An Innovative Hybrid Deterministic/Monte Carlo Radiation Transport Method for Modeling Radiation Sensor Systems

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Introduction

GOAL

The main objective of this project is to develop a novel hybrid radiation transport method to combine the best of stochastic (Monte Carlo) and deterministic methods for modeling active interrogation systems. An accurate and efficient computational tool, capable of determining radiation fields and modeling all physical processes within radiation detector systems, is essential for predicting the performance of any detection system, for interpreting/analyzing measurement results, and consequently optimizing the detection system.

Active Interrogation System

An active interrogation system is comprised of three components:

i) Neutron Source
ii) Region of Interest (ROI)
iii) Detector

Methodology

In order to develop an efficient and accurate methodology, we have identified the following tasks::

Task 1 - A "forward" Monte Carlo and/or deterministic S_N for transport of the source particle to the ROI

Task 2 - An "adjoint" deterministic method for calculation of the particle flow density to the detector window

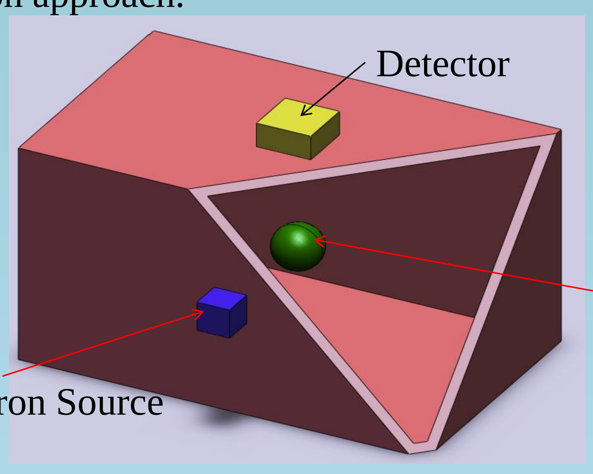
Task 3 - An incident flux expansion method to determine the detector response

Task 4 - The development of a library of detector responses (spectra) as a function of source/cargo combination, with focus on the details of the inverse map.

Work Done

Developed a set of benchmark problems for active interrogation system

Figure below shows the reference benchmark model developed for this study. This model represents a cargo container which is inspected using a detector-source assembly through active interrogation approach.



Neutron Source : D-T, 14.1 MeV (size = 13.5x13.5 cm^2)
SNM : Sphere of 25 kg of HEU; R=6.75 cm
Detector window size : 13.5x13.5 cm^2.

Cargo materials

Material	Density (g/cc)
Water – third density	0.33
Water – half density	0.50
Wood	0.52
Steel – third density	2.62

Developed a hybrid multi-step methodology

Step 1

Forward neutron transport from the source to the cargo, yielding a gamma source inside the cargo container

$$H_n\phi_n = S(fis.+idep.)$$
$$S_{\gamma,i,g} = \sum_{g'} \phi_{n,i,g'}\sigma_{(n,\gamma)i,g'\to g}$$

Step 2

Adjoint gamma transport to determine the flux at the detector face from the gamma source in the cargo (adjoint source located in the detector)

$$H_\gamma^+\phi_\gamma^+ = \sigma_{d,g}$$
$$\phi_g = \sum_i \sum_{g'} \phi_{i,g'}^+ S_{i,g} V_i$$

Step 3

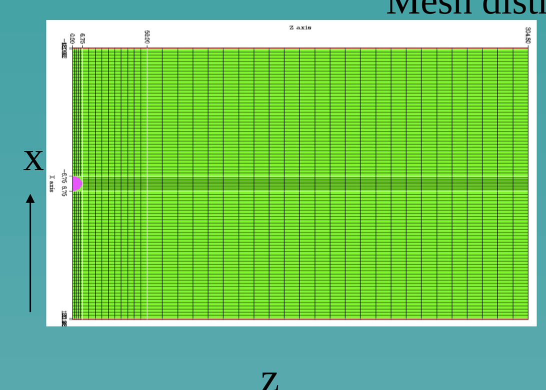
Conversion of the incoming flux at the detector into a detector response spectrum

