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Parking Garage Measurements Indicating a Gamma Spectrometer-Neutron Counter Background Correlation

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Abstract

Gamma spectroscopy and gross neutron counting systems are commonly employed together during nuclear security operations, particularly mobile searches. The data from these systems are typically analyzed independently; however, operational data suggest a relationship between the background signals from both systems. This relationship appears to occur between the neutron count rate and the high energy (greater than 3 MeV) gamma spectrometer count rate for background conditions. To verify the presence of this correlation, high energy gamma ray and neutron count rates were measured in five parking garages on the Texas A&M University campus. These measurements employed one 4" x 4" x 16" NaI detector with an Ortec digiBASE MCA, four moderated 1" x 18" ³He tubes (part of the Ortec NAI-SS system), and two unmoderated 2" x 15" ³He tubes (part of a Thermo PackEye system). The NaI detector was calibrated to a 50 MeV scale and ignored signals less than 4 MeV. Results show a decrease in the count rate of each detector as the systems were moved further below the roof of each garage. These decreases appear linear, but exponential relationships are plausible. More importantly, the data also show that the count rates from the two different detector types are linearly related. The linear relationships are strong, and the slopes vary depending on which neutron counter is considered against the gamma spectrometer. While it is possible that these relationships are the result of the NaI system detecting 4-50 MeV (or even higher energy) gamma rays, it is more likely that this system is detecting charged particles: muons generated by cosmic ray interactions with the atmosphere or protons produced by the decay of free neutrons. All three of these particles would be produced proportionally to the neutrons that the ³He tubes would detect, either from the decay of the neutrons themselves or by being produced from the same cosmic ray interactions that produce the neutrons.

I. Introduction

Radiological search operations typically use both gamma spectroscopy and gross neutron counting systems. These systems are usually considered independent from one another, but there is a possible relationship between the background count rates in both of these systems. This connection appears to be between the background neutron count rate and the background count rate of signals greater than 3 MeV in the gamma spectrometer. This study sought to show this relationship using data collected with these

systems from different floors of five parking garages. If a relationship exists for background measurements, it is possible that the background count rate in the gamma spectrometer could be used to predict the background count rate in the neutron counting system.

A. Background

Nuclear security operations commonly employ the simultaneous collection gamma spectra and neutron counts. This enables operators to find man-made radiological materials ranging from industrial and medical sources, which generally emit gamma-rays, to special nuclear materials, many of which emit both gamma and neutron radiation. Locating sources of gamma radiation is relatively simple because gamma rays have discrete energies which can be distinguished using a gamma spectrometer. Because of this, it is possible to quickly discern background gamma radiation from man-made sources [1]. Conversely, locating sources of neutron radiation is more difficult because the detection systems typically only collect counts resulting from neutron interactions within the detection media. These interactions are most likely to occur when these neutral particles have very little kinetic energy (< 1 eV), but most neutrons - either background or emitted from a source - have energies greater than 1 MeV (with background neutrons often having energies over 100 MeV). Therefore, these detectors are often surrounded by materials that moderate neutrons to improve detection efficiency [1]. Despite this moderation, the background neutron count rate is typically very low and can vary with search environmental changes like elevation or surrounding building materials, particularly if the operation is a mobile search. The result is that the true background neutron count rate is difficult to identify in many situations.

A way to mitigate this issue is to estimate the expected background neutron count rate, which could be done based on the collected gamma ray spectrum. Gamma spectroscopy systems are often calibrated to a 3 MeV scale. With this calibration, gamma rays (or other particles) detected that have energies greater than 3 MeV are ignored. This is typical because the vast majority of gamma ray emitting radioisotopes emit gamma rays with energies less than 3 MeV [2]. While employing this scale for search operations, it is also possible to implement an “overflow” channel, which counts all the signals above 3 MeV. Analysis of data from operations with this feature indicated a possible relationship between the background count rates of the overflow channel and the neutron counter. The overflow channel count rate is unlikely to be the result of gamma rays since gamma rays from terrestrial sources rarely have energies above 3 MeV; therefore, these counts are likely a result of a different particle or a rare gamma ray of extraterrestrial origin. Measurements at various levels in a parking garage will illustrate this relationship between the background responses of these two systems at varying levels of intervening materials.

