Advancing a Systems Optimization Tool for Monitoring Special Nuclear Material

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ABSTRACT

Under its international safeguards obligations, a nuclear facility will implement a security system that is developed and designed to incorporate (and hopefully integrate) elements of physical protection and containment and surveillance. Simple nuclear security components can range from closed-circuit camera systems, electromagnetic door locks, motion sensors, physical barriers, portal monitors and other radiation sensors, and radio-frequency identification tags. Integrating these various components into an effective system is difficult yet essential in providing confidence in the security and control of the special nuclear material within the facility. A tool for optimizing various material control and containment and surveillance systems would facilitate effective implementation of these systems for high assurance that material diversion could occur. At Texas A&M University, staff at the Nuclear Security Science and Policy Institute (NSSPI) has begun investigating such a systems optimization tool for various material control and containment/surveillance systems that is to be implemented in a small static, storage facility: an applied safeguards teaching laboratory for graduate-level nuclear engineering students. The facility simulates a typical static professional research laboratory with special nuclear material. The tool is based on using a stochastic radiation transport code for determining vulnerabilities of the installed radiation monitoring systems within the laboratory. In early 2010, NSSPI staff completed a proof of concept by simulating the movement of one highly-enriched uranium source though and out a single room with a single point of exit. The results were indicative of suspected vulnerabilities by the investigators and a more complex design and scenario was then devised for the next scenario: increased radiation attenuation, elevated radiation backgrounds, accelerated motion, more points of access, etc. This presentation will discuss the results of this advanced modeling endeavor and present the work into a hypothetical systems optimization tool that could eventually benefit the nuclear safeguards and security industry.

1. Introduction

The Nuclear Security Science and Policy Institute (NSSPI) at Texas A&M University (TAMU) currently operates an applied safeguards technologies laboratory where various material control and accounting (MC&A), physical protection (PP), and containment and surveillance (C/S) systems are used for educational and research purposes for graduate students receiving nuclear engineering degrees yet specializing in nuclear nonproliferation, safeguards, and security. This laboratory is to be used for educating students in various technologies needed to effectively apply nuclear security and safeguards measures via practical exercises using all the equipment and special nuclear material (SNM) housed in the lab space. A basic radiation monitor-based C/S system has been put in place to secure a small number of SNM sources within the lab and a basic vulnerability assessment of the system has been conducted. The information from a vulnerability assessment is used to optimize the C/S system for maximized material diversion interdiction. The theory behind this system optimization will eventually be translated to other technologies and systems within the laboratory.

2. Vulnerability Assessment on the TAMU ASTL

In the nuclear security industry, vulnerability assessments are used mainly to detect and identify weaknesses in a physical protection system. The challenge at TAMU was to apply this logic to a C/S radiation measurement system within the Applied Safeguards Technologies Laboratory (ASTL). Apart from the primary objective of identifying and evaluating these weaknesses, a secondary result of a vulnerability assessment includes optimization to mitigate the system’s vulnerabilities. This step is discussed within the results section of this paper.

As aforementioned, the ASTL houses portal radiation monitors, SNM standards, four gamma monitoring systems, cameras, remotely-controlled MC&A devices, and physical protection instruments such as balanced magnetic switches and other access restricting devices. The primary intent is to use this lab mainly as a teaching laboratory for holding semester-long courses on applied advanced safeguards and security technologies for graduate-level students within the nuclear engineering department at TAMU. Additionally, the laboratory is available for students in need of using the SNM or equipment for their graduate research projects in safeguards or security.

3. Previous Work

This section details the previous work (simulation and results) that was completed in 2010. New issues and concerns were introduced for 2011 and are discussed in the subsequent section.

