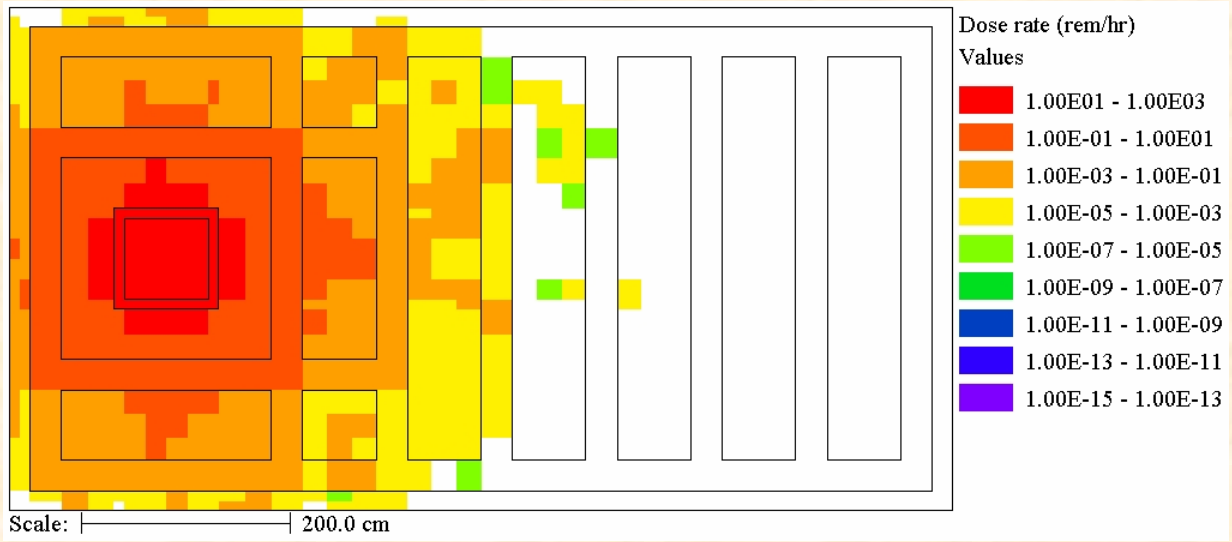
Mesh: 40x24x24 = 23040 voxels

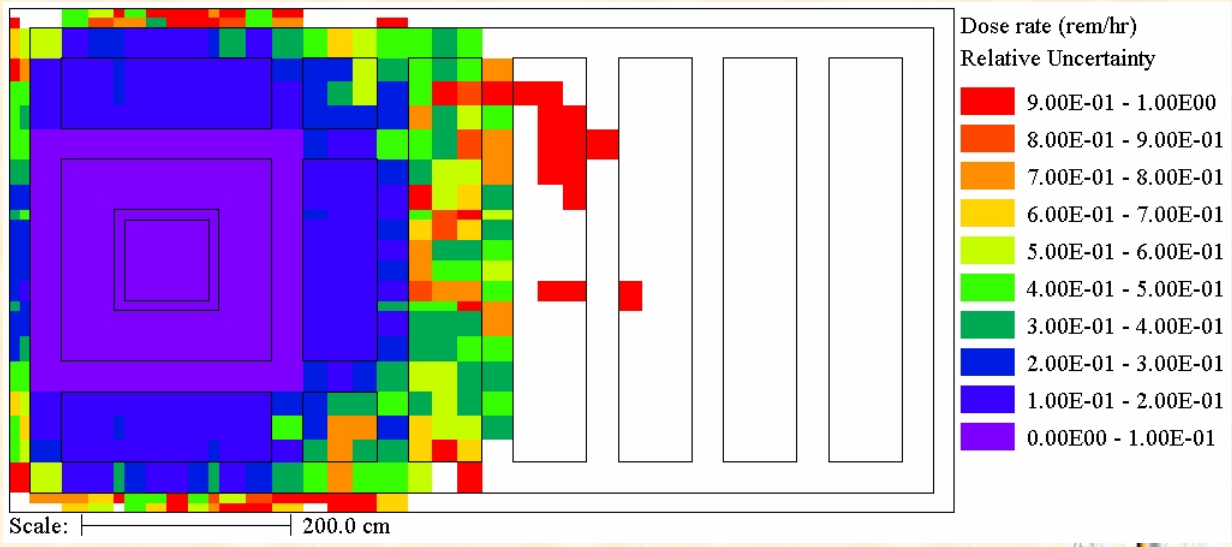
Same run time (90 minutes) each



1. Analog

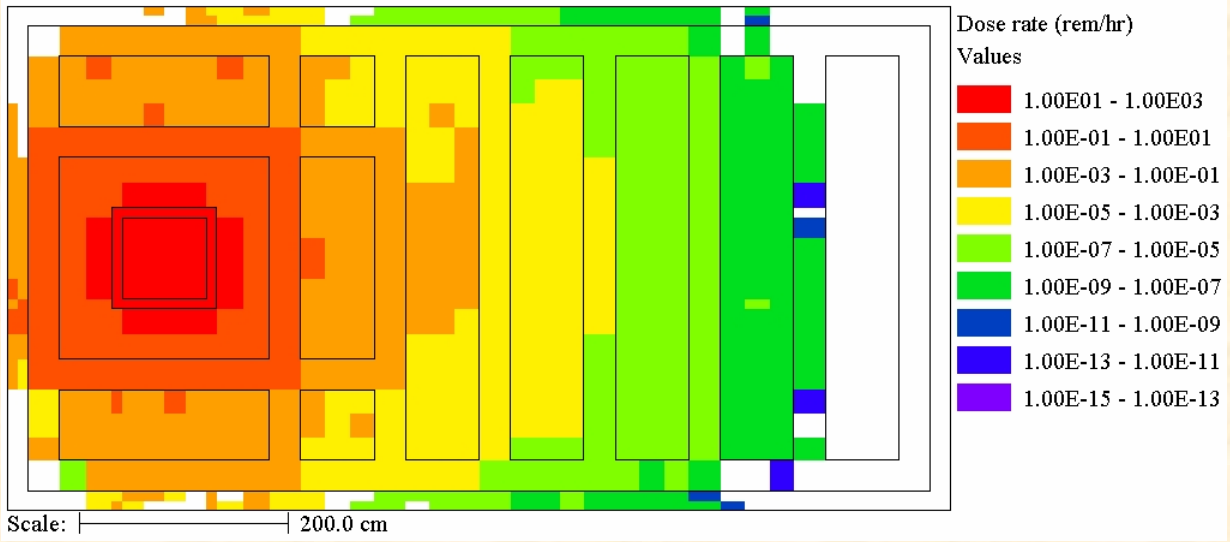
```
read biasing

  windowRatio=10.0
  targetWeights 27r1.0
                18r0.0 end

end biasing
```