II. Materials and Methods

Parking garage measurements were collected using Ortec brand gamma spectroscopy and neutron counting systems (NAI-SS-4-P) [3]. Gamma spectroscopy was employed using one 4”-by-4”-by-16” (10.16 cm-by-10.16 cm-by-40.64 cm) NaI crystal with an Ortec digiBASE tube-base MCA [4]. This detector was calibrated to a 50 MeV scale by setting the bias voltage to 650V and the fine gain to 0.85x, which placed the ^{137}Cs 662 keV photopeak at channel 13 of 1024 channels (the first channel is identified as channel 0). The detector had a shaping time of 2 μs . Since the relationship of concern corresponds to high energy gamma signals, the lower-level discriminator was set to channel 81 such that signals below 4 MeV were ignored. The Ortec neutron counting system employed four 1”-by-18” (2.54 cm-by-45.72 cm) ^3He tubes pressurized to 3.039 bar (3 atm). The tubes were moderated by a layer of high-density polyethylene surrounding each with a minimum thickness of 1” (2.54 cm) [3]. Each ^3He tube had a Precision Data Technology (PDT) monitoring module to process the signals: three had a PDT10A-HN module and one had a PDT20A-HN module [5]. Data from these detectors were collected on a Windows-based computer via a USB connection to the digiBASE. The neutron counting system’s signal output was connected to the digiBASE via the digiBASE’s “enable” port, which allowed its signal to be collected via the digiBASE’s USB connection. The digiBASE system operated on USB power while the neutron

counting system was powered by a 12 VDC car outlet. The connections for this system are outlined in the block diagram shown in Figure 1, and the detectors themselves are shown in Figure 2. Additional neutron counting measurements were collected using a Thermo brand backpack system (FHT 1377 PackEye) which has two 2"-by-15" (5.08 cm-by-38 cm) ^3He tubes pressurized to 2.5 bar (2.467 atm) and a 3.54"-by-4.72" (9 cm diameter-by-12 cm) plastic scintillator detector [6]. The data from this detector were collected via a Windows-based PDA system connected via Bluetooth. The PackEye system is shown in Figure 3, and both this and the Ortec systems were mounted in an SUV-type vehicle as shown in Figure 4.

This system was used to measure the background count rates at as many levels as possible (of the totals listed) within five different parking garages on the Texas A&M University campus:

1. University Center Garage (UCG) – 5 levels
2. Northside Garage (NSG) – 6 levels
3. Central Campus Garage (CCG) – 8 levels
4. West Campus Garage (WCG) – 7 levels (2 roof levels)
5. Cain Garage (CSS) – 5 levels

Since these are active public parking garages, measurements could not be collected in the exact same horizontal position on each floor, and measurements could not be collected on some floors due to the lack of availability or other instituted restrictions. Additionally, since all these garages were within the same general area of College Station, Texas, it was assumed that any differences in elevation would have a negligible effect on background count rates. Data on similar garages suggest that a standard garage floor is 10 inches (25.4 cm) thick, and it was assumed that all these garages followed this standard [7].

Measurements were collected for 15 to 20 minutes at each level of each parking garage in an effort to reduce the variance in the results, particularly in the unmoderated backpack neutron counting system. To reduce the overall time of the campaign, 15-minute measurements were collected on the roof and the first level below the roof since neutron count rates were higher at those locations, and 20-minute measurements were collected at all other levels. The variance was reduced further by applying a five second moving average to the data, which means a count rate at a given time is the average count rate over the previous five seconds (i.e. total counts over the last five seconds divided by five seconds). The Thermo FHT 1377 PackEye system did this automatically when recording its data, and the Ortec NAI-SS-4-P system recorded counts for each second, and the moving average was calculated in post-processing.

