Hybrid Monte Carlo/ Deterministic Methods for Active Interrogation Modeling

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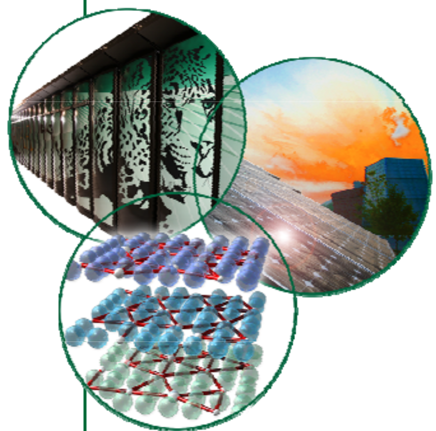

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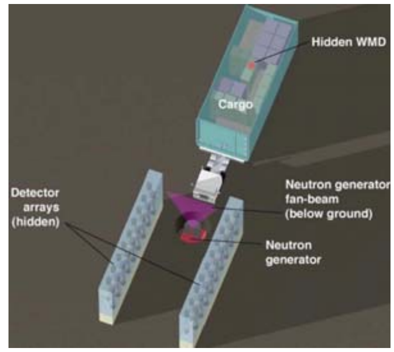
Active Interrogation

- Find illicit nuclear material by sending in particles to induce fission and then detect the fission signature
- DHS Goal: Protect our Nation from Dangerous Goods
  - Scanning nearly 100 percent of arriving containers for illicit nuclear material
  - Implement a National Small Vessel Security Strategy to decrease the risk of weapons of mass destruction delivery via small vessels
  - Screening air cargo on passenger flights

Active Interrogation is Difficult

- Source strength is limited
- Large stand-off distances
- Large amounts of shielding
  - Hydrogenous material preferentially shields neutrons
  - High-Z (proton number) material preferentially shields photons

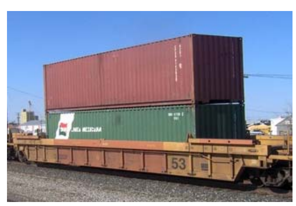


- Eventual designs will probably employ a mix of source types and a mix of detectors

Active Interrogation is Difficult

- Large range of cargos to be scanned

55-gallon barrel



Shipping container

Fishing vessel

- Need to scan efficiently

Active Interrogation Simulation

- Variety of proposed systems
  - Gamma sources: bremsstrahlung, nuclear reactions
  - Neutron sources: D-T, D-D, nuclear reactions, photonuclear reactions
  - Exotic sources: muons
- Variety of detectors
  - Gamma: NaI, HP-Ge, organic scintillators
  - Neutron: ^{3}He, BF_3, organic scintillators
  - Simple to complex (coincidence, n-correlation, etc)
- Variety of containers and cargos
- Simulation is needed to help evaluate and characterize proposed systems

Active Interrogation Simulation

- Everything that makes real active interrogation systems difficult also makes Monte Carlo simulation difficult
  - Large standoff
  - Heavy shielding
  - Huge parameter space
- Variance reduction is needed to reduce MC time for each simulation

Variance Reduction in Monte Carlo

- Bias the random sampling to spend more time on important particles and less time on unimportant particles
- Used for several decades in all of the major Monte Carlo code packages
- The difficult part is determining the importance of a particle to the final answer
  - Usually requires some knowledge of the expected answer
  - May require iteration to develop a good importance map
  - Well automated with the
    - MAVRIC sequence in SCALE
    - ADVANTG tool for MCNP(X)

CADIS Method

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 window target values are inversely proportional to the adjoint flux (measure of importance of the particles to the response).