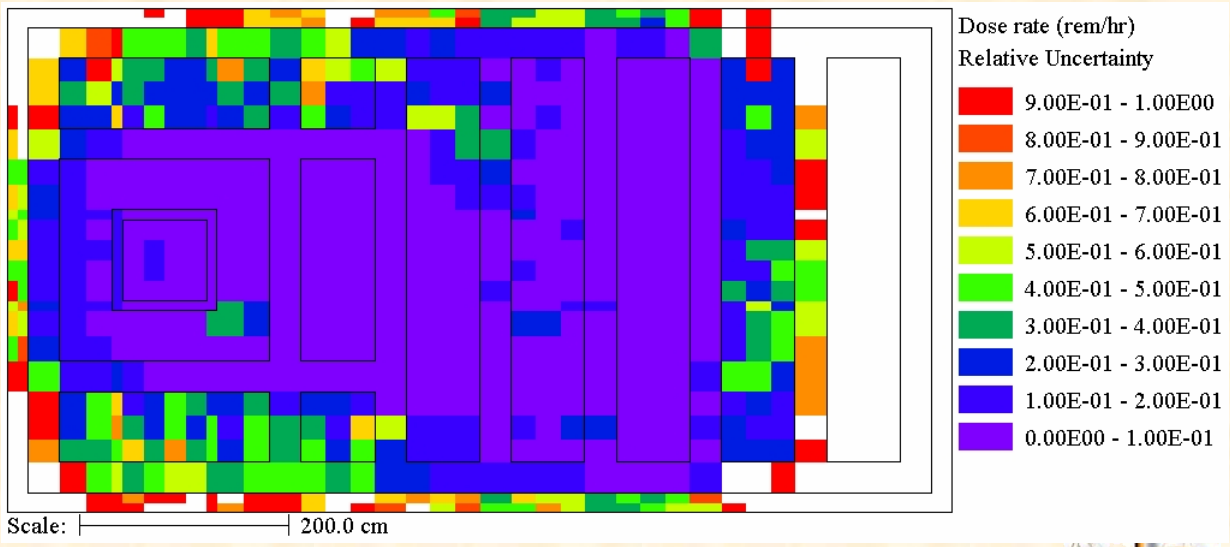




2. Standard CADIS

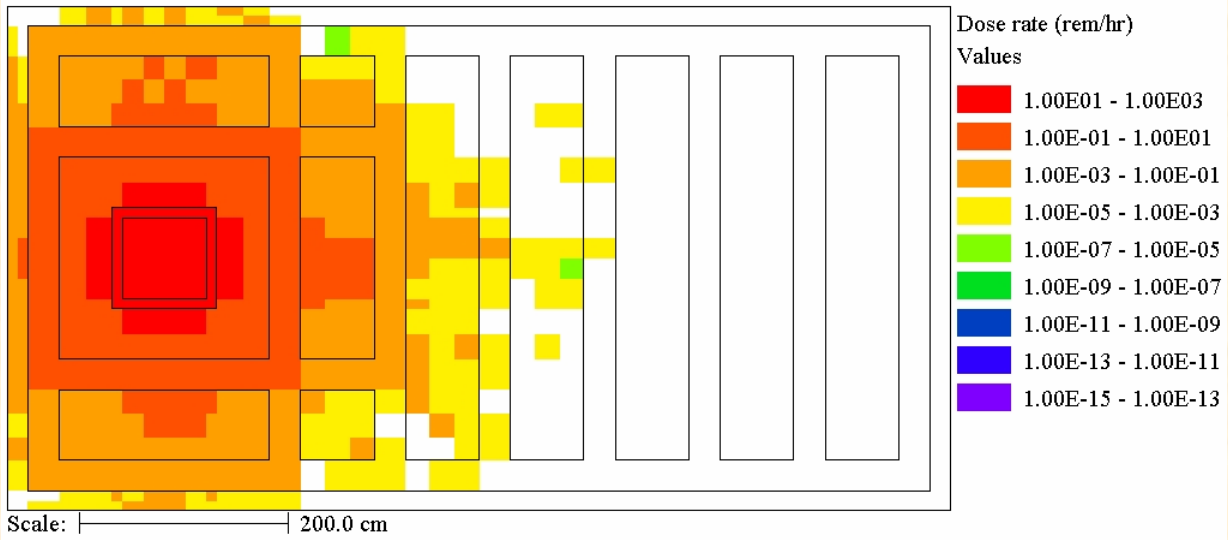
```
read tortImportance

  adjointSource 1
    boundingBox 500 430
      200 -200
      200 -200 end
    responseID=5
  end adjointSource

  gridGeometryID=8

end tortImportance
```

