Table of Contents

Description of Data .................................................. 2
Executive Summary .................................................. 3
Statistical Analyses .................................................. 5
Major Findings ....................................................... 8
Discussion ........................................................... 9
Appendix ............................................................ 10
Description of Data

Proper monitoring of spent nuclear material is of critical importance for the security and safety of our society. The International Atomic Energy Agency (IAEA) is tasked with providing the United Nations Security Council (UNSC) with most of this monitoring capability using sophisticated techniques and technology, to establish whether a state or non-state actor is considered guilty of diverting nuclear material for weapons use. Detection technology is needed to ensure spent nuclear fuel is not diverted in such a way.

The UNSC must be especially vigilant in high risk areas for nuclear proliferation such as Kazakhstan, where spent nuclear fuel from a decommissioned nuclear reactor that produced weapons grade plutonium is stored. Our group used a program called Monte Carlo N-Particle Extended (MCNPX) to model this situation, a program that simulates interaction of radiation with its surroundings [Appendix D]. We simulated the dual slab verification detectors (DSVDs) used by the IAEA for monitoring dual use casks that contain eight spent nuclear fuel canisters arranged in a septagon with one canister at the center and one at each vertex [Appendix A]. The major variables in our simulations were canister position, neutron source histories, source fractions within the canisters, and background radiation. We chose these variables to represent deviations from baseline radiation that would not necessarily indicate that the spent nuclear fuel had been diverted. We wanted to find out if these typical deviations were predictable and therefore distinguishable from atypical deviations.
Executive Summary

The main goal of our group’s project was to prove that uncertainties in physical parameters will lead to distinct, identifiable uncertainties in our simulations. That is to say, we could predict with reasonable accuracy the qualitative outcome of these alterations. By changing four parameters: canister position, neutron source histories, source fractions within the canisters, and background radiation levels, our group was able to attain a reliable set of data that could be used by the IAEA to attribute deviations from baseline neutron counts to these changes in parameter and not to actual diversions of nuclear material. It should be noted the neutrons leave in directional vectors from the sources in a purely random fashion, i.e. the neutron direction vector was not biased in any way.

Our group received reasonable data from shifts in the canisters’ angular position, with an expected periodicity in the data due to the septagonal geometry of the canister arrangement [Appendix A]. We found, for instance, that total neutron count decreased at DSVD 1 as canister 1 moved farther from the detector. When canister 1 and 2 were equidistant from DSVD 1, the neutron count at DSVD 1 was at its minimum; neutron count at DSVD 1 began to increase as Canister 2 was moved closer. By comparing the neutron counts at each detector to the expected periodicity, the UNSC can determine if an angular shift of the canisters has taken place.

The next set of resultant data came from the alteration of the total neutron histories. As expected, running a “low” number of source neutrons (in our case, the lowest was 5e5 source neutrons) resulted in lower overall count rates at DSVD 1-4 and higher standard deviations at each position, about 10% of the mean. The standard deviations from running 5e5 or 5e6 neutrons were high enough that analysis of the data could erroneously indicate that nuclear material had been diverted. Running a higher number resulted in higher neutron counts and much lower standard deviation, about .1% of the mean, which is within our specification to be allowable.
The alteration of source fraction yielded qualitatively predictable mean changes. Comparing changes in mean among the various detectors with these expected changes would allow the UNSC to determine if the changes were due to varying the source fraction or material diversion.

Varying the background radiation had little effect on the front row detectors and a large effect on the back row, which were multiple times the baseline neutron count. Our group simulated background radiation from surrounding dual use casks. The neutron counts varied as expected with the position of the nearby dual use cask, with the closest back row detectors being the most affected and the furthest being affected very little. Our data indicates that background radiation can be accounted for by observing the differences between the front and back row detectors, after taking into account relative geometry of the sources of background radiation.
Statistical Analyses

Our analyses focused on deviation from baseline neutron counts when varying canister position, neutron source histories, source fractions within the canisters, and background radiation levels.

Varying Canister Position

(angle in radians vs. mean neutron count at DSVD1)

We plotted the mean vs. the sine of the angle and the angle and got an $R^2$ value of .897 [Appendix B]. This is very good, and is expected because the period of the fit curve shown (.8757 rads = 51.4°) is the same as the angle measured from the center of the septagonal configuration to each vertex ($360°/7 = 51.4°$). [See Appendix C for R Code]
Neutron Source History

By varying the number of neutrons in each run, we simulated monitoring the casks for varying amounts of time. The more neutrons simulated, this higher the neutron count for the detectors and the lower the standard deviation. The following table shows the standard deviations of each DSVD 1-4.