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

CADIS Method

- We want source particles born with a weight matching the weight window targets

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

- So the biased source needs to be

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

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

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

CADIS Method - Summary

- Define the adjoint source

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

- Solve for the adjoint flux $\phi^{+}(\vec{r},E)$
- Find *c* $c = \iint q(\vec{r},E)\, \phi^{+}(\vec{r},E)\, d\vec{r}\, dE$
- Construct weight windows and biased source

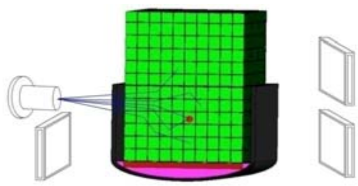
$$\overline{w}(\vec{r},E) = \frac{c}{\phi^{+}(\vec{r},E)}$$

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

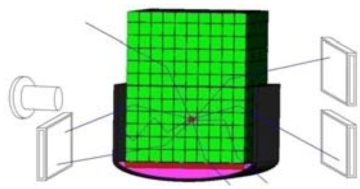
- Run the Monte Carlo

Approach

- Split the problem into several parts
  - Source to threat object
  - Threat object to detector(s)
  - Active background: Source (to whole geometry) to detector
- Optimize each separately with its own importance map
- The ‘target’ of one step becomes the source in the next step



Step 1: Source to Threat Object



Step 2: Threat Object to Detector(s)

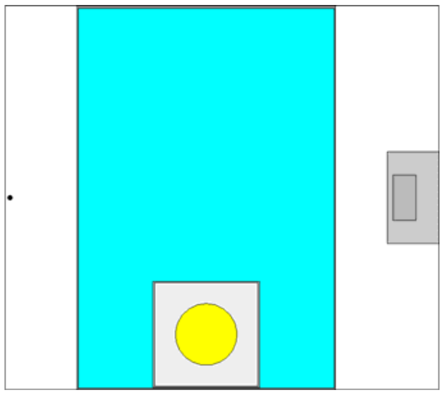
Example Studies

Several Representative Models using various sources, container types, shielding materials, detectors

- D-T neutron source, 55 gallon drum, detect neutrons
- D-D neutron source, 40 ft container, detect neutrons and gammas
- Bremsstrahlung photon source, fishing trawler, detect neutrons

55 Gallon Barrel Scanner

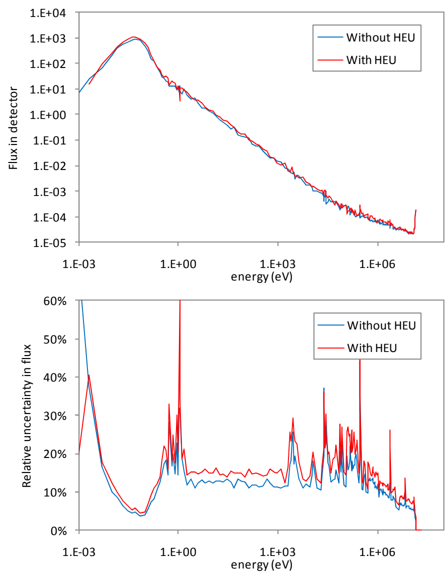
- Barrels on a conveyer belt pass between a source and detector
  - D-T neutron source:14.1 MeV, isotropic, S=10^9 n/s
  - He^3 detector, count rate is $\int \phi(E)\Sigma_{^3He(n,\alpha)}(E)dE$
  - Barrels are filled with water
  - 25 kg HEU in balsa box (to avoid criticality)



55 Gallon Barrel Scanner

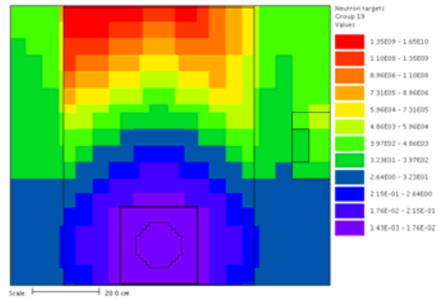
- Analog Results

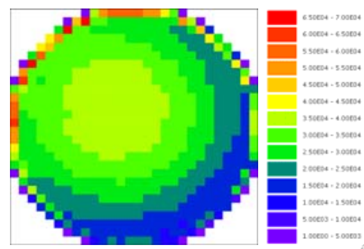
	Detector Count Rate		Time	FOM
	value	rel unc	min	/min
Without HEU	6399	1.7%	1200	2.89
With HEU	7918	2.1%	1200	1.96