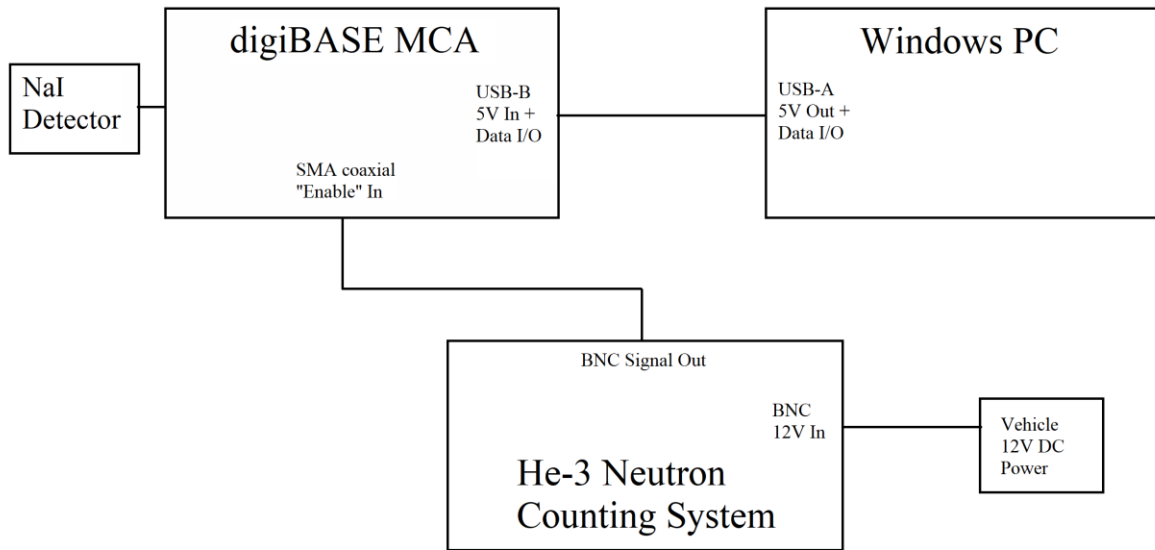


Figure 1. Block diagram outlining the connections when operating the Ortec NAI-SS-4-P system



Figure 2. Photos of Ortec NAI-SS-4-P system in their ruggedized cases including the 4"-by-4"-by-16" NaI scintillation detector (left) and the four ³He tubes in polyethylene moderator (right)

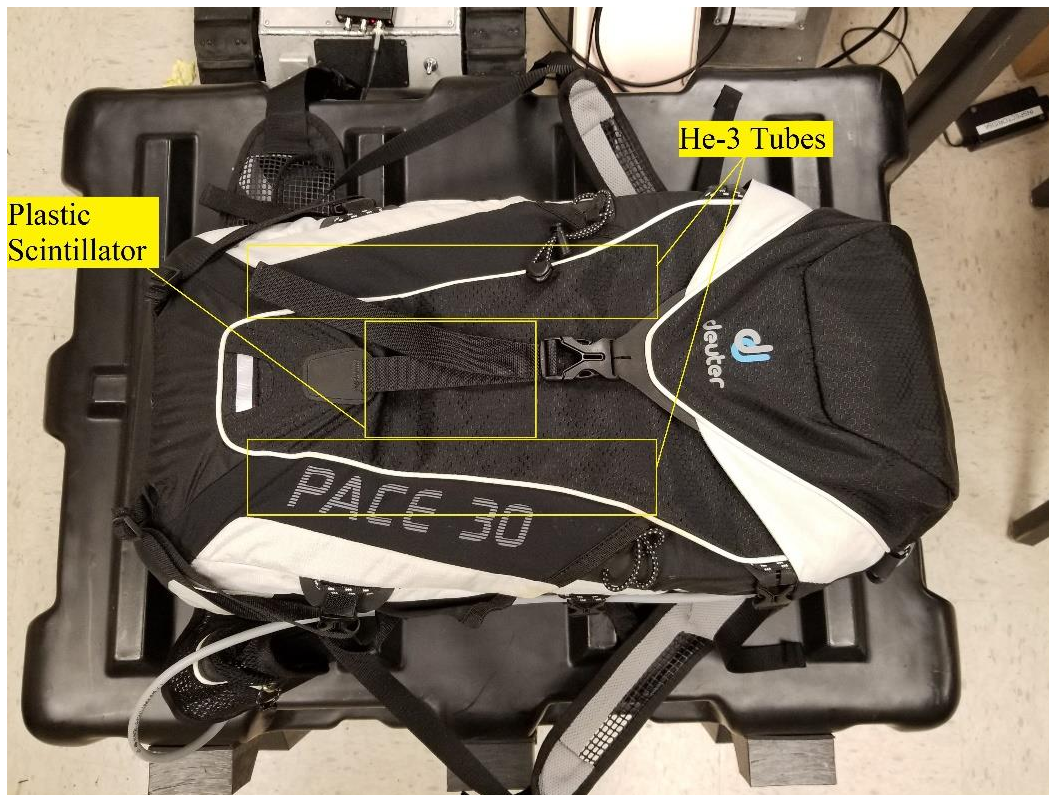


Figure 3. Diagram of Thermo FHT 1377 PackEye backpack detector system displaying the approximate positions of the plastic scintillator detector and the two ^3He tubes.