3.1. Material Movement Simulation

The ASTL was modeled in three dimensions using the stochastic radiation transport code MCNP developed by staff scientists at Los Alamos National Laboratory[1]. The code (MCNP) allows for structural and radiation modeling and a simulation is used to determine the effectiveness of the radiation detection system in place within the lab. For simplicity concerns, the laboratory was modeled as a 30 feet by 24 feet concrete room with 12-foot high concrete ceilings. There is a single point of entry and no other external access points (i.e., windows or gates). The furniture fixtures were kept at a minimum including a wooden work bench along a freestanding concrete wall outlining the entrance/exit ramp into the lab and the steel safe where the sources are housed. Figure 1 shows a bird's-eye view of the laboratory with approximate dimensions (not to scale).

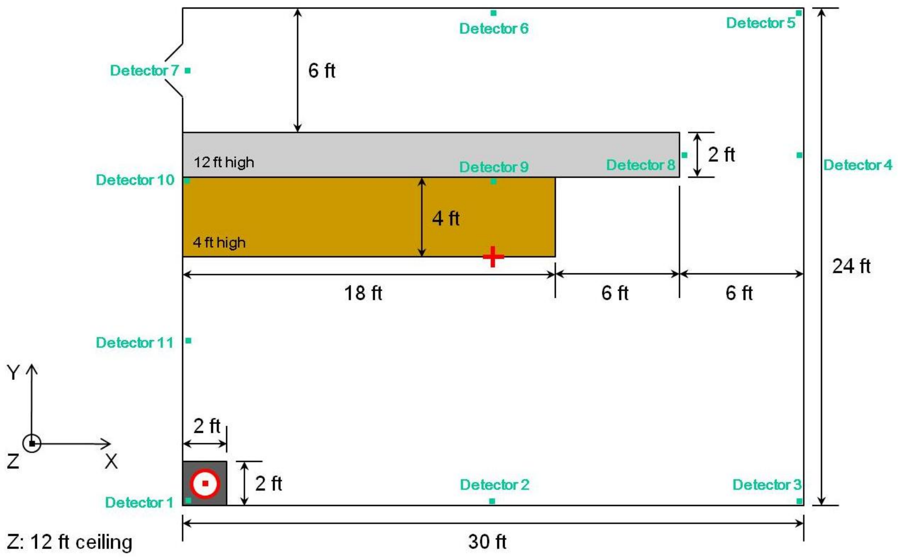

Figure 1. TAMU ASTL with source in safe (the red/white target is the source)

The radiation detection system consists of Canberra G64 Monitors (Geiger-Muller (GM) tube-based detectors) used for gross photon counts and intends to detect any movement of a given radioactive source via the placement of the detectors. A total of eleven point detectors were simulated in the model in order to choose an optimal subset/location of detectors for the given laboratory space. Enriched ^{235}U- radiation source model based on the 4.46%-enriched uranium standard from the NBL CRM 969 set was considered for the simulation placed at various locations along a suspected adversarial pathway within the lab. The results are given per single photon emitted per second and furthermore, the detector tallies are assumed as flux tallies in units of photons/cm^2-s. The adversarial pathway begins from the source kept in the storage safe and twenty source location points outside the safe as the source nears the point of exit. Figure 1 shows the starting point of the simulation (the source is the red/white target within the steel source storage safe in the lower left-hand corner). Figure 2 displays the pathway (21 source positions outside of the safe) with the eleven hypothetical detectors.