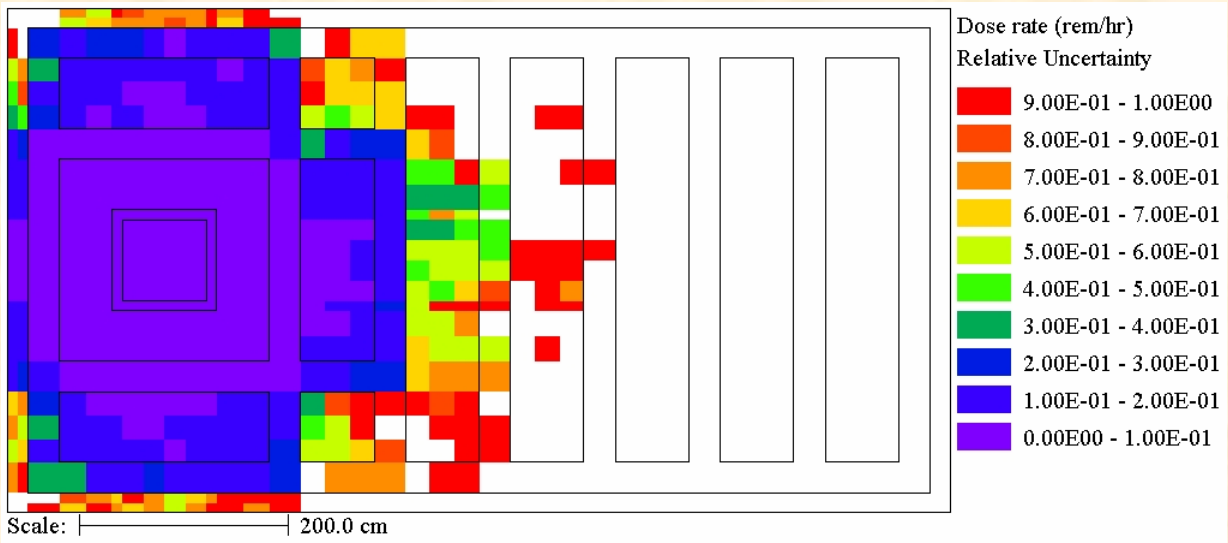




3. Uniformly Distributed Adjoint Source

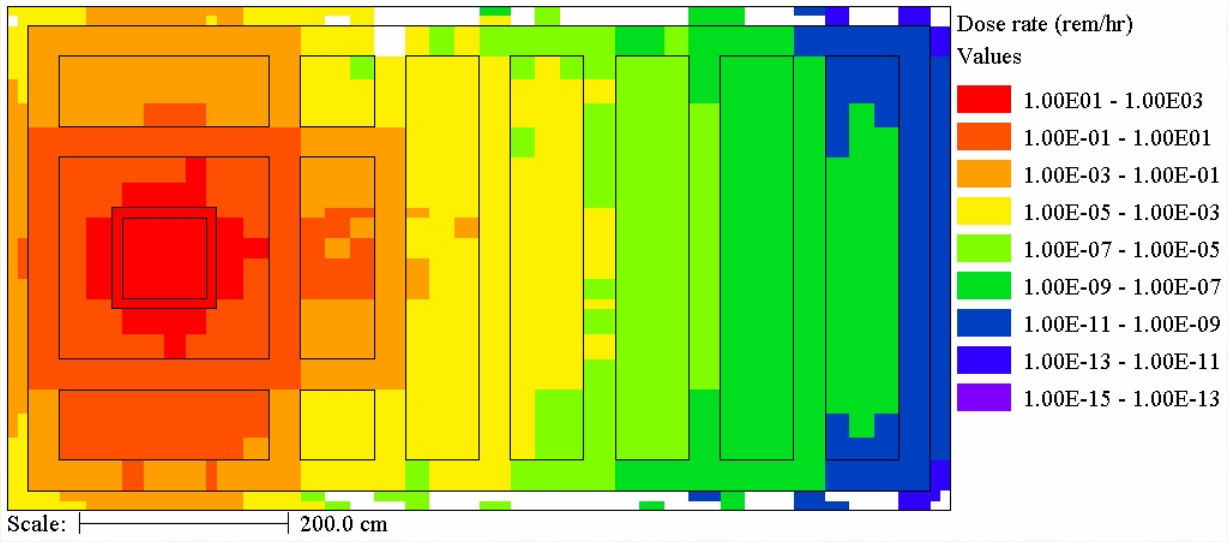
```
read tortImportance

  adjointSource 1
    boundingBox
     750 -150 250 -250
     250 -250 end
    responseID=5
  end adjointSource

  gridGeometryID=8

end tortImportance
```

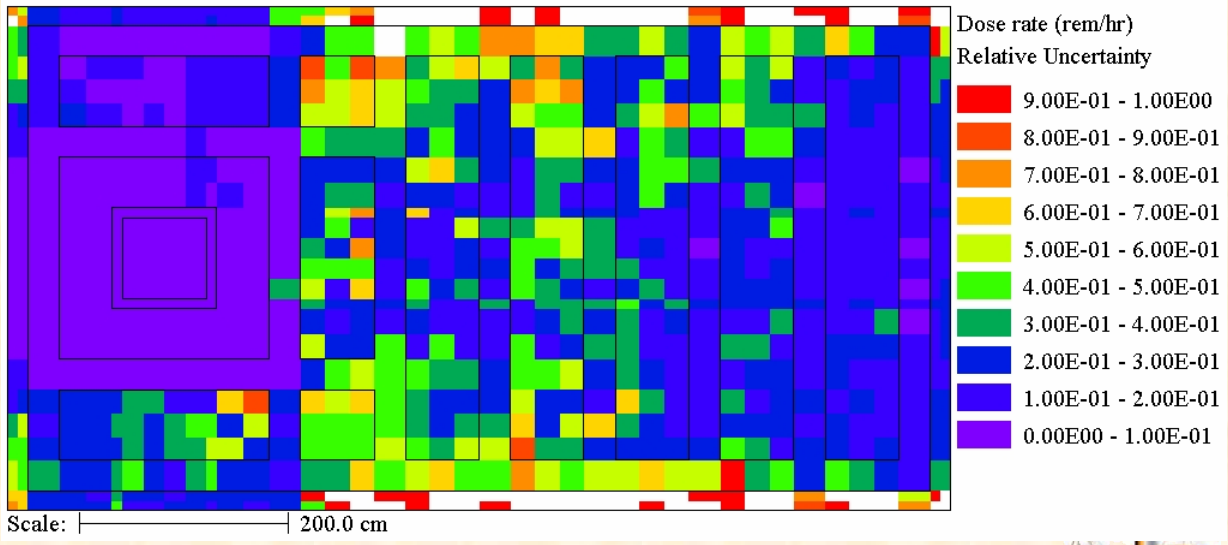




4. Exterior Adjoint Source

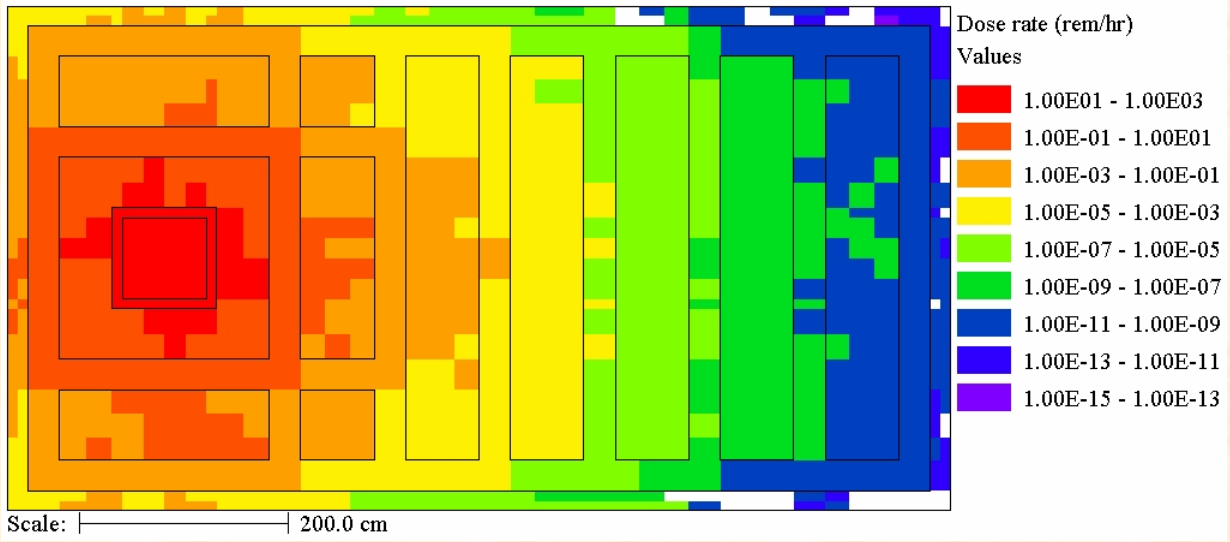
```
read tortImportance

  adjointSource 1
    boundingBox -130 -150
     250 -250 250 -250 end
    responseID=5
    weight=0.05
  end adjointSource

  adjointSource 2
    boundingBox 750 730
     250 -250 250 -250 end
    responseID=5
    weight=3.0e6
  end adjointSource

  adjointSource 3
    boundingBox 750 -150
     -230 -250 250 -250 end
    responseID=5
    weight=1.0
  end adjointSource
  ...
  gridGeometryID=8

end tortImportance
```