Figure 4. Photos displaying the detector systems' placements when mounted in an SUV-type vehicle for these measurements looking into the vehicle from the rear passenger side door (left) and the trunk (right).

III. Results and Analysis

The mean count rate of each detection system at each position was compared against the depth at which the detector was placed in the garage (i.e. the number of levels below the garage's roof) as shown in Figures 5, 6, and 7.

These plots show similar decreases in the count rate in both the Ortec gamma spectroscopy and neutron counting systems as the detectors move further below the roof of each garage. The plot shows that the relationship is linear with a constant slope up to a depth of at least four floors below the roof. An indicator of how well a linear equation fits the data is the R^2 value, which is a value between 0 and 1 where a model that fits all the data exactly has an R^2 value of 1. Linear fits on all the data produced R^2 values of 0.9119 and 0.8823, respectively, and linear fits excluding data below the fourth floor produced R^2 values of 0.9657 and 0.9045, respectively. A similar relationship appears in the Thermo neutron counting system with a key difference: the linear behavior occurs after an increase in the count rate between the roof and the first level down. This is a natural result of the unmoderated neutron counting system: the count rate increases in this way due to the moderation introduced by moving one level below the roof. A fit on these data (excluding the roof) produced an R^2 value of 0.8541. Similar to the Ortec systems, the plot suggests the slope decreases below a depth of five floors from the roof. There is less evidence to support the presence of this feature in all three systems as there were only two garages that allowed measurements below this depth; however, it suggests that an exponential relationship is also plausible. Exponential fits on these data had R^2 values of 0.9491, 0.9154, and 0.9319 for the Ortec gamma, Ortec neutron, and Thermo neutron detectors, respectively.

Because of the apparent relationships between the count rates and depth, it is meaningful to compare the mean neutron count rate against the mean gamma spectrometer count rate as shown in Figures 8 and 9 for two garages.

Figures 8 and 9 illustrate the linear relationship between the neutron count rate and the NaI count rate between 4 MeV and 50 MeV for both neutron detection systems in the Central Campus and University Center Garages (CCG and UCG). Similar trends appeared in the data collected within the other three garages. The larger values occurred at the roof and higher floors because there was little to no concrete to moderate and shield the particles registered in the higher gamma energy channels. The smaller values occurred at the deepest floors in each garage (greater than 4 floors below the roof) because there was significant amount of intervening concrete. The only significant deviation from a linear relationship appears in the relationship involving the mean Thermo PackEye neutron count rate, and that only occurs when the detectors were on the roof as noted previously. Linear regressions on these data produced equations of the neutron count rate as functions of the 4 MeV to 50 MeV NaI count rate shown in Eq. 1 and Eq. 2. The regression on the data from the Thermo system ignored the data collected from the roofs of the parking garages. These regressions had R^2 values of 0.955 and 0.929, respectively.

$$n_{Ortec} = 0.0245 g - 0.09633 \quad (1)$$

$$n_{Thermo} = 0.0689 g - 0.2621 \quad (2)$$

Where:

n_{Ortec} = mean count rate of the Ortec neutron counting system [s^{-1}]

n_{Thermo} = mean count rate of the Thermo PackEye neutron counting system [s^{-1}]

g = mean count rate of Ortec NaI system between 4 MeV and 50 MeV [s^{-1}]

There are two notable features of these models. First, the intercepts are not zero as initially expected. The models suggest that the mean NaI (4-50 MeV) count rates would be approximately $3.93 s^{-1}$ and $3.80 s^{-1}$ when the mean neutron count rate in the Ortec and Thermo neutron detectors reach zero, respectively. The second feature is that the slope varies for the different systems. The slope of the fit for the Thermo neutron system was nearly three times larger than that for the Ortec neutron system.