<table>
<thead>
<tr>
<th>NPS</th>
<th>DSVD1</th>
<th>DSVD2</th>
<th>DSVD3</th>
<th>DSVD4</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00E+05</td>
<td>0.1989</td>
<td>0.1989</td>
<td>0.1726</td>
<td>0.2287</td>
</tr>
<tr>
<td>5.00E+06</td>
<td>0.064</td>
<td>0.0636</td>
<td>0.0621</td>
<td>0.0645</td>
</tr>
<tr>
<td>5.00E+07</td>
<td>0.0202</td>
<td>0.0204</td>
<td>0.0204</td>
<td>0.0207</td>
</tr>
<tr>
<td>5.00E+08</td>
<td>0.0064</td>
<td>0.0064</td>
<td>0.0064</td>
<td>0.0064</td>
</tr>
</tbody>
</table>

The runs with fewer neutrons (5e5 and 5e6) have standard deviations that are not within a reasonable range to detect if a canister has been removed. One canister holds 12.5% of the nuclear material (1/8 canisters) so standard deviations as high as those in the 5e5 and 5e6 runs could falsely indicate that a canister had been removed while 5e7 or more neutrons have a low enough standard deviation to detect a missing canister.

Source Fraction

We varied the distribution of nuclear fuel within each canister, concentrating it all either at the top or the bottom. This produced a distinct change in neutron counts as shown below.

![Deviation due to Source Fraction Distribution](chart.png)
Background Radiation Level

We modeled changing background radiation by simulating other dual use casks being nearby our detectors in MCNPX. Appendix B has the graphs of neutron counts for front and back row detectors for each DSVD 1-4. They clearly show that the back row detectors are more influenced by background radiation, as expected, and that the geometry of the background radiation relative to the detectors determines which DSVD has the higher reading. Back row detectors closest to the background radiation have mean neutron counts up to six times the baseline while the front row detectors have fractions of the baseline neutron count. By looking at the differences in front and back row and determining the sources of background radiation, the UNSC could easily account for background radiation when checking for diverted nuclear material.
Major Findings

We found that uncertainties in physical parameters cause specific and distinguishable uncertainties in our simulated detectors, as we had hoped. Our findings indicate that the dual slab verification detectors used by the IAEA can distinguish between expected deviations in baseline radiation and deviations that would signify that the spent nuclear fuel had been diverted, as long as it monitors the dual use casks long enough. We found that changing angular position results in recognizable periodicity of DSVD readings, different source fractions give distinct patterns in the mean neutron counts, and background radiation produces predictable differences between the front and back row detectors based on geometry. We also found that this data is only reliable if the IAEA monitors the DUC for a long enough period of time (long enough to get on the order of $5 \times 10^7$ neutrons and a low enough standard deviation in their data). For the IAEA this means that their DSVDs can detect physical anomalies within the cask very well, as long as they monitor them long enough. This reliable data is lets them know whether canisters have been removed, and thus is vital to our security.
Discussion

One limitation to our simulations was that we only used five angles to find the deviations (0 as the baseline, -30 degrees, -15 degrees, 15 degrees, and 30 degrees); more detailed information could have been produced if we used more angles to simulate. Secondly, when we simulated the source fraction (location of the spent nuclear material in a canister) we only calculated the deviations for the top and bottom. It may have been useful to include data for anywhere between the top and bottom. However, with these limitations comes another more problematic limitation—time. We ran four simulations, taking up to thirty-nine hours each, which restricted the amount of data we could gather.
Appendix A

Single DUC with 8 Canisters at Baseline

Components of a DUC [Note front and Back row detectors in (a)]
Spatial Arrangement of Canister Arrangement within DUCs
Appendix B

This appendix shows the neutron count as a fraction of the baseline for each DSVD 1-4 in DUC 1 when the background radiation is coming from the DUC specified at the top of the
graph. See Appendix A for the spatial arrangement of the 4 DUCs. (each bar represents DSVD position, 1-4)
Appendix C

R Code

Fits mean vs angle + sin(angle)
> summary(lm(mean~angle+sin(angle)))
Call:
  lm(formula = mean ~ angle + sin(angle))
Residuals:
   1       2       3       4       5
  2.114e-07 -2.106e-08 -8.466e-08 -2.106e-08 -8.466e-08
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  7.045e-06  7.741e-08  91.004 0.000121 ***
  angle     -1.578e-08  4.217e-09  -3.741 0.064605 .
sin(angle)  -4.183e-07  1.196e-07  -3.498 0.072901 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 1.731e-07 on 2 degrees of freedom
Multiple R-squared: 0.8975,  Adjusted R-squared: 0.795
F-statistic: 8.756 on 2 and 2 DF,  p-value: 0.1025

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Overlays graph of predicted mean onto actual
x<-runif(1000,-.6,.6)
y=7.045*10^(-6)*sin(sort(x)*pi/448)-4.942*10^(-7)*sort(x)
plot(mean~angle)
lines(y~sort(x))

Appendix D

For more information on background for getting our data see
Dual Slab Verification Detector (DSVD) Manual/ Basic MCNPX Code for Simulation
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