Criticality Accident Alarm System Modeling Made Easy With SCALE 6.1

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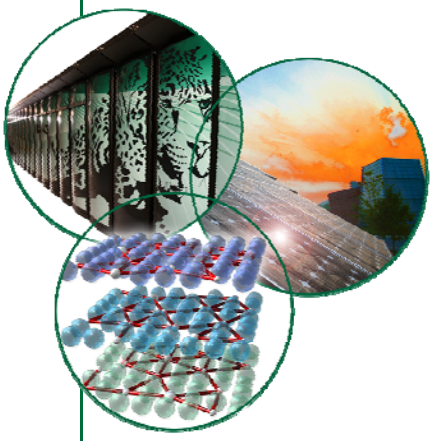

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CAAS Problems

- Criticality accident alarm systems are difficult problems because they consist of
  - Criticality calculation
  - Deep penetration shielding calculation
  - May require "answer everywhere"
- Past approaches include
  - Point source, point-kernel, one-dimensional
  - Build-up factors
  - Three-dimensional discrete ordinates
  - Very long 3-D Monte Carlo

Capabilities in SCALE 6.1

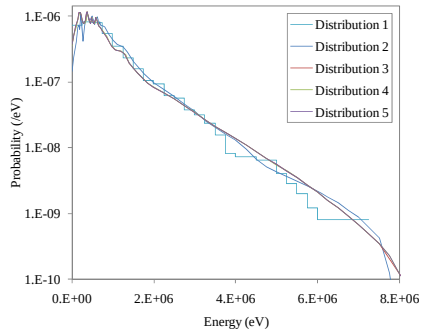
- KENO Family of Criticality Codes
  - KENO-Va Simple geometries, multi-group
  - KENO-VI Quadratic solid geometry, multi-group
  - KENO-CE Quadratic solid geometry, cont. energy
- MAVRIC Shielding Sequence
  - Denovo S_N code: 3-D Cartesian
  - Monaco Monte Carlo: fixed source, same geometry and cross sections (MG) as KENO-VI
  - Hybrid method based on CADIS: uses approximate DO adjoint to form weight windows and biased source for detailed MC
  - Forward-weighted CADIS for "answer everywhere"

CAAS Capability in SCALE 6.1

- Step One – KENO calculation
  - Standard criticality problem
  - Include as much detail as required
  - New option to save the fission neutron distribution, $f(\vec{r},E)$, as a mesh-based tally
- Step Two – Convert mesh tally into a mesh source
- Step Three – MAVRIC shielding calculation
  - Use mesh-based fission source
  - Optionally add fission photons
  - Include building-level details and fine details near critical assembly
  - Use CADIS or FW-CADIS to calculate detector responses

Fission Photons

- 22 isotopes in ENDF/B-VII.0
- 5 distributions
- Multipliticity: 6.31 to 8.18



Californium 98											Cf250 1	Cf251 1
Berkelium 97												
Curium 96							Cm242 5				Cm248 1	
Americium 95							Am241 3		Am243 5			
Plutonium 94						Pu239 4	Pu240 4	Pu241 1	Pu242 5	Pu243 1		
Neptunium 93					Np237 2							
Uranium 92	U232 1	U233 4	U234 1	U235 2	U236 1	U237 1	U238 1	U239 1	U240 1	U241 1		

KENO-VI Calculation

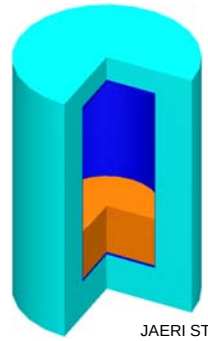
- CSAS6 Sequence
  - User supplies mesh grid and
  - Sets a flag to save fission source neutron distribution $f(\vec{r},E)$

```
'-----------------------------------------------
' Parameters Block
'-----------------------------------------------
read parameters
    ...
    cds=yes
end parameters

'-----------------------------------------------
' Grid Block - mesh grid for source
'-----------------------------------------------
read grid 1
    xLinear 10 -10.0 10.0
    yLinear 10 -10.0 10.0
    zPlanes -10 -8 -6 -4 -2 -1 0 1 2 4 6 8 10 end
end grid
```

KENO-VI Calculation

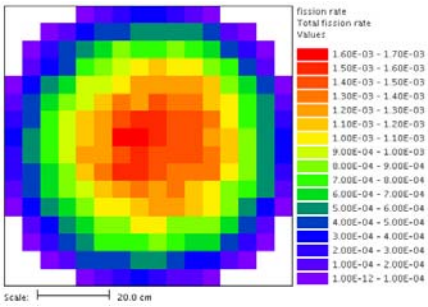
- Output
  - Multiplication k_{eff}
  - Neutrons per fission $\bar{\nu}$
  - Fission source distribution