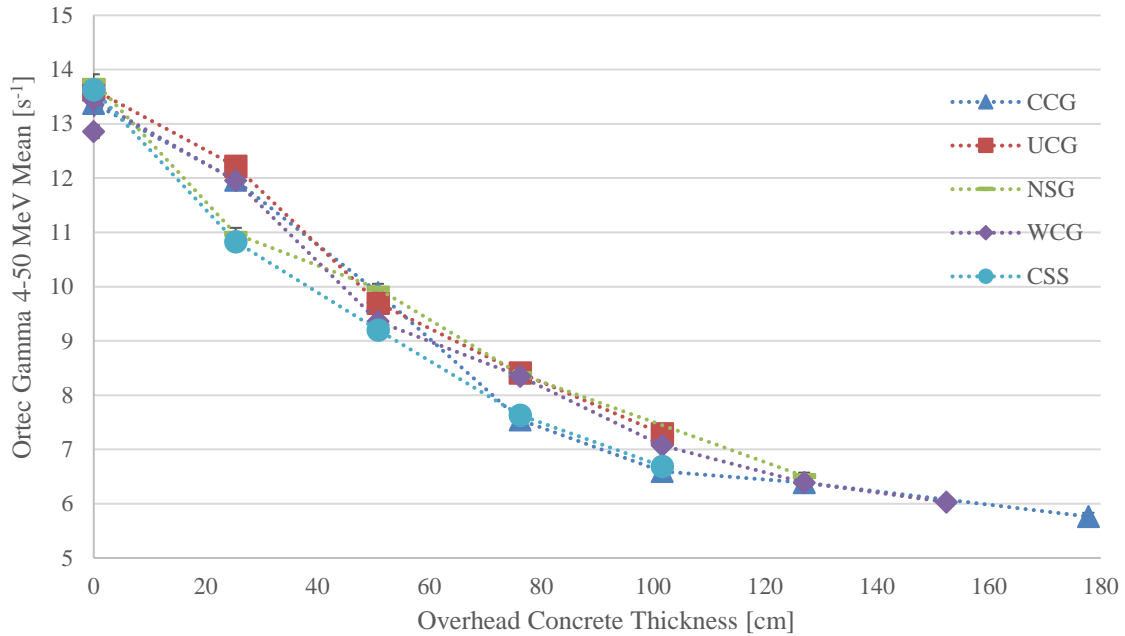


Figure 5. The mean Ortec NaI count rate (between 4 MeV and 50 MeV) at each location in each parking garage plotted as a function of concrete thickness above the detector. The data were collected continuously over 15-20 minutes and had a five second rolling average applied before calculating the mean. 1- σ error bars are shown, but some of them may be obscured by the data markers.