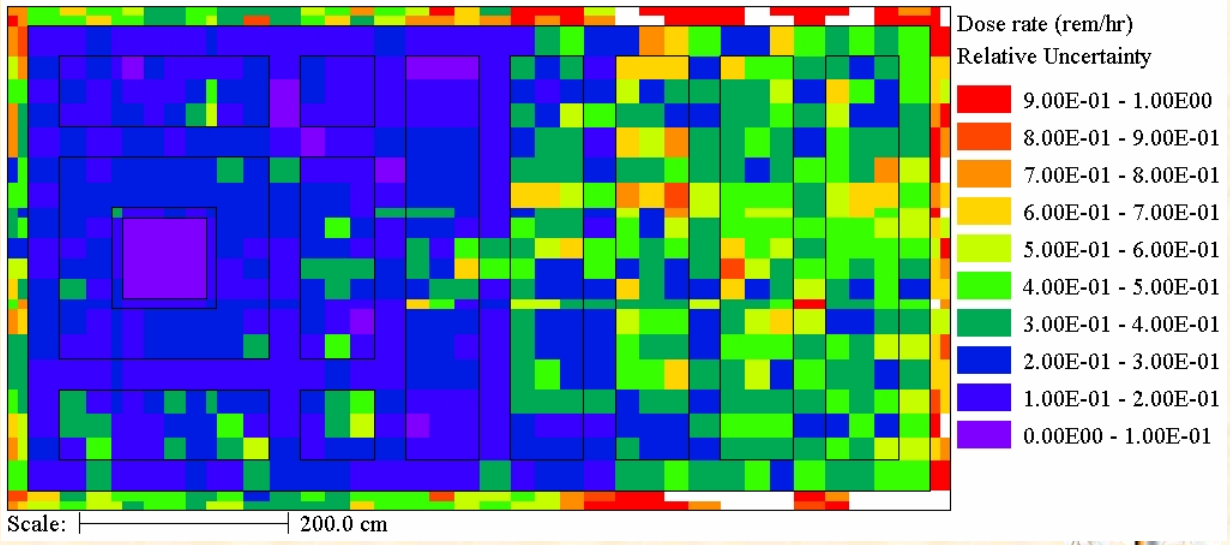




5. Cooper's Method

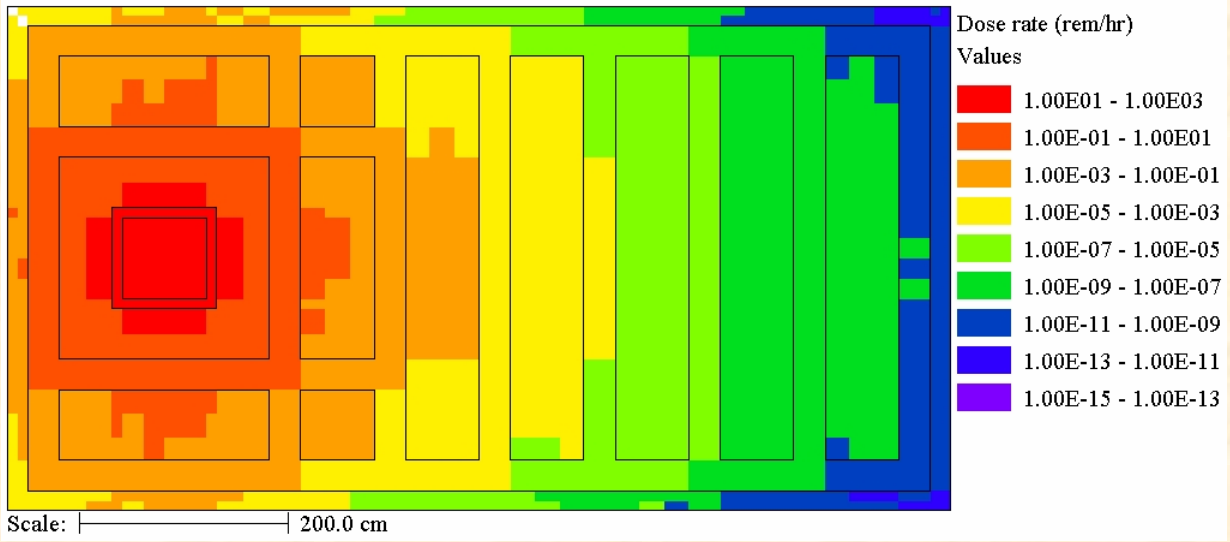
```
read tortImportance

    gridGeometryID=8

end tortImportance
```