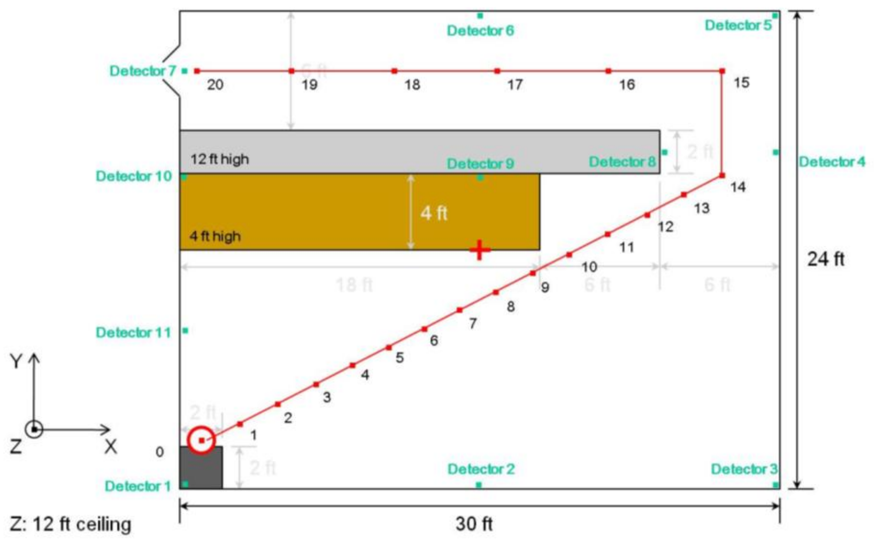

Figure 2. TAMU ASTL with defined source pathway (source is outside safe)

Initially, the defined pathway used is a simple straight-line pathway to the point of exit. For this activity, it was assumed that the simplest case would be evaluated for determining the feasibility of the theory and further scenarios would eventually be implemented if the initial case provided adequate results. With this path, from the eleven detectors flux results were tallied and then a subset from it was chosen to optimize the detector system.

3.2. Simulation Results

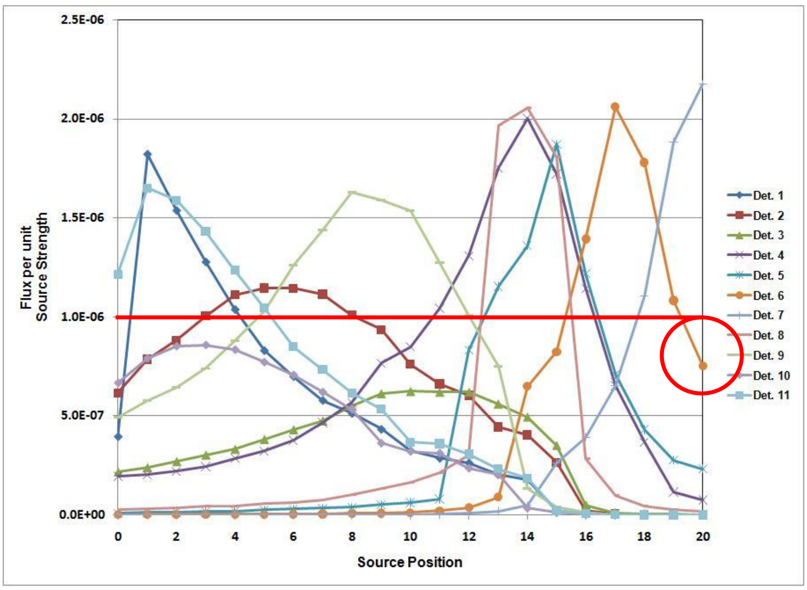

Figure 3. Flux per unit Source Strength vs Source Position for 11 detectors

The simulation results shown in figure 3 are in units of photons/cm^2-sec per source strength of one photon per second. There are twenty-one positions. Conceptually, the data supports the theory of tracking material movement via the detector system. With a given threshold of 1E-6 photons/cm^2-sec per one photon per second, figure 3 conveys that an aggregate of detector locations 11, 9, 4, and 6 will create the closest semblance of continuous material tracking using the minimal number of detectors from initially removing the source from the safe to removing the source entirely from the room.

Figure 4 shows the resulting detector profiles when the superfluous detectors are removed. It is important to note that at source location 20, the reading from Detector 6 drops below the aforementioned threshold (circled in red). Ideally, it would benefit the facility to utilize Detector 7's location but within the limitation of resources posed by the exercise, it is beneficial to show the efficacy of optimizing the placement of Detector 6 to meet the needs of the system.