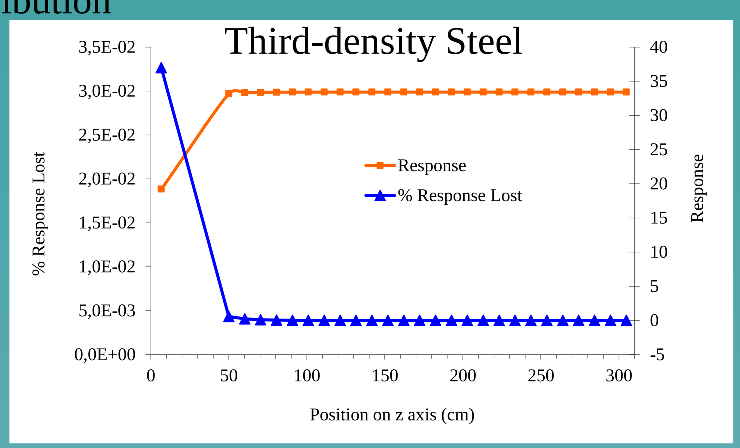
$$R = \sum_g \varepsilon_g \phi_g$$

Determination of Detector field-of-view (FOV)

Using the 3-D parallel Sn TITAN code system
Cross –section library – 47 neutron & 20 gamma (BUGLE-96)
Quadrature set : S20

Mesh distribution





The depth is 314 cm, considering the FOV, the depth reduces to:

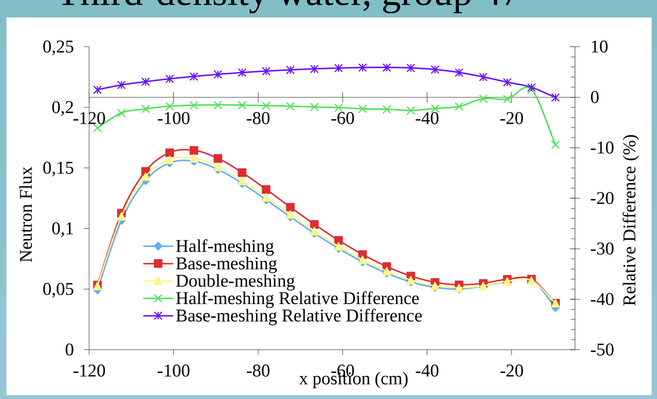
Cargo Material	Z-axis Depth (cm)	Percent of Total Response
Third-density Water	70.384	99.2
Half-density Water	70.384	99.4
Wood	80.576	99.4
Third-density Steel	50	99.4

Sensitivity Studies

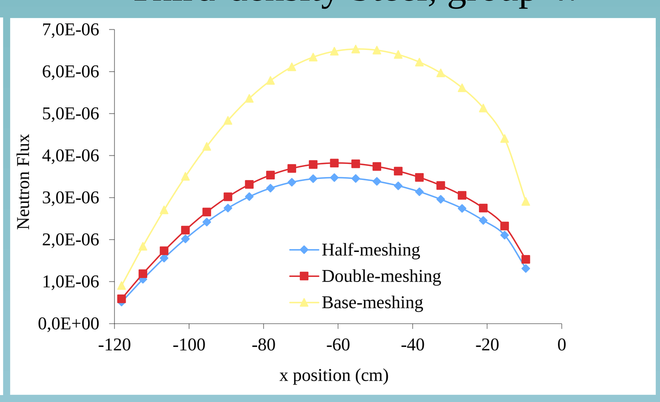
Mesh distribution

Neutron flux distribution (Source to SNM)

