U.S. DEPARTMENT OF ENERGY

PNNL-18855

Assessment of Cosmic Background Attenuation at Building 3425 (Underground Laboratory)

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October 5, 2009

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Richland, Washington 99352

Executive Summary

Specifications for the Underground Facility (Building 3425) in the Radiation Detection and Nuclear Sciences complex presently under construction at Pacific Northwest National Laboratory mandate a 30 meters water equivalent shielding for cosmic background attenuation at the 30-foot (9.1-m) underground depth of the laboratory. A set thickness of a specified fill material was determined; however a thinner layer of a higher density material was used for the earthen bunker. Questions arose as to whether this altered configuration met the required shielding specifications. A series of measurements with a 4"x4"x16" NaI(Tl) detector (Scionix Holland, 3.5N-E2-X) were made to address this concern . Data were obtained at the surface and several locations within the underground facility in order to obtain an experimental value for the attenuation of cosmic radiation. This experimental result was compared with the contracted attenuation.

The result of the measurement indicates that the maximum depth of the underground facility (Building 3425) is **~35 meters water equivalent**. However, this is a maximum effective depth, since the measured surface flux has contributions to the spectrum from sources other than muons, resulting in an increase in the measured counts on the surface and an overestimate of the equivalent depth. This is because most surface contributions other than muons are easily stopped within a short penetration of the soil.

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1. Introduction

Contracted specifications for the underground facility at Building 3425, a 30-foot (9.1-m) depth underground facility that is part of the Radiation Detection and Nuclear Sciences complex presently under construction at Pacific Northwest National Laboratory, require an attenuation of cosmic background equivalent to 30 meters water equivalent. A specific thickness of a specific density fill was selected to make the earthen bunker, whose function is to provide additional surface shielding for this facility. A thinner layer of a higher density material than soil was used to meet the specification.

This report details cosmic ray measurements made in August 2009 to test this assertion. The concept was to measure the muon flux above ground and below ground at three locations in the 3425 facility and from this determine the attenuation factor.

2. Background

Cosmic rays are energetic particles of extra-terrestrial origin that enter the Earth's atmosphere. The primary cosmic radiation is made up of charged particles, predominantly protons, plus some heavy ions that have energy spectra extending into the GeV range and beyond. Cosmic sources can vary with the solar cycle and are influenced by latitude, barometric pressure, solar activity, diurnal cycle, and weather [Keller 2009]. This primary cosmic radiation interacts with the atmosphere, generating a shower of very high-energy secondary particles, including electrons, protons, neutrons, photons, and unstable mesons that quickly decay into muons. Muons minimally interact with the atmosphere, which, with the relativistic time dilation effect, allow them to reach the surface of the Earth. The muon flux for momenta ≥350MeV/c at sea level is about $170/(m^2 \cdot sec)$ [Grieder 2001, pg 354]. At the Earth's surface this secondary cosmic radiation is narrowly collimated along the line of the original radiation. Fast neutrons from cosmic interactions can also create additional gamma rays.

The specific energy loss for many charged particles decreases exponentially, reaching an approximately constant asymptotic value of 2 $MeV/(g/cm^2)$ in light materials at cosmic energies above several hundred MeV [Knoll 2002, page 32]. Beyond this incident cosmic ray energy threshold these "minimally ionizing particles" lose a set amount of energy in a given thickness of a specified material (Figure 1).

For a 4"x4"x16" (10.2cm x 10.2cm x 40.8cm) thallium-doped sodium iodide [NaI(Tl)] detector, with a density of 3.67 g/cm^3 [Knoll 2002, page 234], the energy deposited in the crystal is found to be 74.5MeV:

$$\left(\frac{dE}{dx}\right) = \left(\frac{dE}{d\sigma}\right)(\rho) = \left(2\,\frac{MeV}{(g/cm^2)}\right)\left(3.67\,\frac{g}{cm^3}\right) = 7.34\,\frac{MeV}{cm}$$

$$E_{loss} = \left(\frac{dE}{dx}\right)\left(dx_{\det ector}\right) = \left(7.34\,\frac{MeV}{cm}\right)(10.2cm) = 74.5MeV$$

Therefore, to detect the incident muons in a NaI(Tl) detector, the detector gain must be adjusted to extend the observed spectra to beyond 75MeV.