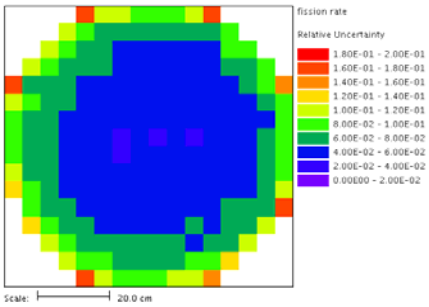


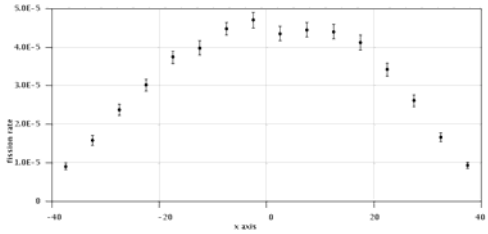
JAERI STACY $UO_2(NO_3)_2$
leu-sol-therm-020

```
*****************************************************************************************************************
***                                                                                                           ***
***   leu-sol-therm-020 (jaeri stacy) - keno-vi criticality calculation                                       ***
***                                                                                                           ***
*****************************************************************************************************************
***                                                                                                           ***
***                                  ******      final results table      ******                              ***
***                                                                                                           ***
***        best estimate system k-eff                                  0.9989 + or - 0.0015                   ***
***                                                                                                           ***
***        Energy of average lethargy of Fission (eV)                  3.71503E-02 + or -  2.54660E-05        ***
***                                                                                                           ***
***        system nu bar                                               2.43840E+00 + or -  6.88197E-06        ***
***                                                                                                           ***
***        system mean free path (cm)                                  6.41181E-01 + or -  9.66868E-04        ***
***                                                                                                           ***
***        number of warning messages                                  7                                      ***
***                                                                                                           ***
***        number of error messages                                    0                                      ***
***                                                                                                           ***
***        k-effective satisfies the chi**2 test for normality at the 95 % level                             ***
***                                                                                                           ***
***                                                                                                           ***
*****************************************************************************************************************
*****************************************************************************************************************
```

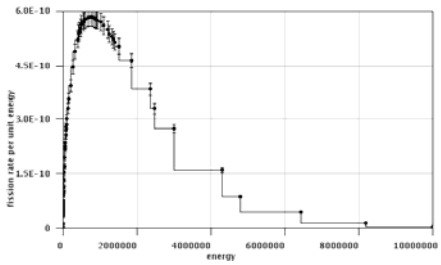

KENO-VI Results

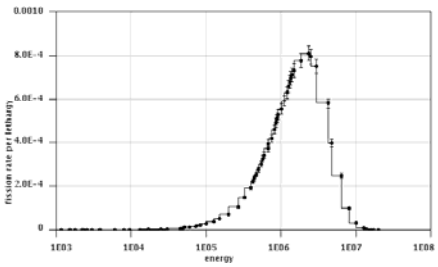






KENO-VI Results





MAVRIC Calculation

- Use the KENO-VI generated fission source
  - Value of $\bar{\nu}$ is read from KENO-VI output
  - optionally add fission photons, the user specifies the ZAID

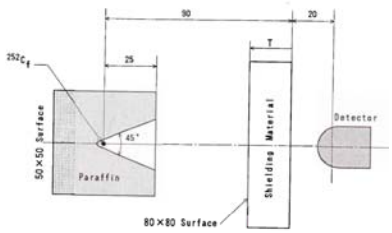
```
'-----------------------------------------------
' Source Block – for 1e18 fissions
'-----------------------------------------------
read sources
    src 1
        meshSourceFile="fissionSource.msm"
        origin x=280 y=300 z=100
        fissions=1e18
        fissPhotonZAID=92235
    end src
end sources
```

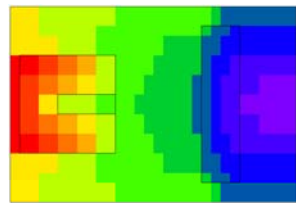
- Use automated variance reduction (importance map and biased source) to optimize detector response FOM

CADIS Methodology

Consistent Adjoint Driven Importance Sampling

An importance map and biased source are developed that optimize the calculation of a specific tally.





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

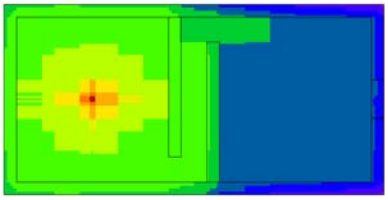
CADIS Methodology in MAVRIC

- Nearly automatic – user supplies only
  - Mesh grid (coarse) for the discrete ordinates calculations
  - Adjoint source, which corresponds to the tally to optimize

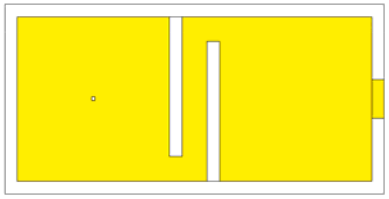
Define the adjoint source	$q^+(\vec{r},E)=\sigma_d(\vec{r},E)$
Solve for the adjoint flux	$\phi^+(\vec{r},E)$
Estimate detector response	$c=\iint q(\vec{r},E)\,\phi^+(\vec{r},E)\,d\vec{r}dE$
Construct weight windows	$\overline{w}(\vec{r},E)=\dfrac{c}{\phi^+(\vec{r},E)}$
Construct biased source	$\hat{q}(\vec{r},E)=\dfrac{1}{c}q(\vec{r},E)\,\phi^+(\vec{r},E)$

Optimizing Multiple Tallies

- In order to calculate multiple tallies (or a mesh tally), calculate the adjoint flux from multiple adjoint sources.