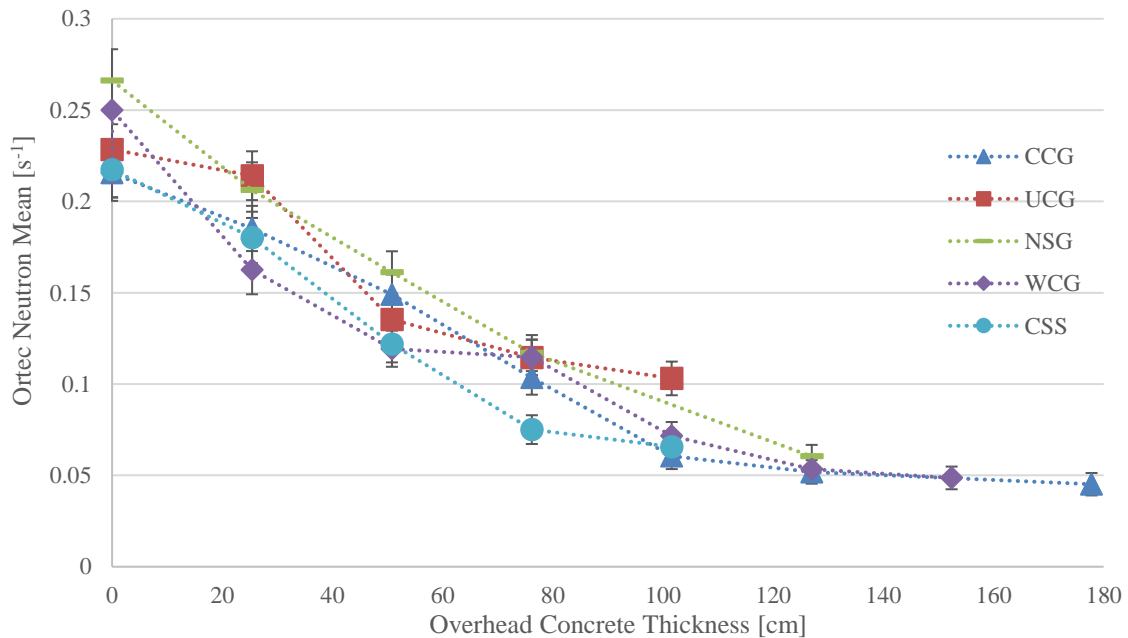


Figure 6. The mean Ortec neutron count rate at each location in each parking garage plotted as a function of concrete thickness above the detector system. The data were collected continuously over 15-20 minutes and had a five second rolling average applied before calculating the mean. 1- σ error bars are shown, but some of them may be obscured by the data markers.

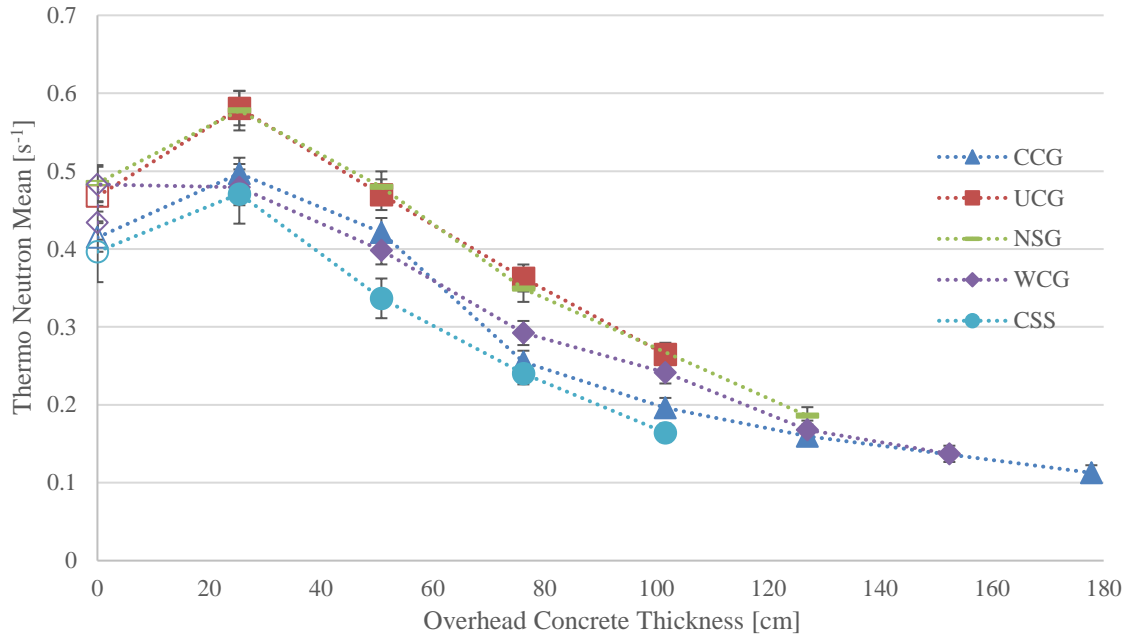


Figure 7. The mean Thermo PackEye neutron count rate at each location in each parking garage plotted as a function of concrete thickness above the detector system. The data were collected continuously over 15-20 minutes and had a five second rolling average applied before calculating the mean. 1- σ error bars are shown, but some of them may be obscured by the data markers.