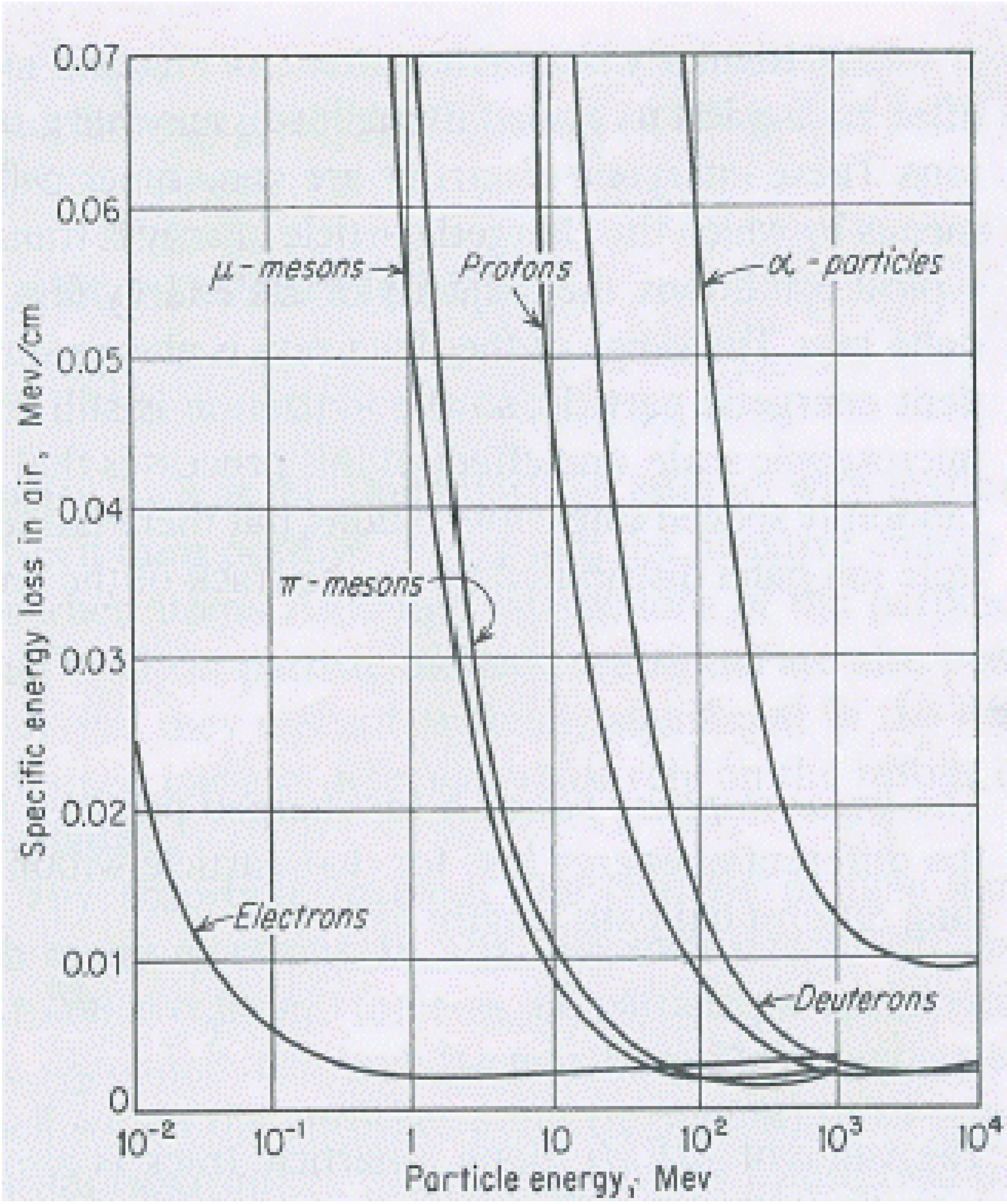


Figure 1. Variation of the specific energy loss in air versus energy of the charged particles shown. (From Beiser.2) [Knoll 2002, page 32]

3. Method

To assess the attenuation in the underground facility, cosmic radiation measurements were taken at the surface to establish a comparative baseline with no terrestrial attenuation, and at several locations within Building 3425, the underground laboratory at a surface depth of 30' (9.1 m). Additional terrestrial shielding is provided by the earthen bunker on the surface (Figure 2a and 2b), whose attenuation efficacy is being evaluated with these measurements.