$D(\vec{r},E)$

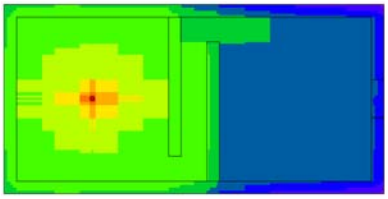


$q^{+}(\vec{r},E)$

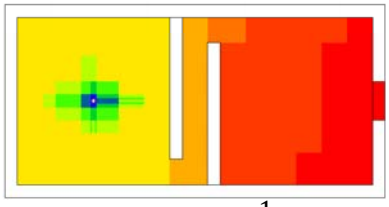
- To compute more uniform relative uncertainties in the tallies (or across a mesh tally), weight each adjoint source inversely by the expected tally values

Optimizing Multiple Tallies

- In order to calculate multiple tallies (or a mesh tally), calculate the adjoint flux from multiple adjoint sources.



$D(\vec{r},E)$



$$q^{+}(\vec{r},E) \propto \frac{1}{D(\vec{r},E)}$$

- To compute more uniform relative uncertainties in the tallies (or across a mesh tally), weight each adjoint source inversely by the expected tally values

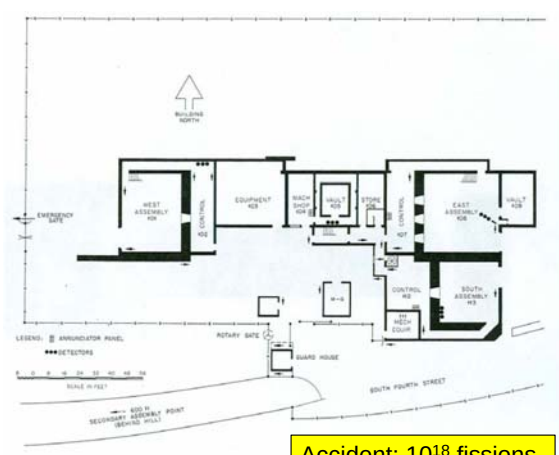
Forward-Weighted CADIS

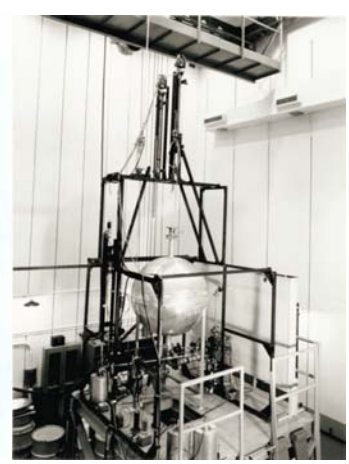
FW-CADIS in MAVRIC

Estimate the forward flux	$\phi(\vec{r},E)$
Define the adjoint source	$q^{+}(\vec{r},E)=\dfrac{\sigma_d(\vec{r},E)}{\iint \sigma_d(\vec{r},E)\,\phi(\vec{r},E)\,d\vec{r}\,dE}$
Solve for the adjoint flux	$\phi^{+}(\vec{r},E)$
Estimate "detector" response	$c=\iint q(\vec{r},E)\,\phi^{+}(\vec{r},E)\,d\vec{r}dE$
Construct weight windows	$\overline{w}(\vec{r},E)=\dfrac{c}{\phi^{+}(\vec{r},E)}$
Construct biased source	$\hat{q}(\vec{r},E)=\dfrac{1}{c}q(\vec{r},E)\,\phi^{+}(\vec{r},E)$

Example Problem

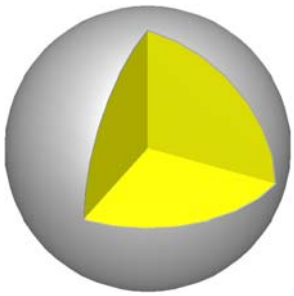
- Simulation of u233-sol-therm-008 experiment in the Oak Ridge Critical Experiments Facility





Accident: 10^{18} fissions

KENO-VI Model



```
'uranyl nitrate
    u-233  1 0.0 3.3441E-05 end
    u-234  1 0.0 5.2503E-07 end
    u-235  1 0.0 1.0184E-08 end
    u-238  1 0.0 2.5474E-07 end
    th-232 1 0.0 1.4756E-07 end
    n      1 0.0 7.4943E-05 end
    h      1 0.0 6.6357E-02 end
    o      1 0.0 3.3469E-02 end

'type 1100 aluminum
    al     2 0.0 5.9881E-02 end
    mn     2 0.0 1.4853E-05 end
    fe     2 0.0 1.0958E-04 end
    cu     2 0.0 5.1364E-05 end
    si     2 0.0 2.1790E-04 end
```