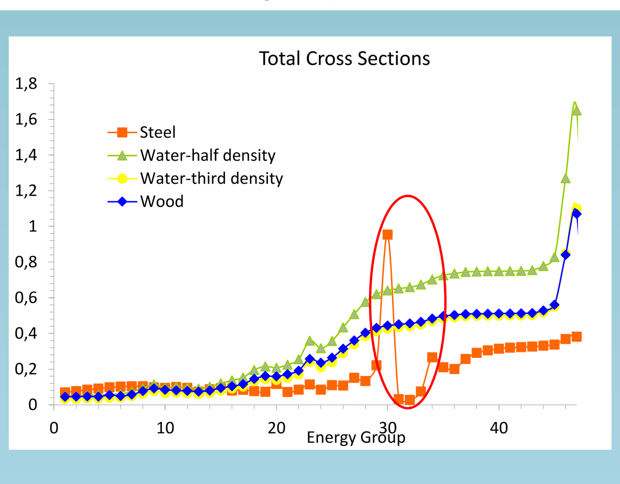
Third-density water, group 47



Third-density Steel, group 47



Comparison of cross sections for different cargo materials



NOTE: This peak at ~30 keV could be cause of the difficulty in steel cargo simulations.

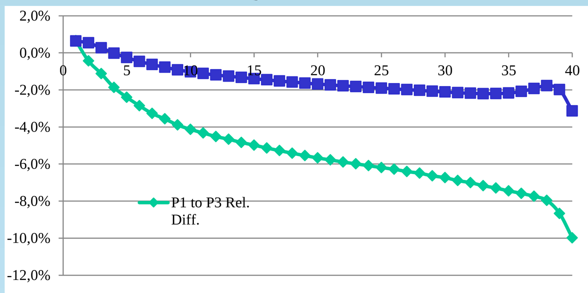
Adjoint gamma distribution for the detector

The mesh distribution is adequate.

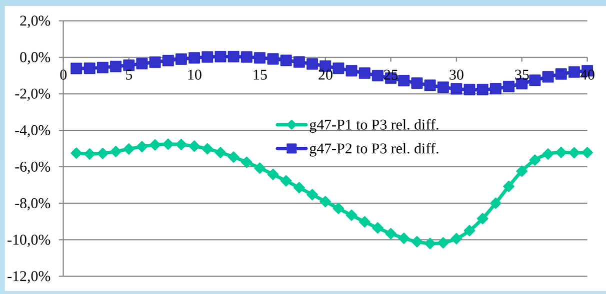
Scattering Pn order

Neutron flux (source to SNM)

Third-density water, 13.2 MeV



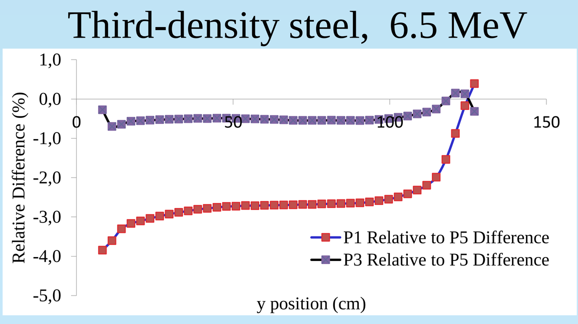
Third-density water, ≤0.1 eV



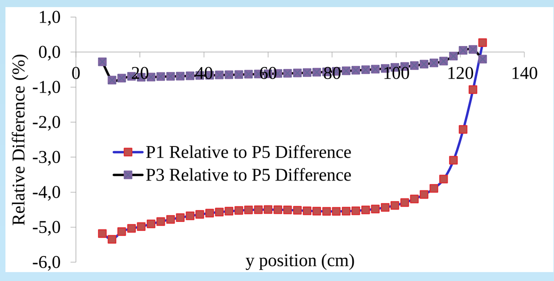
NOTE: P3 is adequate for neutron transport for all cargo materials.