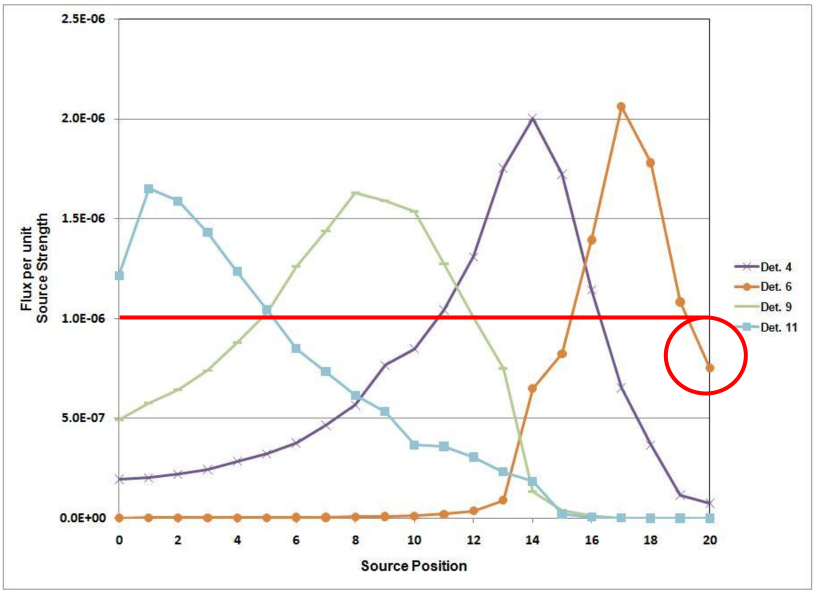

Figure 4. Flux per unit Source Strength vs Source Position for Detectors 4, 6, 9, and 11

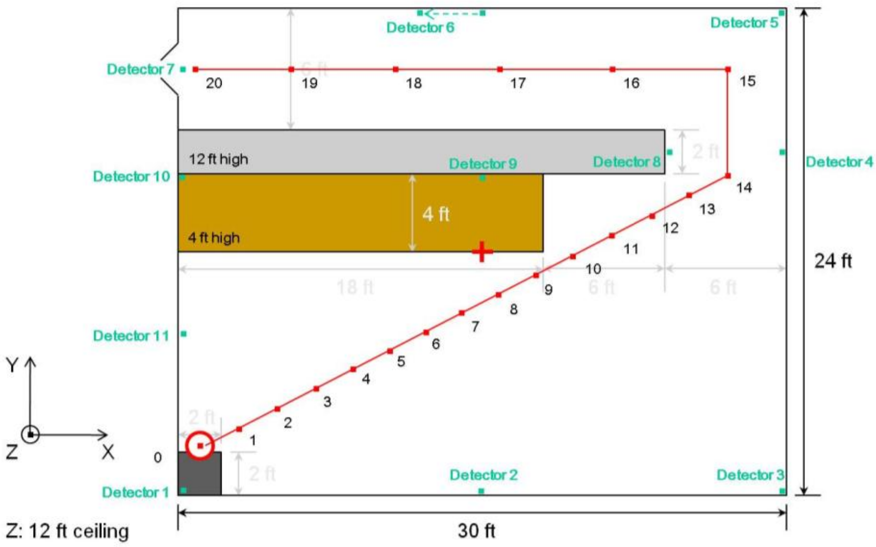

Figure 5. Detector 6 repositioned for 4-detector optimized system

Within the confines of only using four detectors, Detector 6 was repositioned to an optimized location (80 centimeters in the –X direction) that will mitigate the low count rates exhibited by source location 20. Figure 5 shows the repositioning of Detector 6 and figure 6 shows the effect of this on the profile of the source tracking.

Overall, the results convey that the exercise was a success and that material, albeit in a rudimentary setting, can be tracked through a given, simple facility based on these simulations.