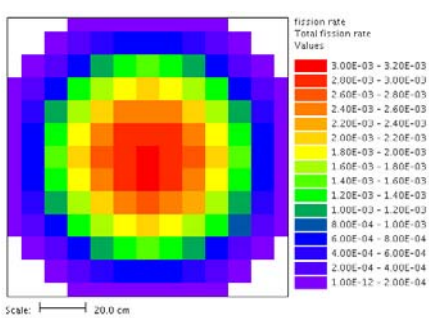
```
sphere 21  61.011
sphere 22  61.786
media 1 1  21     vol=951290.2363
media 2 1  22 -21 vol=36714.09735
```

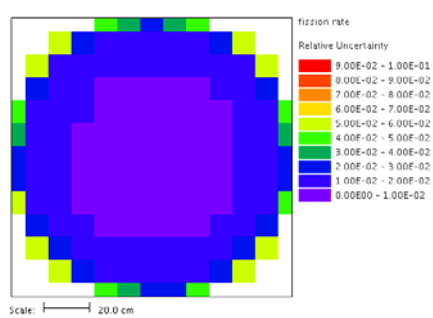
```
read gridGeometry 1
    xplanes -61.011 -55 -45 -35 -25 -15 -5 5 15 25 35 45 55 61.011 end
    yplanes -61.011 -55 -45 -35 -25 -15 -5 5 15 25 35 45 55 61.011 end
    zplanes -61.011 -55 -45 -35 -25 -15 -5 5 15 25 35 45 55 61.011 end
end gridGeometry
```


KENO-VI Results

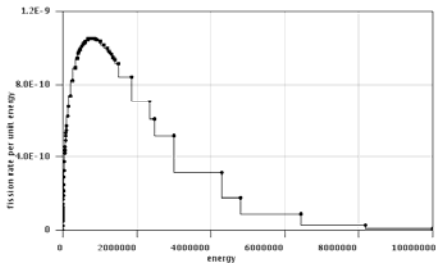
- 21 minute calculation (5x longer than benchmark)

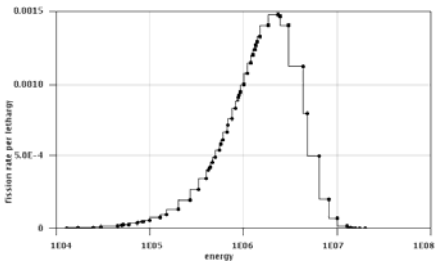
Quantity		Value	Uncertainty
k_{eff}	best estimate system k-eff	1.00146	0.00022
$\bar{\nu}$	system nu bar	2.49719	2.497E-07