55 Gallon Barrel Scanner

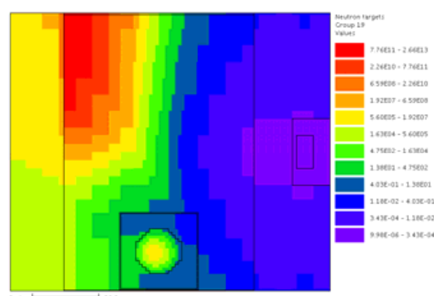
- Step 1: Determine fission source
  - Use original D-T source, 10^9 n/s
  - Allow fission multiplication
  - Mesh tally of fission neutron production, $\int \phi(E) \nu \Sigma_f (E) dE$
  - Bias for that mesh tally
  - Strength of 4.16×10^7 n/s
  - Convert mesh tally into mesh source using ^{235}U fission $\chi(E)$





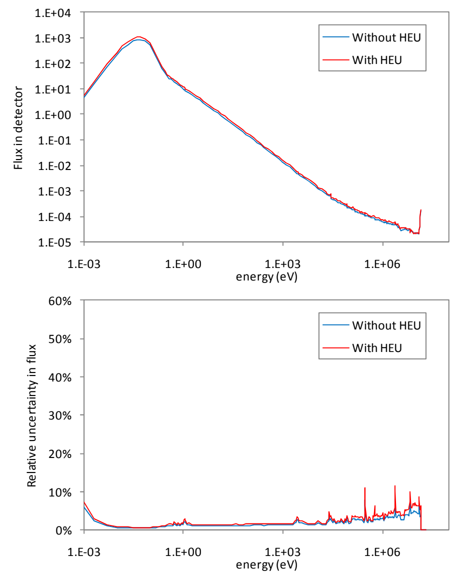
55 Gallon Barrel Scanner

- Step 2: Determine total detector count rate
  - Include original D-T source (10^9 n/s)
  - Include new mesh source (4.16×10^7 n/s)
  - Do not allow fission multiplication
  - Bias for computing $\int \phi(E) \Sigma_{^3He(n,\alpha)} (E) dE$ in the detector



55 Gallon Barrel Scanner

- CADIS Results

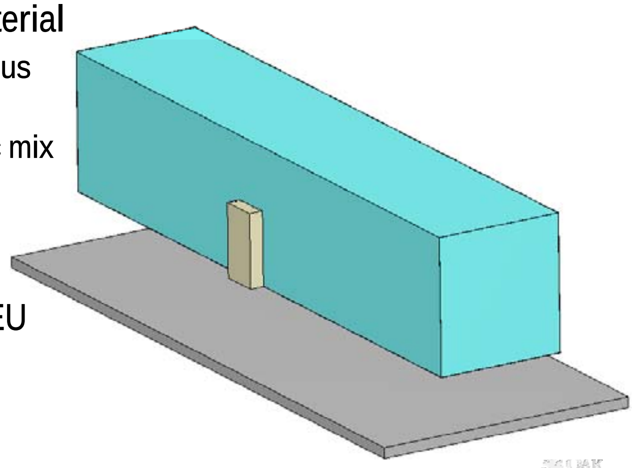


	Detector Count Rate		Time	FOM
	value	rel unc	min	/min
Without HEU	6432	0.43%	61.23	867
With HEU	7742	0.53%	129.37	272