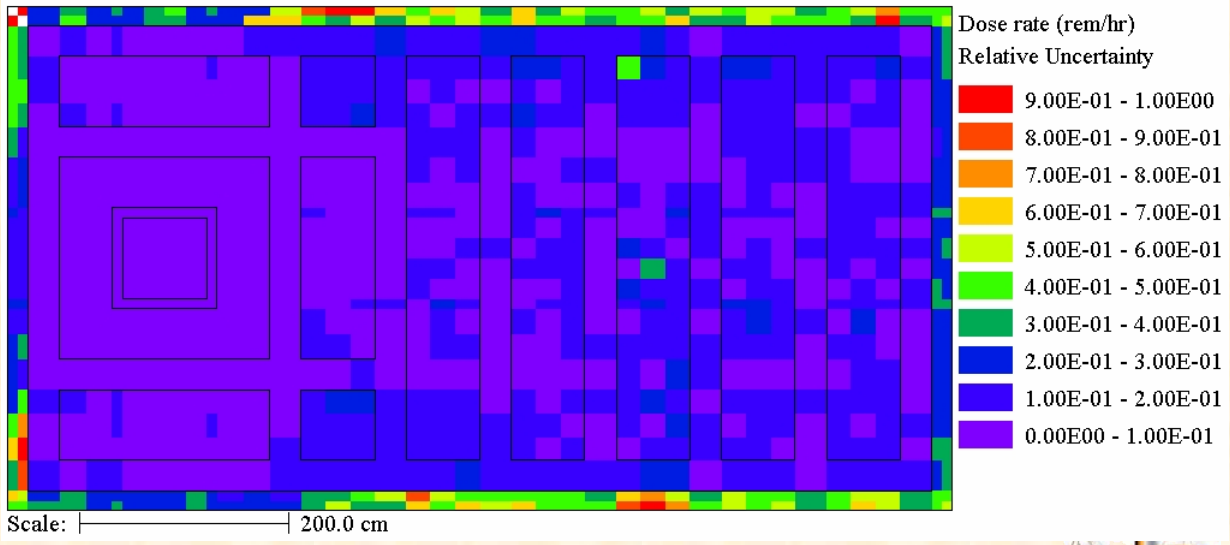




6. Forward-Weighted CADIS

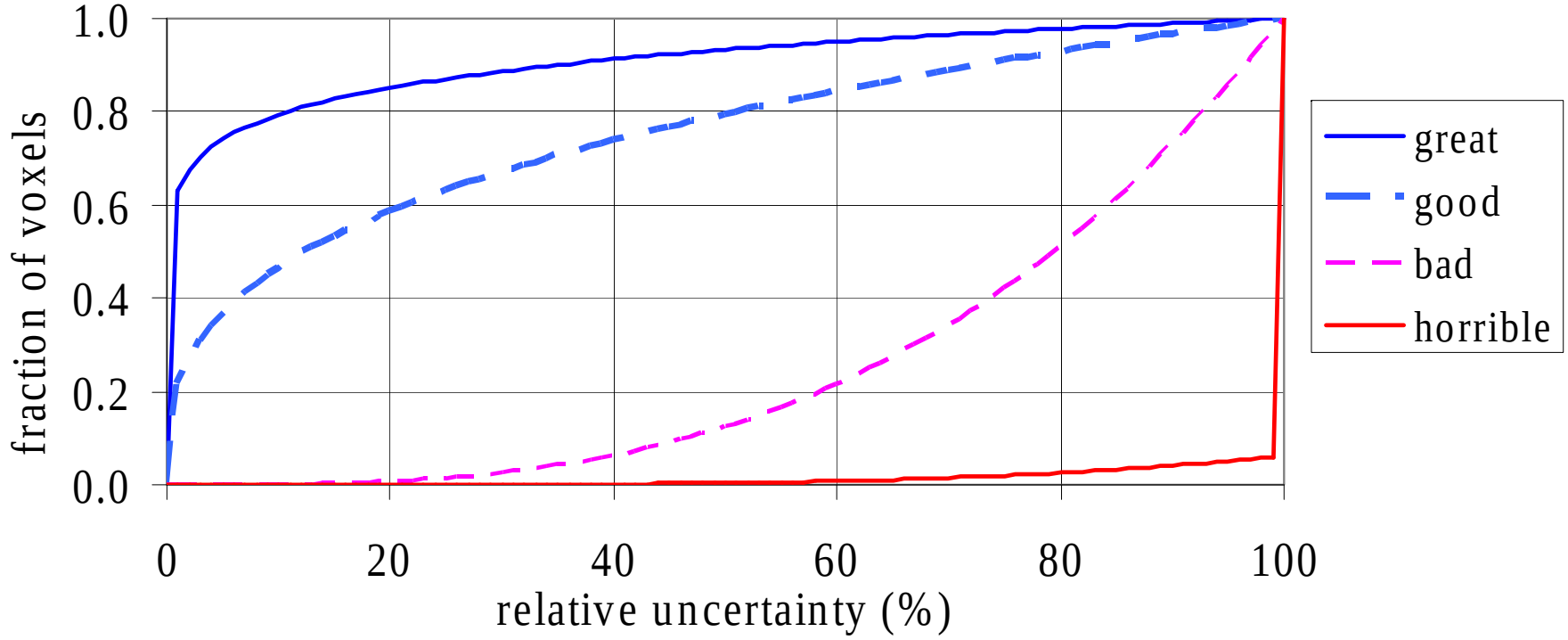
```
read tortImportance

  adjointSource 1
    boundingBox
     750 -150 250 -250
     250 -250 end
    responseID=5
  end adjointSource

  gridGeometryID=8

  forwardWeighting
  responseID=5

end tortImportance
```