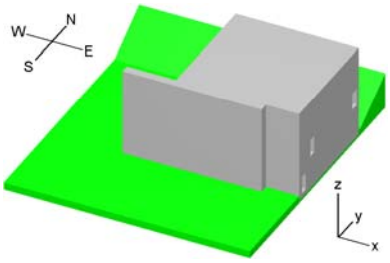
KENO-VI Results

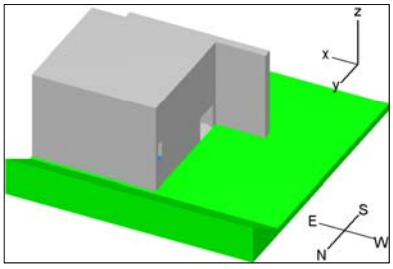


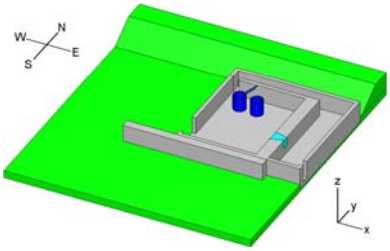


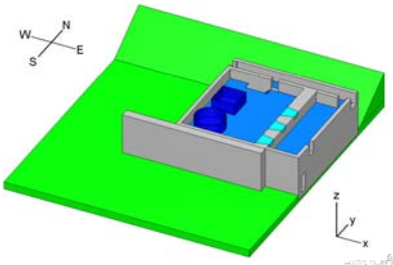
MAVRIC Model

- West Assembly modeled



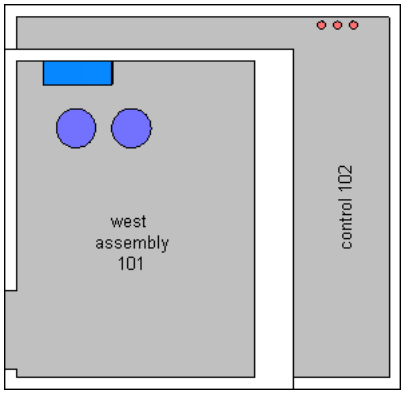




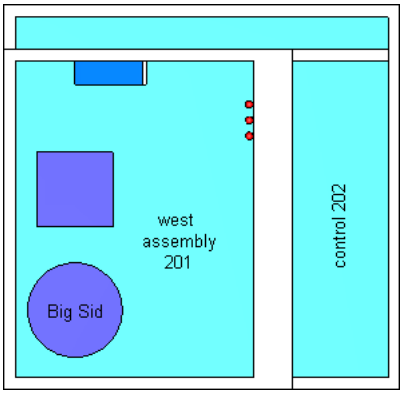


MAVRIC Model

- Detectors on both levels of west assembly



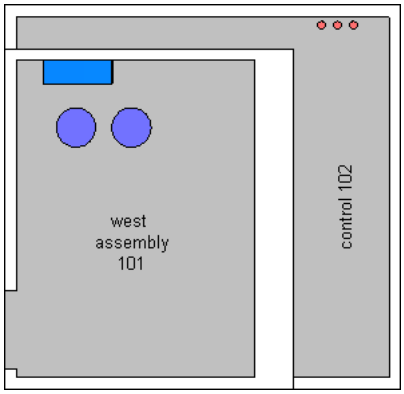
lower level



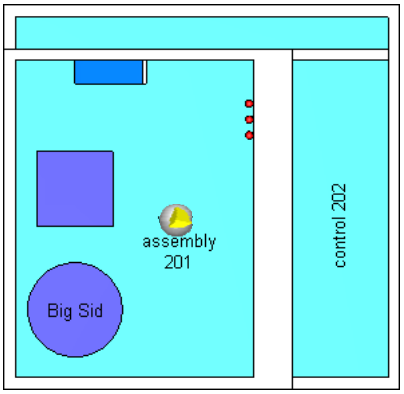
upper level

MAVRIC Model

- U233-sol-therm-008 model placed in center of upper level



lower level



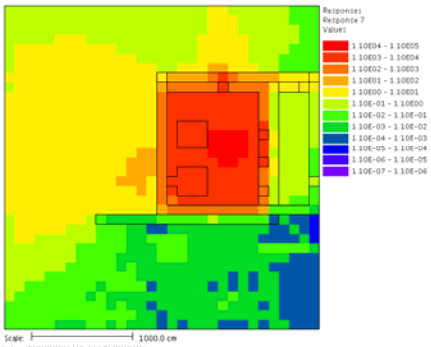
upper level

Analog Calculations

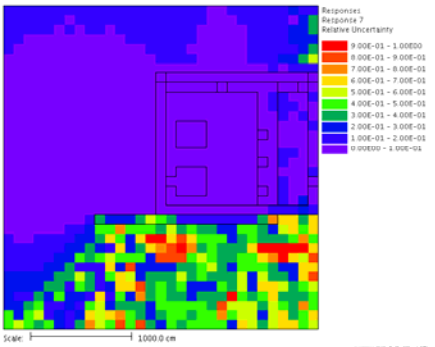
- 42 CPU•days
  - Using only implicit capture
  - Neutron dose~10*photon dose
  - Will take too long to get 5% r.u.

Level	Detector	Total Dose Value (rem)	Total Dose Rel. Unc.
lower	west	4.48	12.8%
	center	5.24	18.9%
	est	3.73	21.5%
upper	south	4.83E+03	0.8%
	center	4.23E+03	0.8%
	east	3.65E+03	0.9%

Total dose (rem)



Relative Uncertainty



Variance Reduction in MAVRIC

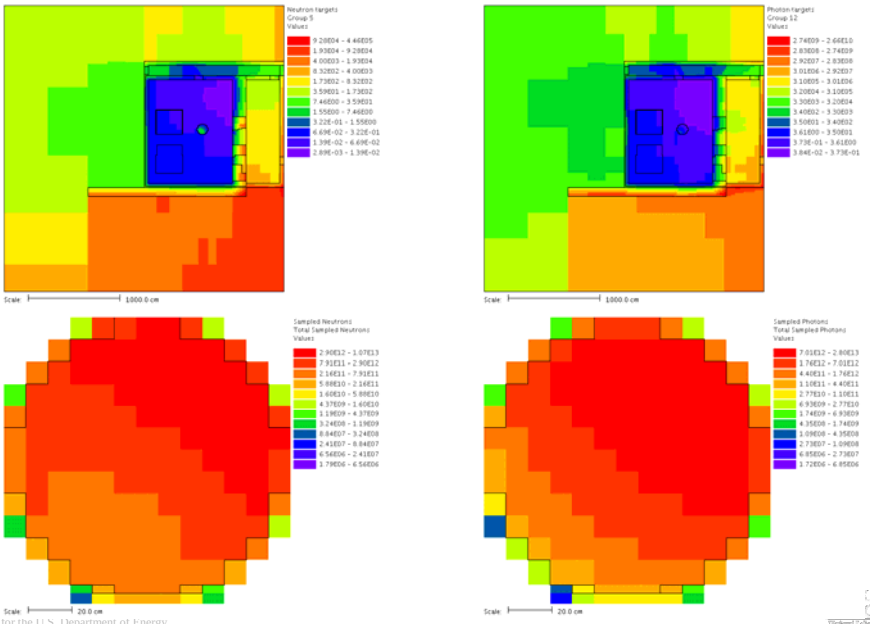
Three calculations:

A. Upper level detectors
B. Lower level detectors
C. Mesh tally in and around west assembly bay

Optimize both the neutron and photon dose calculations

Requires FW-CADIS

A. Upper Level Detectors



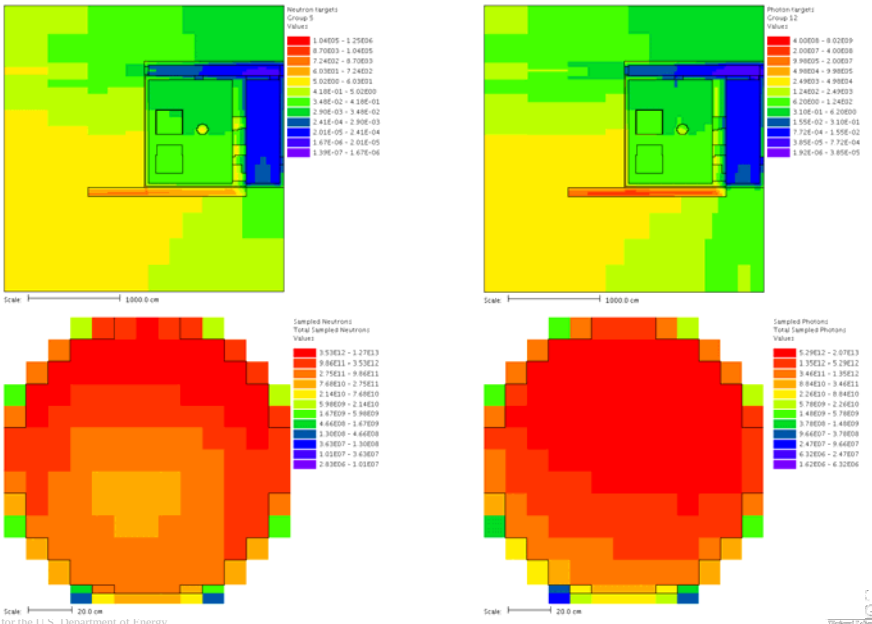
A. Upper Level Detectors

- Using FW-CADIS in MAVRIC
  - 17 minute forward DO calculation with Denovo
  - 20 minute adjoint DO calculation with Denovo
  - 725 minute forward Monte Carlo calculation with Monaco
    - Using mesh-based weight windows
    - Using mesh-based biased source

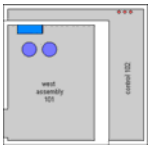
	Neutron		Photon		Total	
Detector	Value (rem)	Rel. Unc.	Value (rem)	Rel. Unc.	Value (rem)	Rel. Unc.
south	4409	0.7%	664.5	1.0%	5073	0.6%
center	3785	0.7%	565.4	1.1%	4350	0.6%
north	3313	0.8%	476.9	1.1%	3790	0.7%

FOM ratio: ~55000 | FOM ratio: ~8500

B. Lower Level Detectors



B. Lower Level Detectors



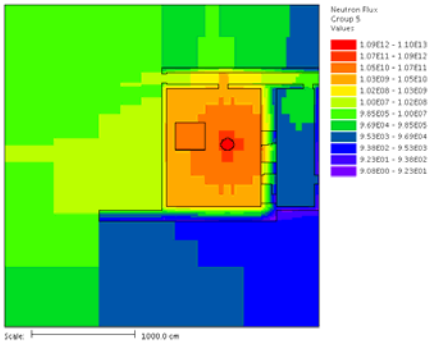
- Using FW-CADIS in MAVRIC
  - 20 minute forward DO calculation with Denovo
  - 20 minute adjoint DO calculation with Denovo
  - 1440 minute forward Monte Carlo calculation with Monaco
    - Using mesh-based weight windows
    - Using mesh-based biased source

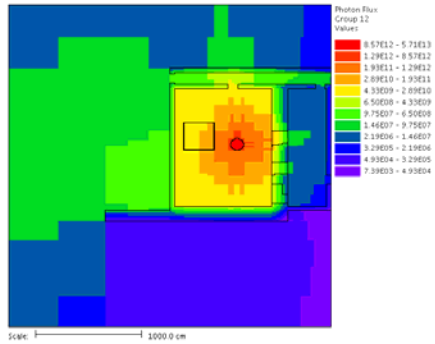
	Neutron		Photon		Total	
Detector	Value (rem)	Rel. Unc.	Value (rem)	Rel. Unc.	Value (rem)	Rel. Unc.
west	5.67	1.5%	0.489	4.6%	6.15	1.4%
center	4.48	1.6%	0.379	4.9%	4.86	1.6%
east	3.74	2.1%	0.289	2.9%	4.03	2.0%