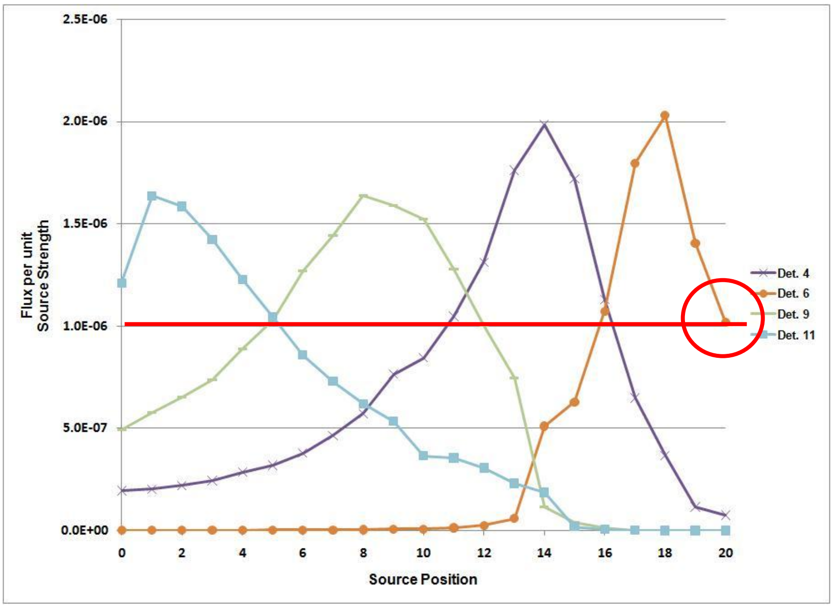

Figure 6. Flux per unit Source Strength vs Source Position for Detectors 4, 6 (modified), 9, and 11

4. Simulation Modifications

In the past year, the investigators incorporated background counts in order to determine the sensitivity of the devised system. In order to accomplish this, a constant background source of potassium-40 was introduced to simulate the room made of concrete (as it actually is housed within the TAMU nuclear engineering building). Furthermore, in order to appropriately model how detrimental the characteristic photo-electric peak of 1.46 MeV from ^{40}K could be to the designed system, the model had to be reworked to introduce energy discretization (though still utilizing the previously-defined stochastic point detectors). With the energy bins defined to focus specifically on the ^{40}K 1.46 MeV peak, the ^{235}U 186 keV peak, and the ^{137}Cs 662 keV peak, simulations were run to determine the background without any source and then run to incorporate a 1 μCi ^{137}Cs source and 100 grams of 5%-enriched uranium following the predetermined adversarial pathway defined in the previous year's work. The results are discussed in this section.

4.1. Modified Simulation Data

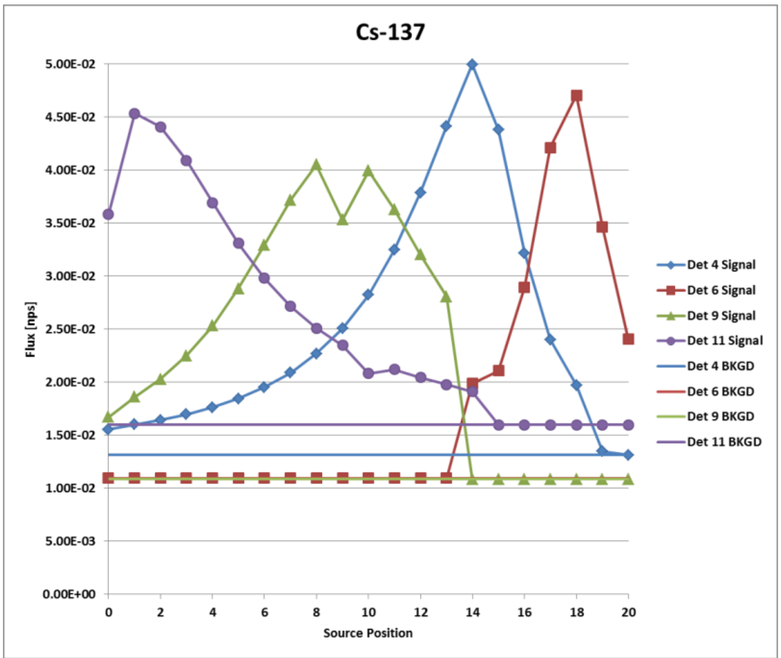

Figure 7. Tracking ^{137}Cs with 4 detectors and associated background from ^{40}K

The data of the results is shown here in graph form. Figure 7 represents the removal of a 1 μCi ^{137}Cs source. The energy bin is focused about the 662 keV photoelectric peak and the profile is similar to the previous work (when merely accumulating gross counts). With the background contribution from the concrete walls, ceiling, and floor, it is easily noted that the ^{137}Cs (albeit 1 μCi) is visible by detectors 4, 6, 9, and 11. Furthermore, the simulation was duplicated but with 100 grams of 5%-enriched uranium. Figure 8 exhibits the data.