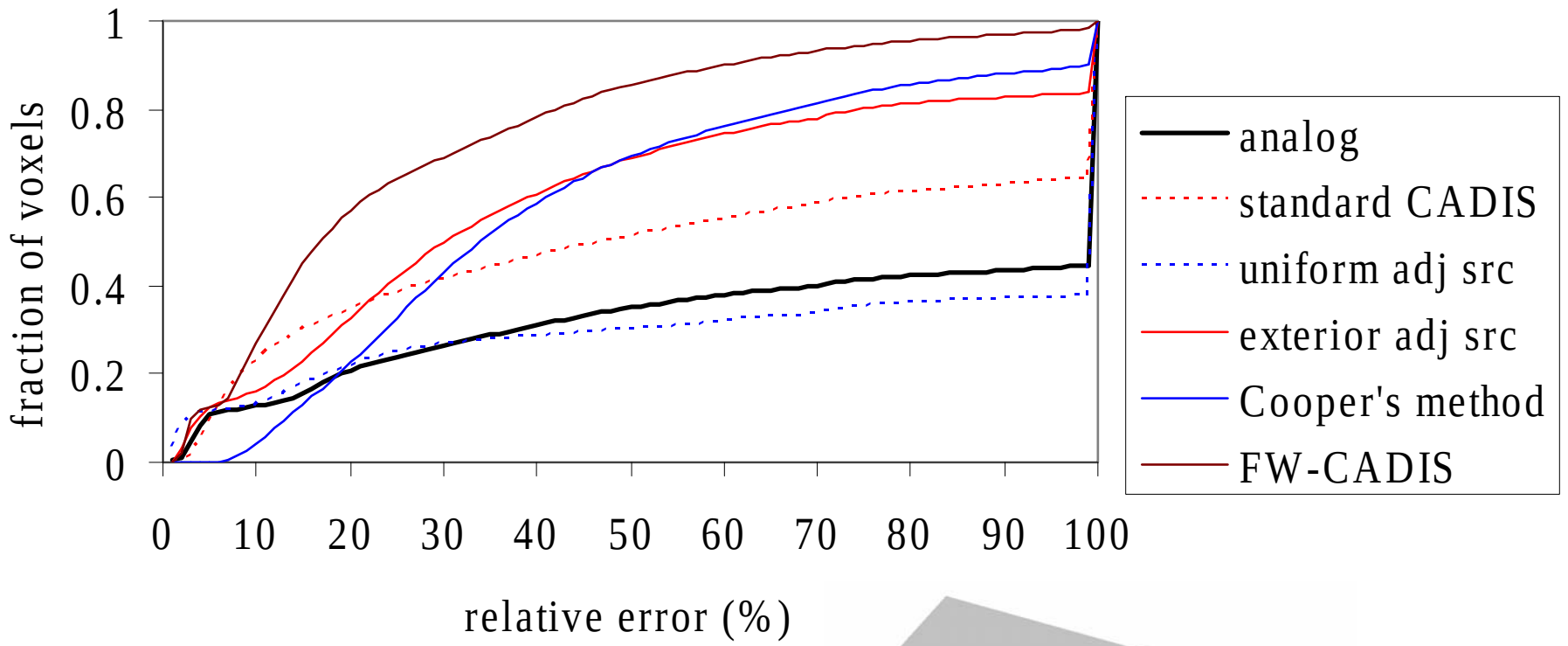


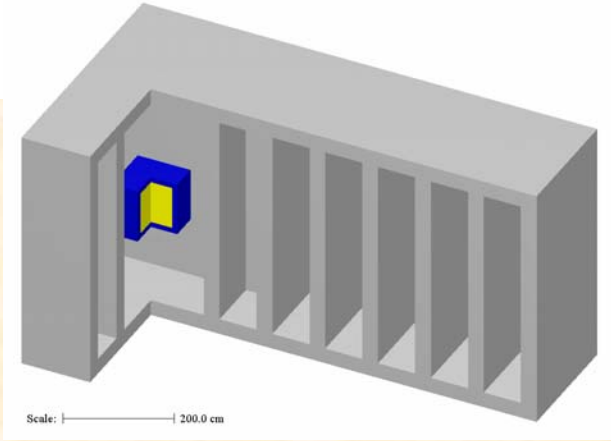
How to Compare Mesh Tallies

- **No single measurement like FOM**
- **Instead compare what fraction of voxels have less than some amount of relative uncertainty.**