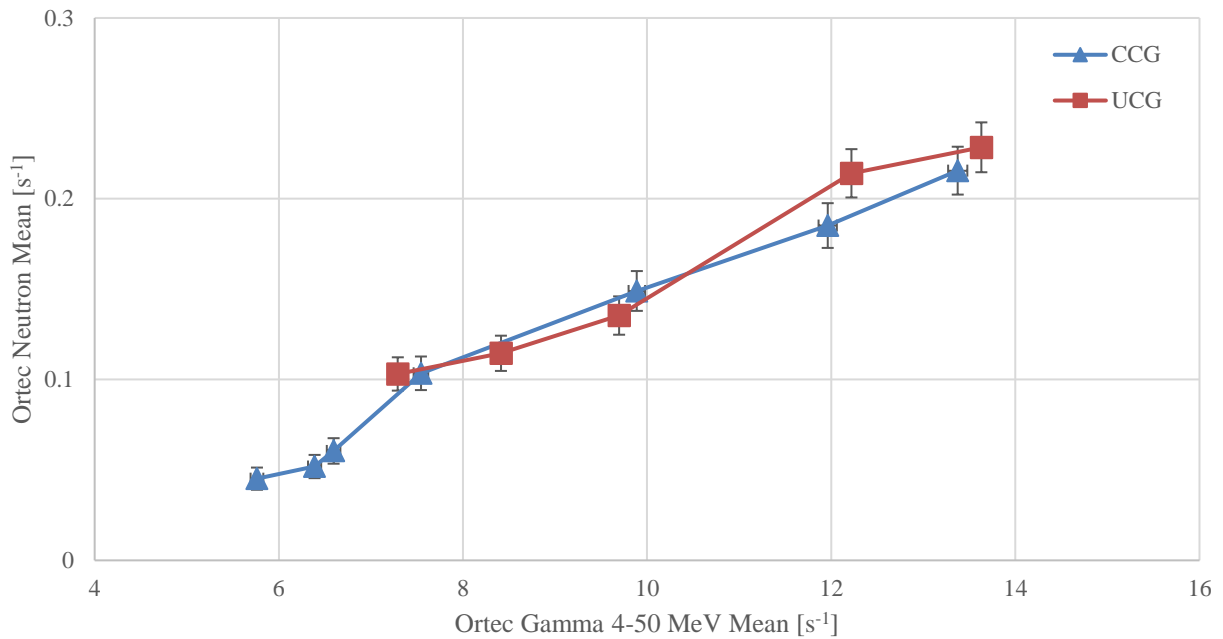


Figure 8. The mean Ortec neutron count rate as a function of the mean Ortec NaI count rate (between 4 MeV and 50 MeV) at each location in the Central Campus and University Center Garages (CCG and UCG). The data were collected continuously over 15-20 minutes and had a five second rolling average applied before calculating the mean. 1- σ error bars are shown, but some of them may be obscured by the data markers.