It can be shown that regardless of the amount of material, the profile is similar with the repositioned radiation monitors and that all counts are above the background contribution of the concrete surroundings. Although the results are very promising, consideration of the realistic signal given by any detector will not distinguish between the background signal and the source signal. In order to determine the actual source readings in any given detector in this scenario, the background must be discounted in the signal reading given by the detector. The 1.46 MeV photoelectric peak is simple to remove yet the Compton scattering from the partial interactions of that photoelectric peak contributes too many counts for regions of interest about 662 keV (for ^{137}Cs) and 186 keV (for ^{235}U). Therefore, it was determined that energy discretization is necessary for accurate readings of material movements within the ASTL.

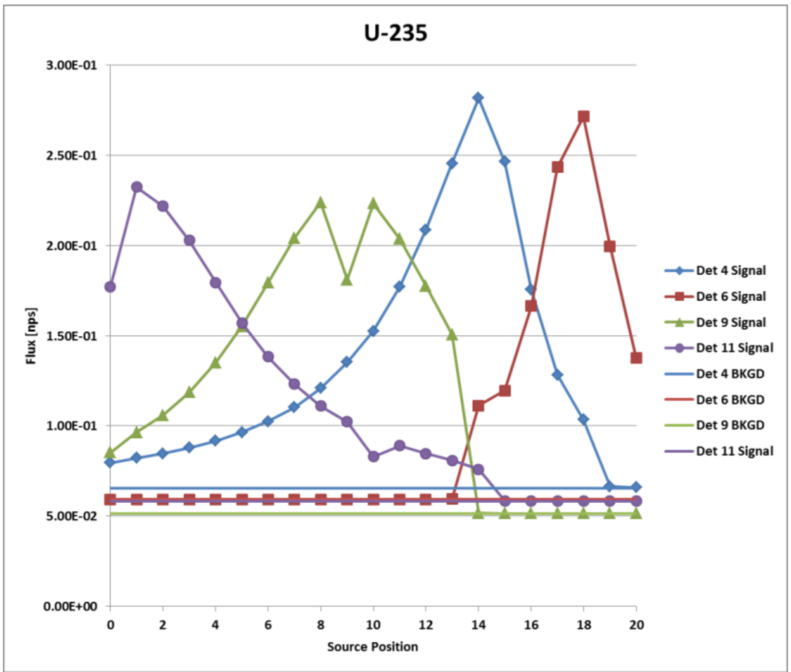

Figure 8. Tracking ^{235}U with 4 detectors and associated background from ^{40}K

4.2. Results

As shown in the data, when using discrete energy bins for a radioactive source (^{137}Cs) or nuclear material (U), the profiles match the gross counts exhibited in the previous work from 2010. The magnitude of the flux is the main difference between the 100 grams of uranium and the 1-μCi ^{137}Cs source. The next step was to determine how precise would the characterization of the 100-gram uranium source with an elevated background that includes the 1μCi ^{137}Cs source. This challenge was presented as a spoofing mechanism by a potential adversary within the facility. Hence, the uranium sample was plotted with an elevated background signature resulting from the ^{40}K and the 1-μCi ^{137}Cs in the 186-keV-range energy bin. Figure 9 shows the resulting uranium tracking profile of the four detectors and the associated background signatures for each. When compared to Figure 8 (with only the ^{40}K contributing to the 186-keV-energy bin background), it is noticeable that the background is elevated slightly. Figure 10 uses a 10-μCi ^{137}Cs source and Figure 11 displays the results when a 1-mCi ^{137}Cs source is used to spoof the energy bins for detecting the 186-keV peak of ^{235}U.