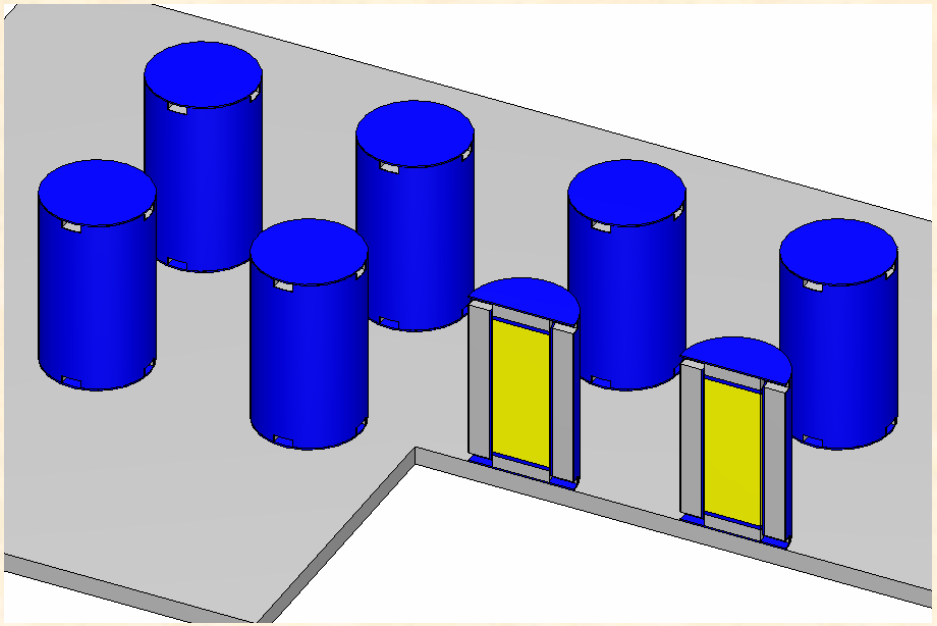


Six Methods: Comparison



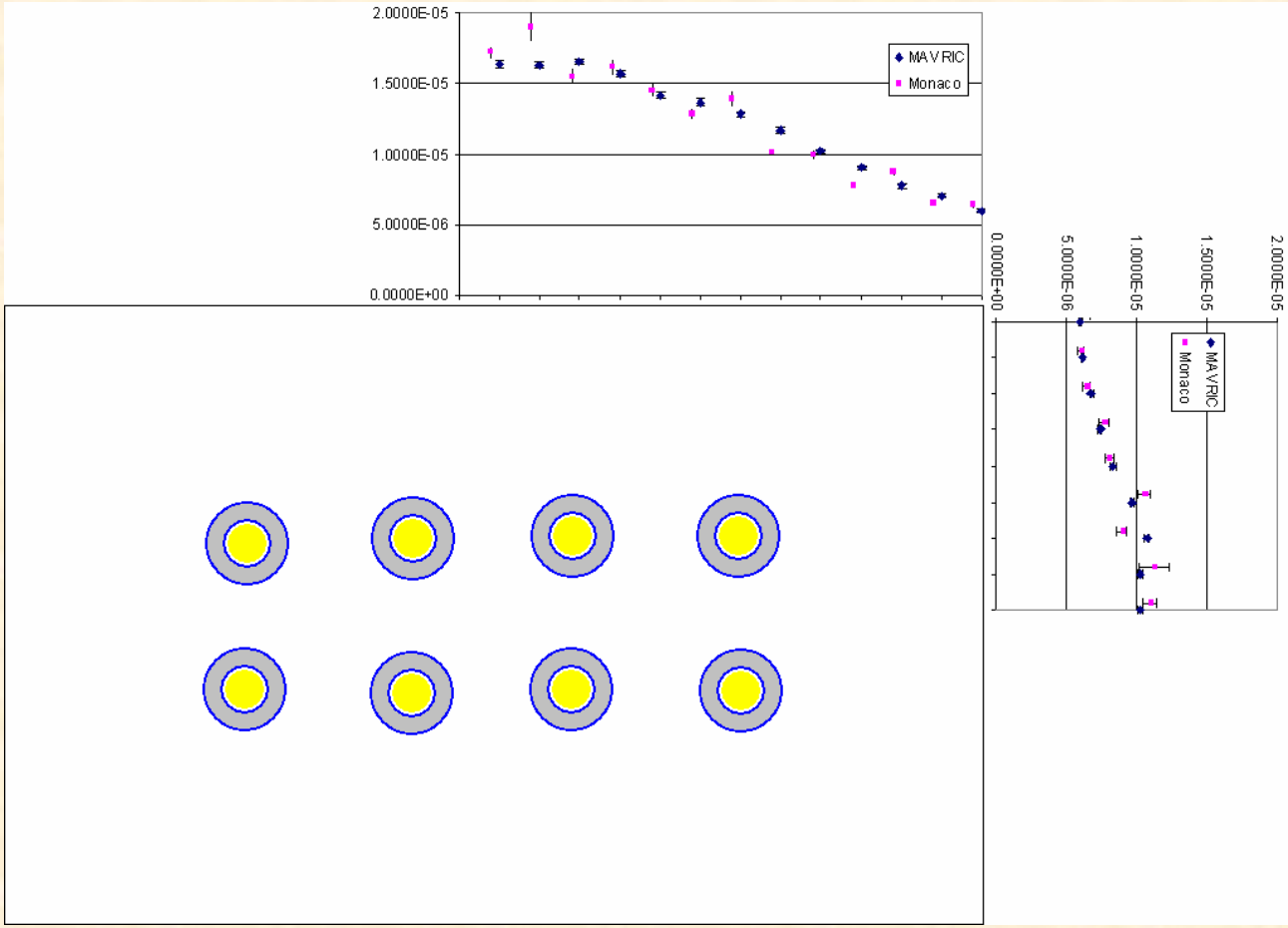


Dose Rates Near A Cask Array



Standard CADIS - one point at a time

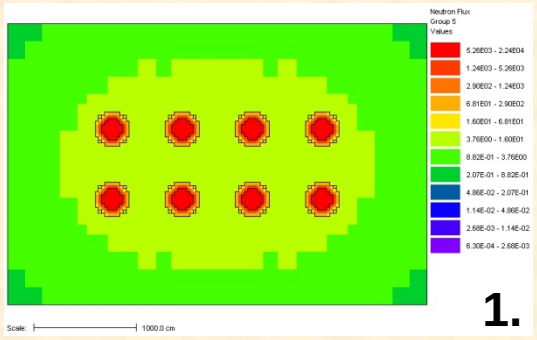
- **Slow**

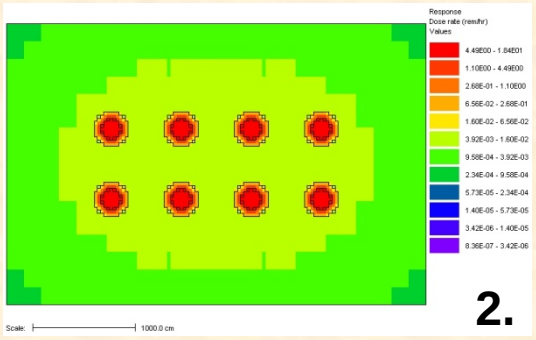


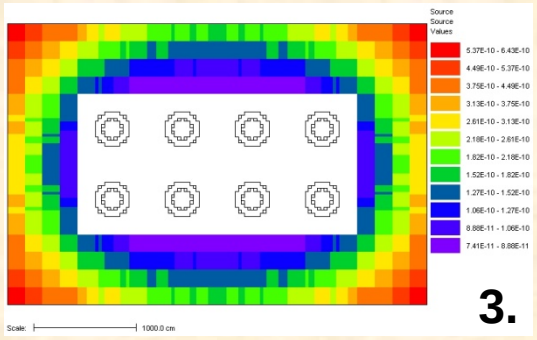
- **Need a mesh tally**

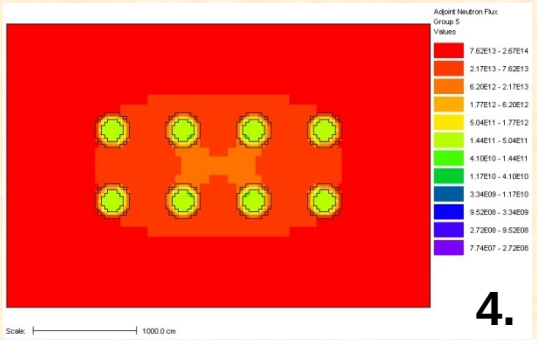
Forward-Weighted CADIS

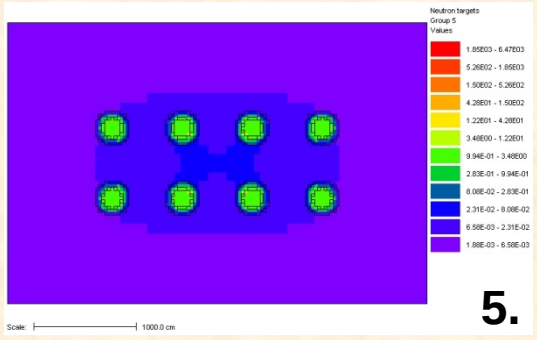
1. **Forward Discrete Ordinates – forward fluxes**
2. **Forward dose rate estimate**
3. **Adjoint source, weighted by dose**
4. **Adjoint Fluxes**
5. **Importance Map**
6. **Biased Source**