Speed-Up over Analog:
Without HEU 300
With HEU 139

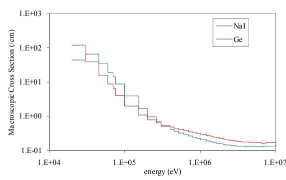
40 ft Sealand Container

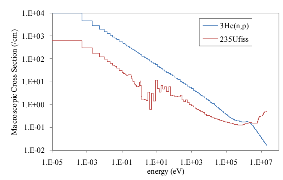
- Container 1 m above concrete floor
- Homogenous Material
  - PNNL hydrogenous ($0.2\ g/cm^3$)
  - DHS iron/organic mix ($0.4\ g/cm^3$)
  - PNNL high Fe ($0.6\ g/cm^3$)
- Look for 25 kg HEU sphere

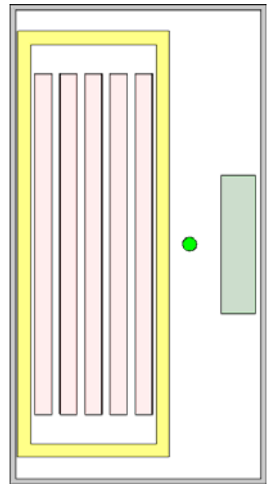


40 ft Sealand Container

- Source:
  - D-D, 2.45 MeV neutrons, isotropic
- Detectors:
  - NaI (gammas)
  - HP-Ge (gammas)
  - ^{3}He (neutrons)
- Neutrons and photons from fission

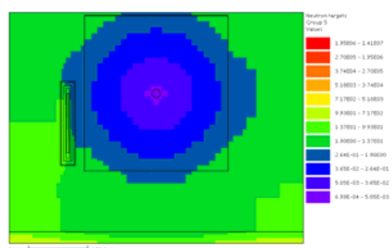


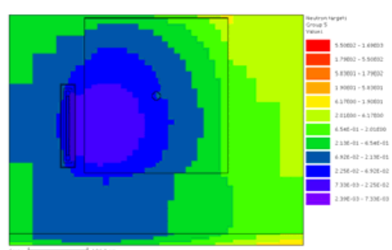




40 ft Sealand Container

- Methods
  - Two-Step CADIS
    1. Find fission source from U
    2. Find detector count rate from interrogation source and the fission source
  - Modified
    - Find detector count from fission source alone
- Nine calculations
  - Three materials
  - Optimized for three detectors





40 ft Sealand Container

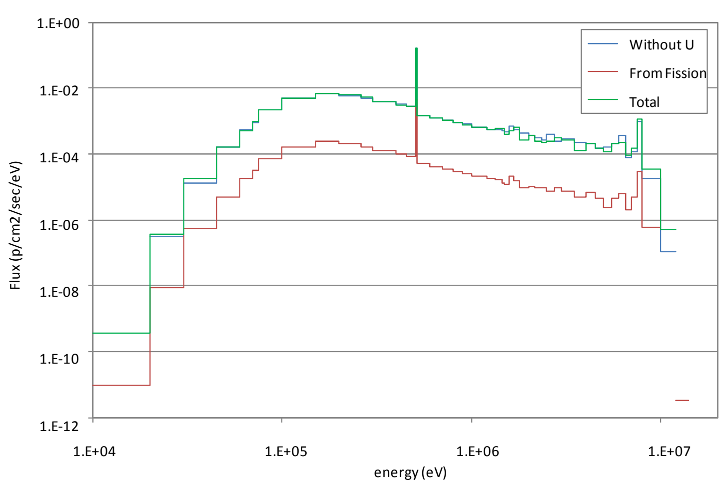
- Results for DHS Cargo (0.4 g/cm^3) and HP-Ge detector

Uranium	Time (min) Denovo	Time (min) MC	Count (Rx/s/Ci)	Relative Uncert.	MC FOM (/min)
Analog without		1442	9.365E+04	4.9%	0.287
Analog with		1443	1.046E+05	4.5%	0.348
CADIS without	70	643	9.901E+04	1.2%	10.1
fission rate	83	62	7.292E+07	0.4%	1210.0
CADIS with	104	465	9.963E+04	1.4%	10.9
CADIS fission	105	462	3.166E+03	1.0%	22.4