FOM ratio: ~100000 | FOM ratio: ~9000

Mesh Tally In and Around Building

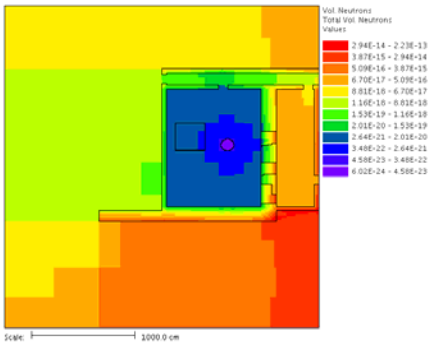
- S_N estimate of forward fluxes $\phi(\vec{r},E)$

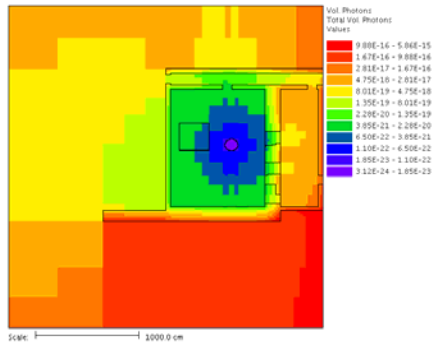




Mesh Tally In and Around Building

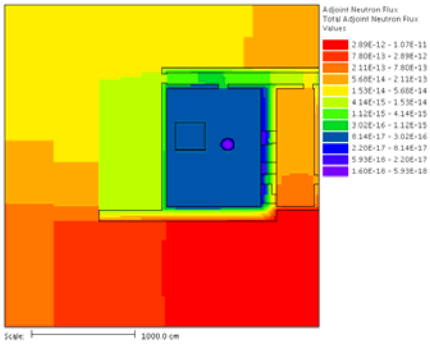
- Adjoint source $q^{+}(\vec{r},E)=\dfrac{\sigma_d(\vec{r},E)}{\iint \sigma_d(\vec{r},E)\,\phi(\vec{r},E)\,d\vec{r}\,dE}$

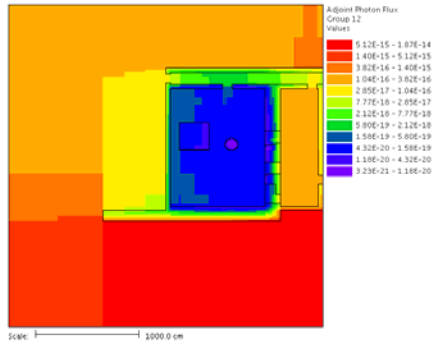




Mesh Tally In and Around Building

- S_N estimate of adjoint fluxes $\phi^+(\vec{r},E)$

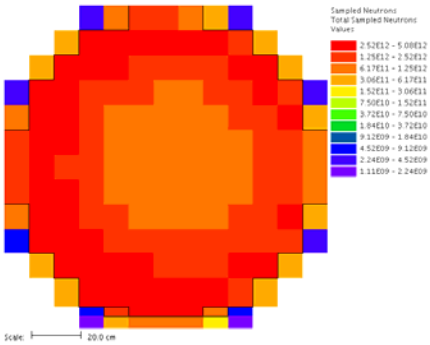


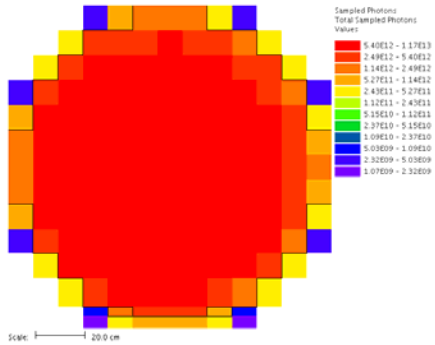


Mesh Tally In and Around Building

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

- Biased mesh sources $\hat{q}(\vec{r},E) = \frac{1}{c} q(\vec{r},E)\,\phi^+(\vec{r},E)$