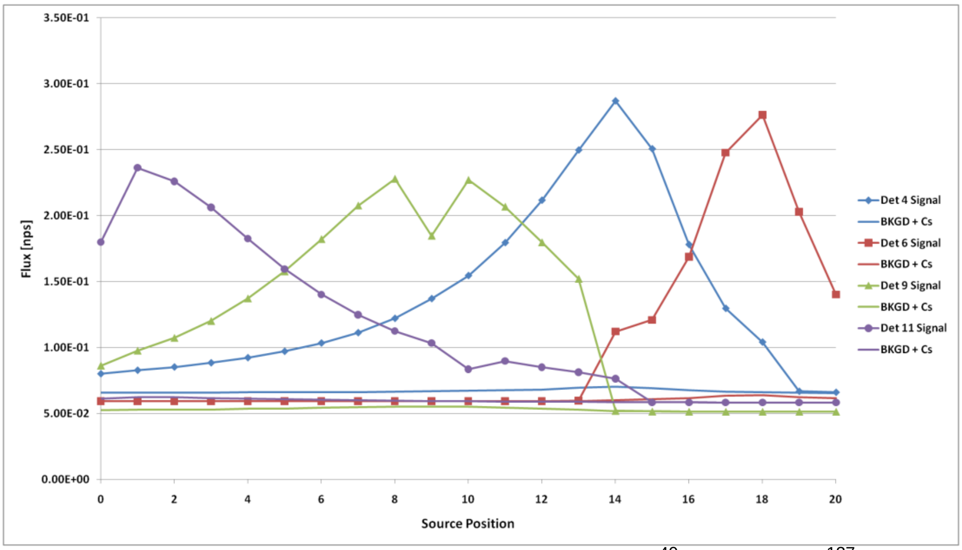

Figure 9. Tracking U with background contributions from ^{40}K and 1-μCi ^{137}Cs source

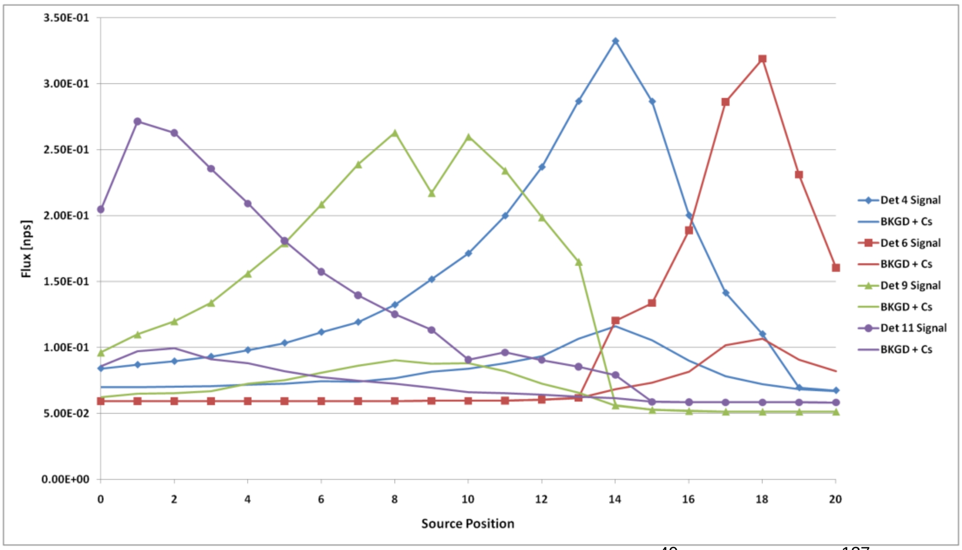

Figure 10. Tracking U with background contributions from ^{40}K and 10-μCi ^{137}Cs source