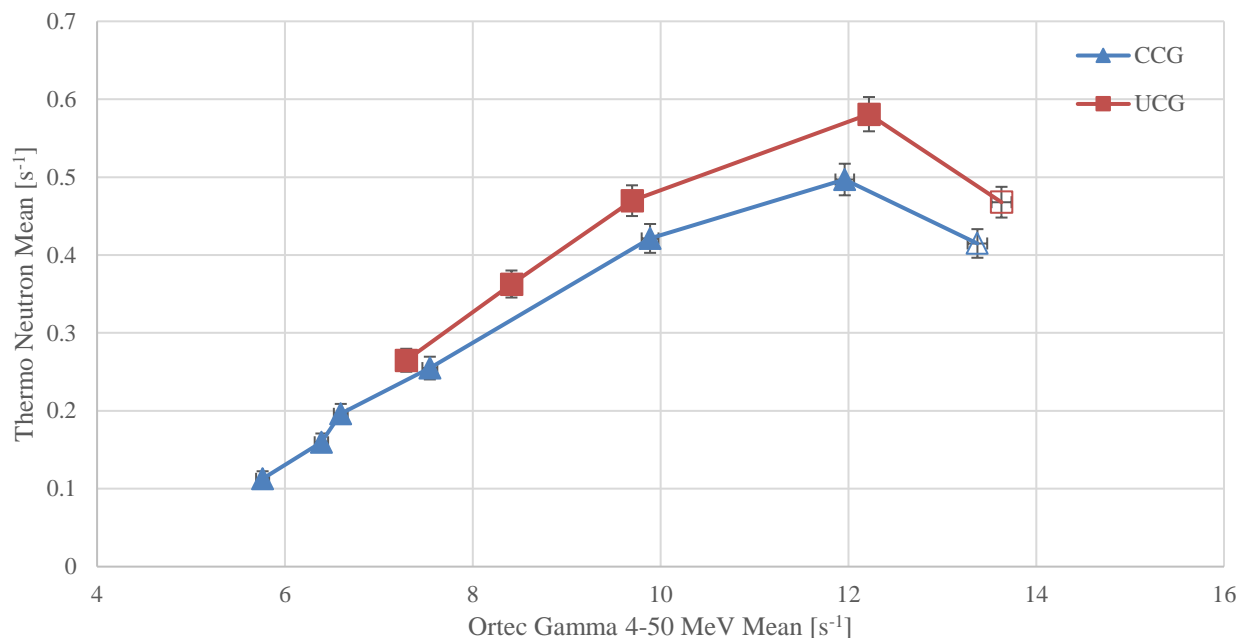


Figure 9. The mean Thermo PackEye neutron count rate as a function of the mean Ortec NaI count rate (between 4 MeV and 50 MeV) at each location in the Central Campus and University Center Garages (CCG and UCG). The data were collected continuously over 15-20 minutes and had a five second rolling average applied before calculating the mean. Data collected from the roof of a garage are denoted by the unfilled points. 1- σ error bars are shown, but some of them may be obscured by the data markers.

There are three theories that would explain the cause of the high energy signal in the NaI detector:

1. High energy cosmic gamma rays
2. Cosmic muons
3. Protons from the decay of background neutrons (free neutron half-life is ~11 minutes)

All these theories are based around interactions of cosmic rays in the upper atmosphere, which produce all of these particles and the majority of the background neutrons that the ³He systems count. Extraterrestrial cosmic rays interact with the upper atmosphere and create showers of various particles, including neutrons, muons, and gamma rays (among others). These theories assume the particles produced by these showers are produced in similar amounts (i.e. the production rate of each particle follows a normal distribution with a different mean)

For theory 1, gamma rays produced by cosmic rays appear on a wide spectrum, which would not produce a peak in the NaI spectrometer on the 4 MeV to 50 MeV range. Additionally, the NaI count rate versus depth relationship could be considered as exponential rather than linear, which is the usual behavior gamma ray attenuation. If that were the case, the data suggest that the half value layer of concrete was approximately 50'' (127 cm - assuming each level of each garage was 10'' thick) [7]. However, NIST reports the mass attenuation coefficient of 20 MeV gamma rays as 0.01539 cm² g⁻¹ that remains relatively constant as the energy increases [8]. This results in a half value layer of 19.6 cm, but the half value layer suggested by the data is approximately 6.5 times larger. While an exponential relationship may explain the decrease in slope of the NaI count rate versus depth data, this discrepancy cannot be overlooked without additional research.

Theories 2 and 3 are similar to each other. The muons and protons that would reach the detector would likely have energies much greater than 100 MeV. These particles would then deposit energy in the NaI

detector proportional to the particle's energy and the path length it travels in the detector, which would frequently produce signals in the 4 MeV to 50 MeV range. Both particles would also have the energy to penetrate the concrete shielding seen in this study. The range of an average energy background muon (4 GeV) in concrete is approximately 13 km, and the range of a proton produced by the decay of an average energy neutron (100 MeV) in concrete is approximately 58.3 cm [9, 10]. The former means that muons would only see linear energy loss with each layer of concrete they penetrate. The latter would suggest that protons from neutron decay outside the garage would not penetrate the third level of the garages; however, it is plausible for neutrons to decay after penetrating multiple levels in the garage and be detected.

IV. Conclusion

This research indicates a correlation between the background high energy count rate of an NaI scintillator (between 4 MeV and 50 MeV) and the background count rate of a neutron counting system, which appeared to be linear as a function of the amount of intervening moderating material. The results of this work also suggest that the background high energy count rate of the NaI scintillator is likely the result of particles that are different from common background gamma rays.

Additional work will be required to test the suggested theories regarding the cause of the relationship. If one or more of these theories are true, it would indicate the cause of the linear relationship shown: the background NaI 4-50 MeV count rate would be proportional to the background neutron count rate because the particles being detected are produced proportionally by cosmic ray interactions with the upper atmosphere. The result would be the ability to use these or more robust versions of the linear models shown to infer the true background neutron count rate using the high energy NaI count rate. Future research could produce algorithms to distinguish neutron "background" count rates from man-made neutron sources. This improvement would make search operations more efficient by reducing the need to investigate nuisance neutron alarms.

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