Similar results for other cargo material/detector combinations

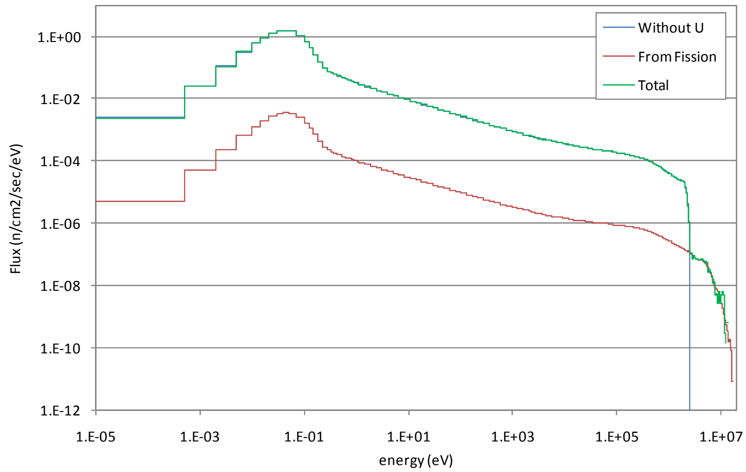
40 ft Sealand Container

- Photon flux inside the HP-Ge detector (Cargo: 0.4 g/cm^3)



40 ft Sealand Container

- Neutron flux inside the ^3He detectors (Cargo: 0.6 g/cm^3)



40 ft Sealand Container

- Increase in count rate with HEU present

	Fission/ Act. Back.
PNNL hydrogenous (0.2 g/cm^3)	
Sodium Iodide Detector	4.7%
High-Purity Germanium Detector	10.7%
Helium-3 Detectors	1.3%
DHS iron/organic mixed cargo (0.4 g/cm^3)	
Sodium Iodide Detector	2.8%
High-Purity Germanium Detector	3.2%
Helium-3 Detectors	2.3%
PNNL high iron mixed cargo (0.6 g/cm^3)	
Sodium Iodide Detector	0.8%
High-Purity Germanium Detector	1.1%
Helium-3 Detectors	0.3%

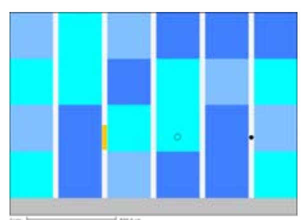
40 ft Sealand Container

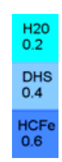
- Speed up compared to analog calculations

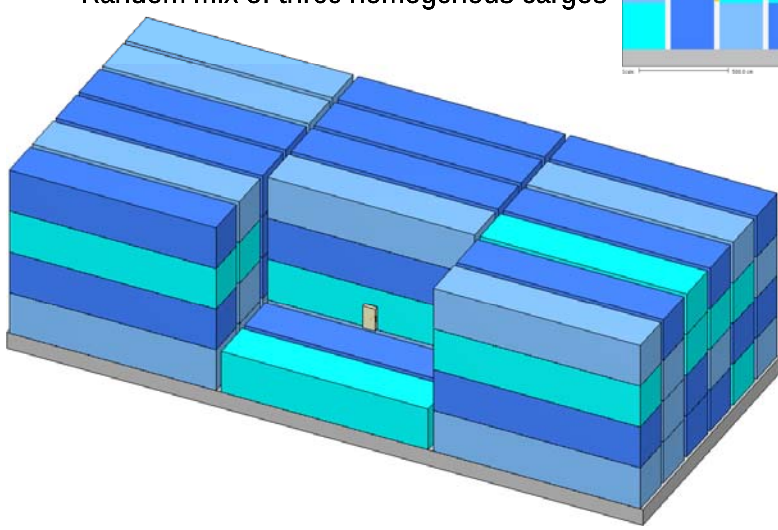
	without uranium	with uranium
PNNL hydrogenous (0.2 g/cm^3)		
Sodium Iodide Detector	10	16
High-Purity Germanium Detector	93	72
Helium-3 Detectors	114	87
DHS iron/organic mixed cargo (0.4 g/cm^3)		
Sodium Iodide Detector	6	4
High-Purity Germanium Detector	32	20
Helium-3 Detectors	60	46
PNNL high iron mixed cargo (0.6 g/cm^3)		
Sodium Iodide Detector	21	14
High-Purity Germanium Detector	132	74
Helium-3 Detectors	96	64