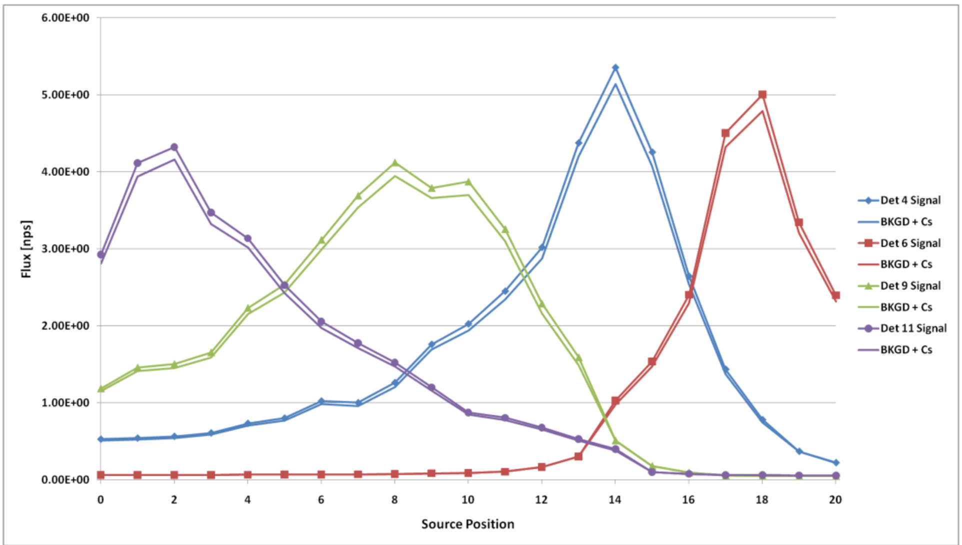

Figure 11. Tracking U with background contributions from ^{40}K and 1-mCi ^{137}Cs source

5. Future work

This work made use of energy demarcation for simulating spectral analysis. Though not ideal, this allowed for a more detailed analysis in lieu of gross counts as in previous simulations. Ultimately, more detailed detectors (scintillators or solid-state devices), more detailed background model, higher enrichment SNM sources, and facility space will be incorporated to better fit the needs of the system and the ASTL. In light of the simplification measures taken by the team, it is believed that the resulting data convey favorable results for optimizing a material tracking system using a stochastic method/code such as MCNP5. Furthermore, beyond modifying detectors, sources, and the lab space, it is envisioned that the research team will utilize knowledge gained from this exercise and apply it to other relevant containment and surveillance technology in a given static facility monitoring such as optical surveillance. It is believed that lessons learned from the basic stochastic modeling methods used in a Monte Carlo code, can be applied to other fields and this exercise is a clear step in that direction.

6. Conclusions

As discussed in previous work, this exercise validates the use of MCNP as system optimization tool for a basic C/S or material tracking system using radiation monitors in a static facility. Lessons from this work can be used in safeguarding a nuclear facility where optimization of a limited number of radiation detectors is essential. This limitation is a real-world situation that almost all facilities face continuously in today's world. Whereas the initial reaction for enhancing an existing system would be to merely add detectors, this exercise determined that detector placement is just as important to the adequate and effective operation of a radiation C/S system in a given facility. Furthermore, as exhibited in the recent advancements of this exercise, this system has been shown that vulnerabilities to spoofing exist where, given another source (representing an authorized removal of material), SNM can be masked (though, with the elevated background contribution, this may be easily mitigated against). Under TAMU's nuclear engineering MS degree program in nonproliferation, this activity is being used as an educational tool in the ASTL to educate graduate students on the value of optimizing a system using a code with which they are highly familiar.

7. Acknowledgements

The research team would like to extend gratitude to Dr. William S. Charlton of Texas A&M University and the Nuclear Security Science and Policy Institute for providing the means and resources in conducting this work as well as provided the initial idea for this exercise.

8. References

1. X-5 Monte Carlo Team, 2005 MCNP-A general purpose Monte Carlo N-Particle Transport Code, Version 5, LANL Report No. LA-UR-03-1987.