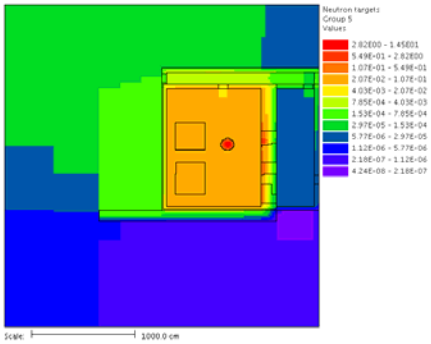


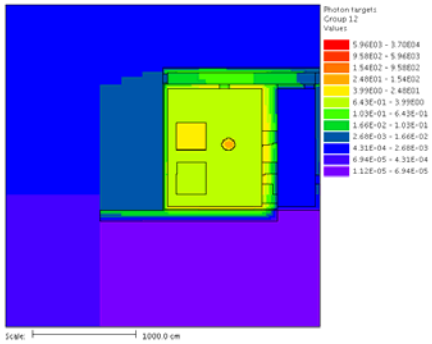


Mesh Tally In and Around Building

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

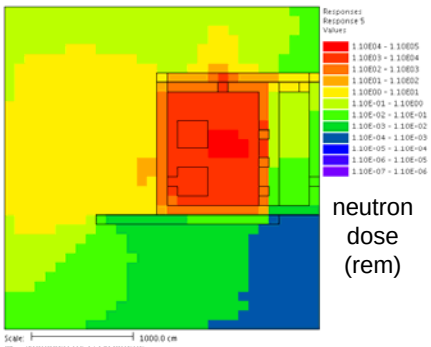
- Target weight values $\overline{w}(\vec{r},E) = \dfrac{c}{\phi^{+}(\vec{r},E)}$



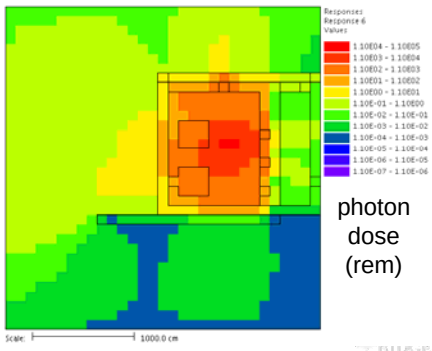


C. Mesh Tally In and Around Building

- Using FW-CADIS in MAVRIC
  - 17 minute forward DO calculation
  - 20 minute adjoint DO calculation
  - 1445 minute forward MC calculation
    - Using mesh-based weight windows
    - Using mesh-based biased source

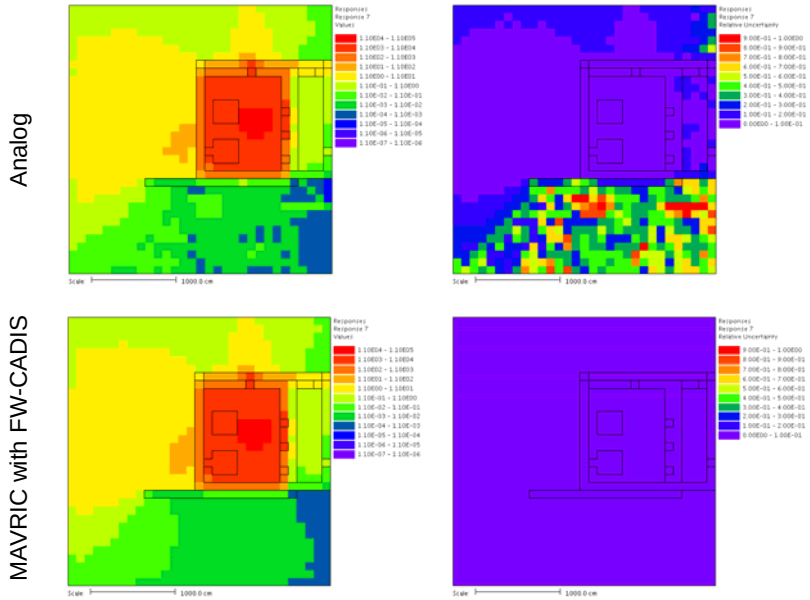


neutron dose (rem)



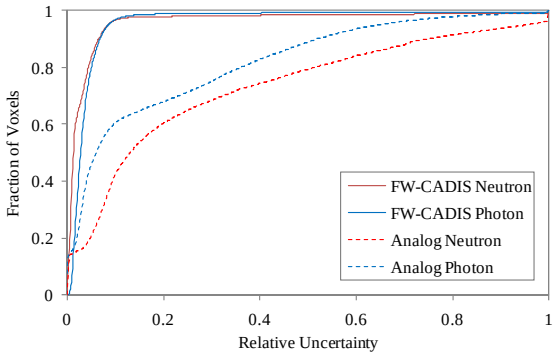
photon dose (rem)

C. Mesh Tally: Total Dose (rem)



C. Mesh Tally: Compare to Analog

- Create a pdf for relative uncertainty in the mesh tally
  - What fraction of voxels (11594) have less than some level of relative uncertainty?
  - 90% of voxels have less than 7% relative uncertainty
  - Analog: 42 days; FW-CADIS:1 day



Summary

- New capability in SCALE 6 designed for CAAS problems
- Addresses the difficulties in CAAS problems:
  - Criticality problem and deep-penetration shielding problem
  - Small scale detail for criticality, large scale for shielding
  - Full three-dimensional modeling in both
- Automated Variance Reduction in MAVRIC optimizes calculations for a specific tally – with huge speed-ups
- Future Work for CAAS in SCALE 6.2 and beyond
  - Warehouse problems – many fissionable regions
  - Comparisons to measured doses/dose rates