Gamma adjoint (for the detector)

Third-density steel, 6.5 MeV



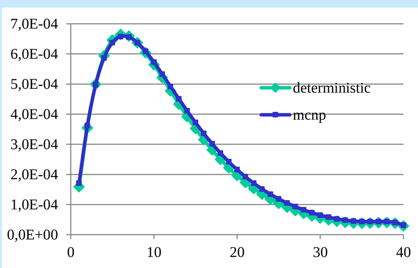
Third-density steel, 0.9 MeV



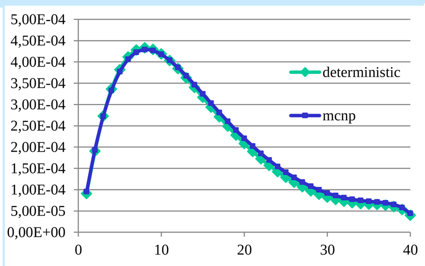
NOTE: For third-density water, half-density water, and wood, the P3 adjoint function is adequate, but in the case of steel, P4 is needed

Comparison of the TITAN deterministic thermal neutron flux with the reference MCNP5 Monte Carlo predictions

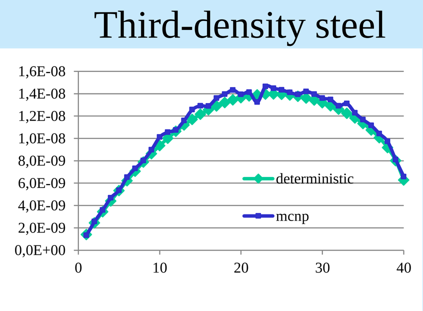
Half-density water



Wood



Third-density steel



Development of Advanced methodologies

Development of an effective methodology for determination of the background radiation for different cargo densities. Developed a mapping formulation given by

$$\phi_1(r) = \left(\frac{\rho_1}{\rho_0}\right)^2 \phi_0\left(r\frac{\rho_1}{\rho_0}\right)$$

Cargo Material	Method		Difference
	Transport	Estimated	
Water 0.50 g/cc (50%)	2.42E-03	2.45E-03	1.3%
Water 0.33 g/cc (33%)	3.15E-03	3.45E-03	8.8%
Steel 1.31 g/cc (50%)	8.04E-04	7.38E-04	-8.9%
Steel 0.87 g/cc (33%)	2.37E-03	2.82E-03	15.9%

Incident Flux Response Expansion Method

Transport equation with arbitrary boundary condition

$$H\psi(\vec{r},\hat{\Omega},E) = S(\vec{r},\hat{\Omega},E) \quad + \text{ external } BC, \quad where \;\; \text{S= fiss + ext source}$$

$$H\psi(\vec{r},\hat{\Omega},E) \equiv \hat{\Omega}\cdot\vec{\nabla}\psi + \sigma_t(\vec{r},E)\psi - \int_0^\infty \int_{4\pi} \sigma_s(\vec{r},\hat{\Omega}',E'\to\hat{\Omega},E)\psi(\vec{r},\hat{\Omega}',E')d\hat{\Omega}'dE',$$

If BC $\psi(w_s^-) = \gamma(w_s^-)$ is not known a priori then calculate RF using a set of arbitrary complete orthogonal expansion functions

$$HR_s^m(w) = S(w) \;\; with \;\; R_s^m(w_s^-) = \begin{cases} \Gamma^m(w_s^-), & \text{for } \vec{r}\in\partial V_s \\ 0, & \text{otherwise} \end{cases}$$

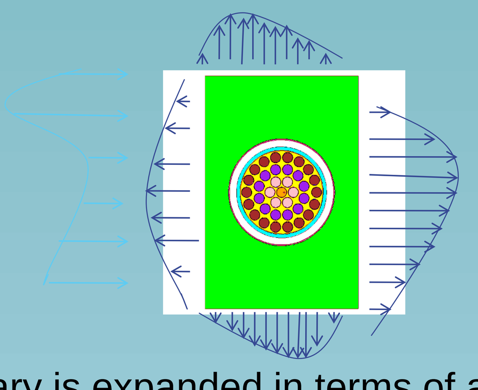
e.g., in reactor calculations use Legendre polynomials

$$\Gamma^{m,n,p,q,g}(x,y,\mu,\varphi) = \delta_g P_m(x)P_n(y)P_p(\varphi)P_q(\mu)$$