Multiple Containers

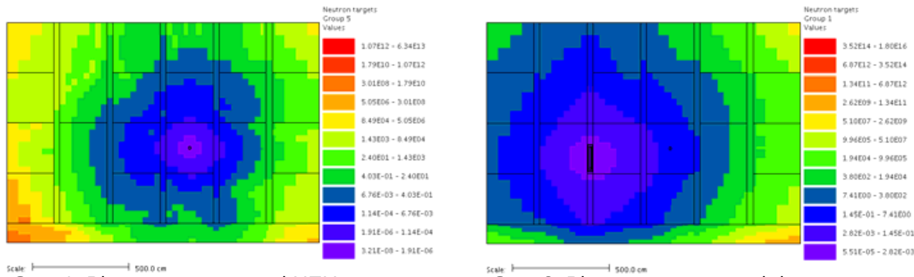
- 4×6x3 array of 40 ft containers
  - Random mix of three homogenous cargos







Multiple Containers



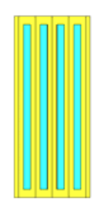
Step 1: Bias neutrons toward HEU

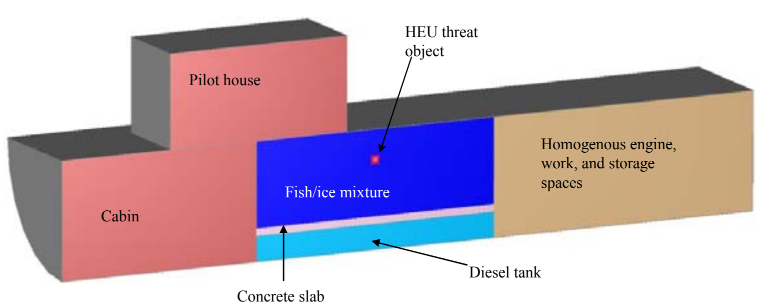
Step 2: Bias neutrons toward detector

	Analog		CADIS			FOM
	Time (min)	Result	S_N (min)	MC (min)	Result	Ratio
Active background	5770	0	74	5811	1.5 ± 36%	∞
Fission rate	5575	294 ± 100%	59	1440	151 ± 0.3%	$4{\times}10^5$
Fission detection	5769	$4.3{\times}10^{-7}$ ± 19%	140	1440	$5.4{\times}10^{-5}$ ± 1.3%	800

Fishing Trawler

- Source: 20 MeV bremsstrahlung spectrum above 1 MeV
- Detector: ^{3}He and plastic scintillator, 25 m from boat
- Active Background: photoneutrons





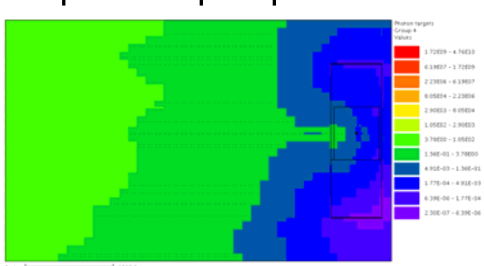
Fishing Trawler

1. Compute photonuclear reaction rate as a function of energy and space (group - wise mesh tally) for HEU, fish/ice mix and hull materials. Photon-only problem.
2. Convert mesh tallies of photonuclear reaction rate into neutron mesh sources.
3. Compute the fission neutron production rate in the HEU sphere from the three photonuclear neutron sources. Neutron-only with fission on.
4. Convert fission neutron production rate mesh tally into a neutron mesh source.
5. Determine detector response rates from the neutron sources:
    1. HEU fission neutrons
    2. HEU photo-nuclear effect neutrons
    3. fish/ice photo-nuclear effect neutrons
    4. hull photo-nuclear effect neutrons

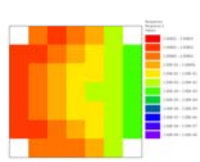
    Neutron-only with fission off.