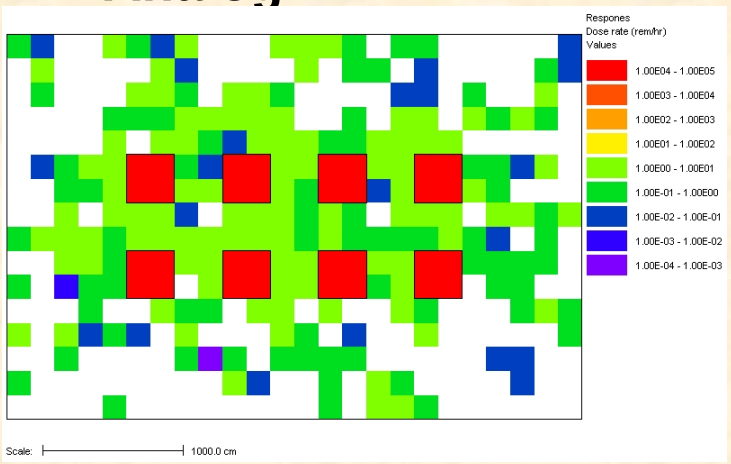


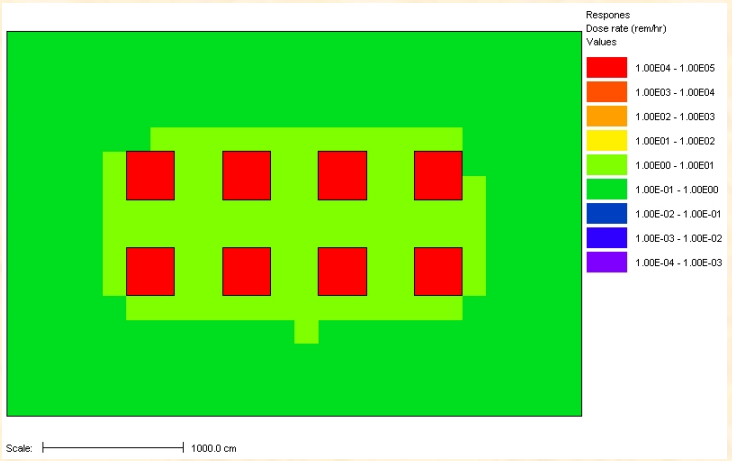


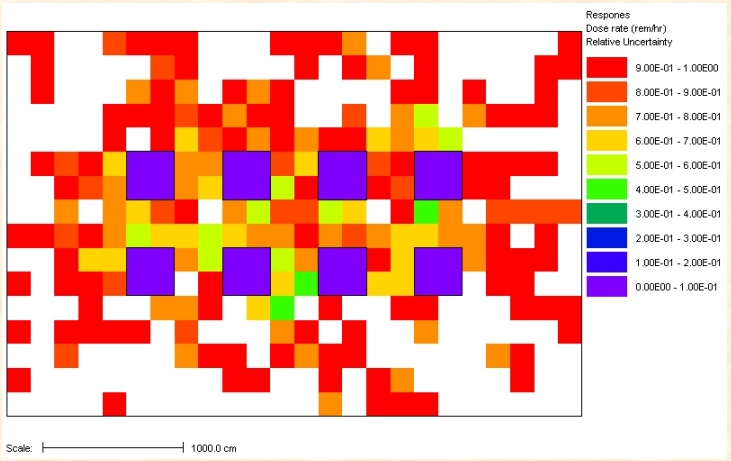
Mesh Tally of Dose Rates (photon)

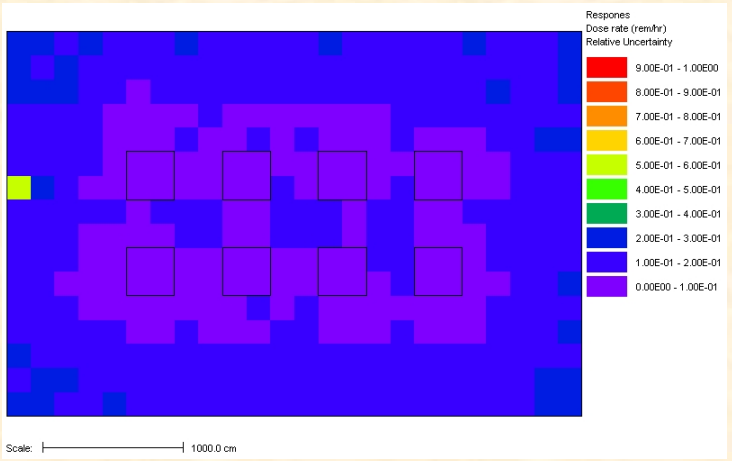
- **Dose Rates and relative uncertainties (5 hrs)**

Analog **FW-CADIS**



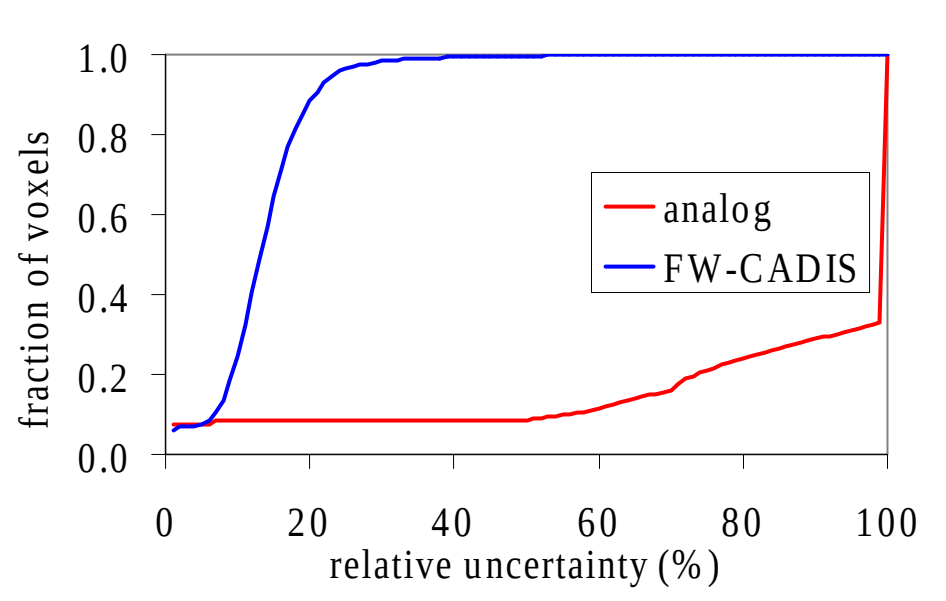




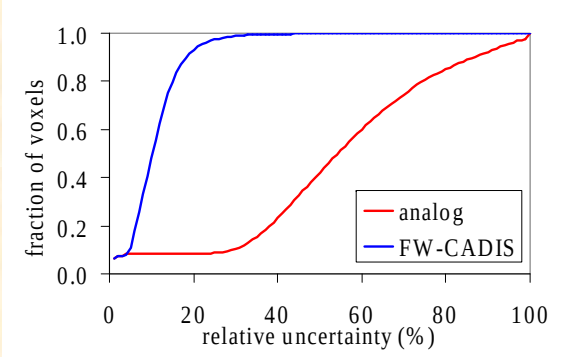


Cask Array: Comparison

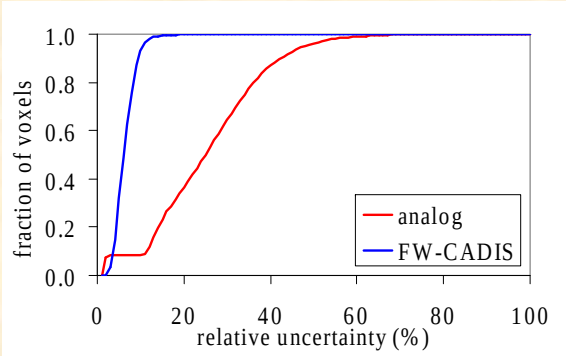
- **FW-CADIS performs well:**
  - **A) photon dose from photon source**



B)



C)



- **From neutron source**
  - **B) Neutron dose rate**
  - **C) Photon dose rate**

Summary

- **MAVRIC offers many ways for automated, advanced variance reduction**
  - **Standard CADIS method – for optimizing a specific response at a specific location**
  - **Forward-Weighted CADIS – for optimizing multiple tallies or mesh tallies over large areas**
- **Easy to use**
  - **In addition to standard MC input description, user provides mesh for DO calc.**
  - **For CADIS, user specifies source position or box**
  - **For FW-CADIS, user adds a single keyword**

UT-BATTELLE

Discussion & Questions

Special thanks to our sponsors:

NRC and DTRA