RF Generation & Mesh Coupling

RFs depend on material composition & geometry

1. Generate RF expansion coefficients
2. RFs relate a quantity of interest to a given incoming flux (or current)



The angular flux at the mesh boundary is expanded in terms of a set of pre-defined orthogonal expansion functions

$$\psi(w_s^-) = \sum_{m=0}^{\infty} c_s^m \Gamma^m(w_s^-) \quad \text{on surface } s$$

$$c_s^m = \int dw_s^- \psi(w_s^-)\Gamma^m$$

$$\psi_i(\vec{r},\hat{\Omega},E) = \sum_{m=0}^{\infty}\sum_s c_s^m R_s^m(\vec{r},\hat{\Omega},E)$$

- Algorithm couples the flux at the detector surface with the detector to generate the detector response.
= The responses were generated using B-spline bases, which can be defined recursively as:

$$B_{j,k}(x) = \frac{x-t_j}{t_{j+k-1}-t_j}B_{j,k-1}(x) + \frac{t_{j+k}-x}{t_{j+k}-t_{j+k}}B_{j+1,k-1}(x)$$

$$B_{j,1}(x) = \begin{cases} 1, & t_j \le x \le t_{j+1} \\ 0, & otherwise \end{cases}$$

$$t_j = \begin{cases} x_0 & 1 \le j \le k \\ x_{j-k} & k+1 \le j \le k+N-1 \\ x_N & k+N \le j \le 2k+N-1 \end{cases}$$

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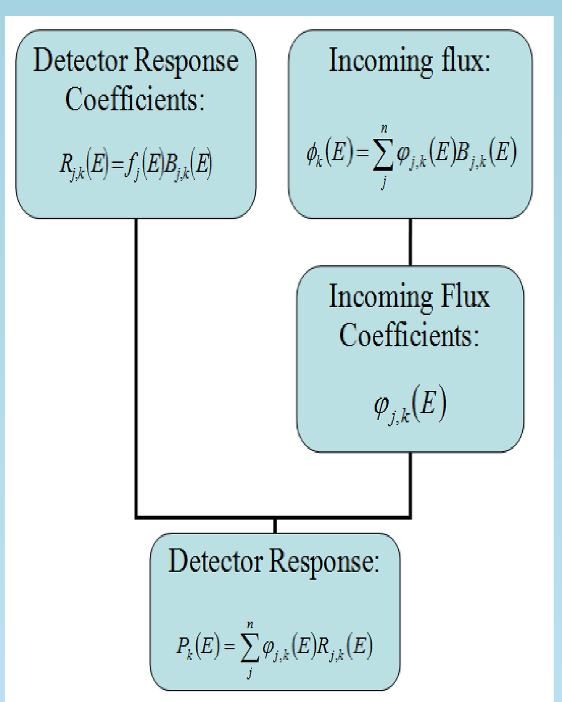
The order of the basis is k (degree k-1)
- The sequence of points {t_j} (spline knot sequence) determines the shape of the spline



Technical Challenges

- Develop an accurate and efficient hybrid deterministic/Monte Carlo method for Active Interrogation (AI) of containers
- Generate a library of response functions, which combine HEU subcritical multiplication due to external neutron source, gamma generation due to fission and (n,γ) activation, gamma transport to detector, and detector response with an assigned probability.

Planned Accomplishments

- Develop an efficient method for subcritical multiplication source determination
- Develop new multigroup libraries
- Completion of sensitivity studies ; angular quadrature sets
- Use of hybrid Sn and Characteristic methods
- Create a reference TITAN model and its comparison with the Monte Carlo predictions
- Completion of 3-D Incident Source Expansion (ISE) for detector response
- Extension of ISE to other steps of AI process