Fishing Trawler

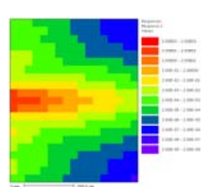
- Step 1. Compute photonuclear reaction rate



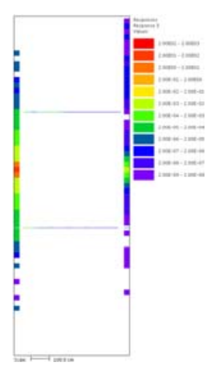
10 MeV photons



HEU



Fish/Ice

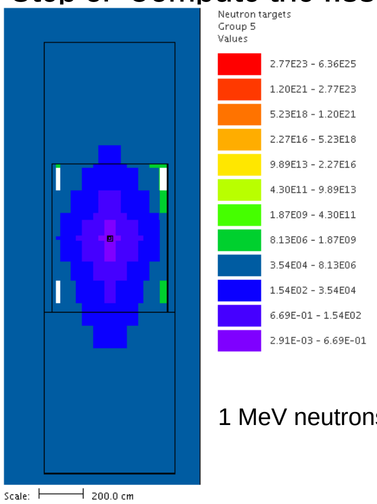


Hull Steel

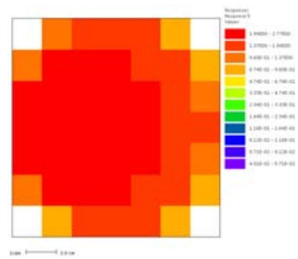
Hours
S_N: 3
MC: 8

Fishing Trawler

- Step 3. Compute the fission neutron prod. rate in the HEU



1 MeV neutrons

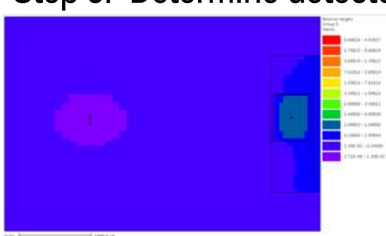


fission rate

Hours
S_N: 1
MC: 1

Fishing Trawler

- Step 5. Determine detector response rates

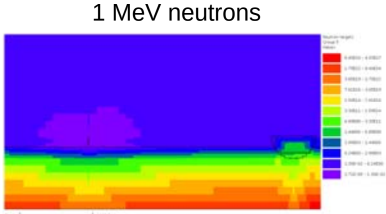


1 MeV neutrons

All neutron sources

	counts	rel unc
He-3 (n,p)	1.44E+00	5.5%
plastic scint	5.68E+02	3.5%

Hours
S_N: 1.5
MC: 8



HEU fission only

	counts	rel unc
He-3 (n,p)	1.92E-07	16.5%
plastic scint	1.56E-04	10.2%

Hours
S_N: 1.5
MC: 8

Fishing Trawler

- Initial results only, no comparison to analog yet
- Beam source – required new version of Denovo S_N code
- Photo-nuclear data – not part of Standard SCALE libraries
- May need CADIS method that is space/energy/angle

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

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

Summary

- Multi-step approach works well
  - Uses one importance map/biased source per step
  - Could reuse similar first steps
- Active interrogation is a challenging problem

Future Work

- Further automation: determine if multiple importance maps could be in memory at once.
  - User describes source, intermediate goal and final goal
  - Sequence would find importance map for each step
  - In the MC, particles would switch which importance map to use based on event history
  - This approach may be needed for coincidence modeling
  - Drawbacks: memory, consistent target weights between maps

- The current work is being funded by the ORNL LDRD Office