Figure 2. a) view of earthen bunker from NE; b) view of earthen bunker from SE

Data were collected utilizing a 4"x4"x16" NaI(Tl) detector (Scionix Holland, 3.5N-E2-X). Multi-channel analyzer emulation software (Ortec Maestro-32 v6.08) was used to collect and process the data. The detector is typically operated at a voltage of ~535V, providing a full-scale upper energy threshold of ~4MeV. The energy spectrum is sequenced over 1024 channels, with a standard gain setting of 0.5.

In an attempt to detect ~75MeV cosmic rays, the gain and voltage were adjusted. The emulation software had a prescribed and unalterable lower gain limit of 0.4, which prevented any meaningful increase in the high-energy sensitivity by this means. To increase the upper limit threshold, the operating voltage was progressively lowered to 375V from the standard 535V while tracking the location of the 1462 keV ^{40}K line in order. At an operating voltage of 375V, the 1462 keV line had moved to channel ~16, corresponding to a full scale energy increase from ~4MeV to ~90MeV.

$$\left(\frac{1462\ keV}{chl\ \ 16}\right) = \left(\frac{E_{full}\ \ keV}{chl\ \ 1024}\right) \Rightarrow E_{full} = \left(\frac{1462}{16}\right)(1024) \cong 90\ MeV$$

This placed the 75MeV marker at channel ~820.

$$\left(\frac{1462\ keV}{chl\ \ 16}\right) = \left(\frac{75000\ keV}{chl\ \ x}\right) \Rightarrow x = \left(\frac{75000}{1462}\right)(16) = chl\ \ 820$$

Note that at this highly compressed scale the energy/channel ratio increased from ~4keV/channel (4MeV/1024 channels) to ~90keV/channel (90MeV/1024 channels).

4. Results

With this experimental setup, measurements were conducted at the surface with no terrestrial attenuation and at several sites at a surface depth of 30’ (9.1 m) in the underground facility at 3425. The earthen bunker provided additional shielding beyond this depth.

There was some concern regarding the performance of the NaI(Tl) crystal, which had previously been used at an outdoors site over a period of two weeks and was subject to diurnal environmental temperatures variations of ~55°F to ~106°F. Several sealed sources with pronounced lines were used to check the performance of the instrument. In each case, identifiable peaks with no evidence of “double peaks” or decreased resolution, indicators of a cracked crystal, were observed. Figure 3 shows the resulting energy calibration with the detector set to an operating voltage of 535V and a gain of 0.5.

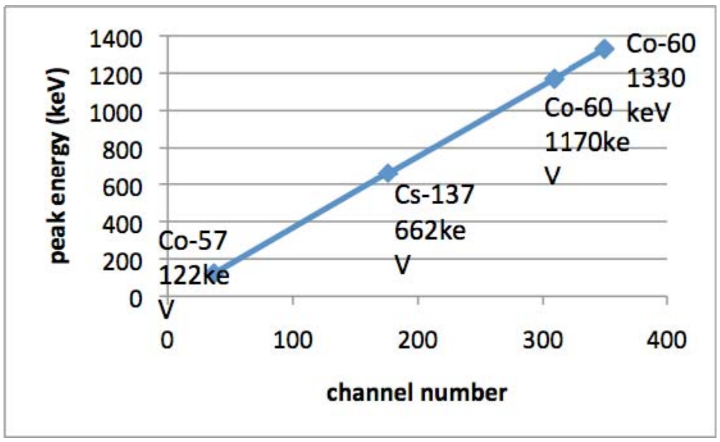
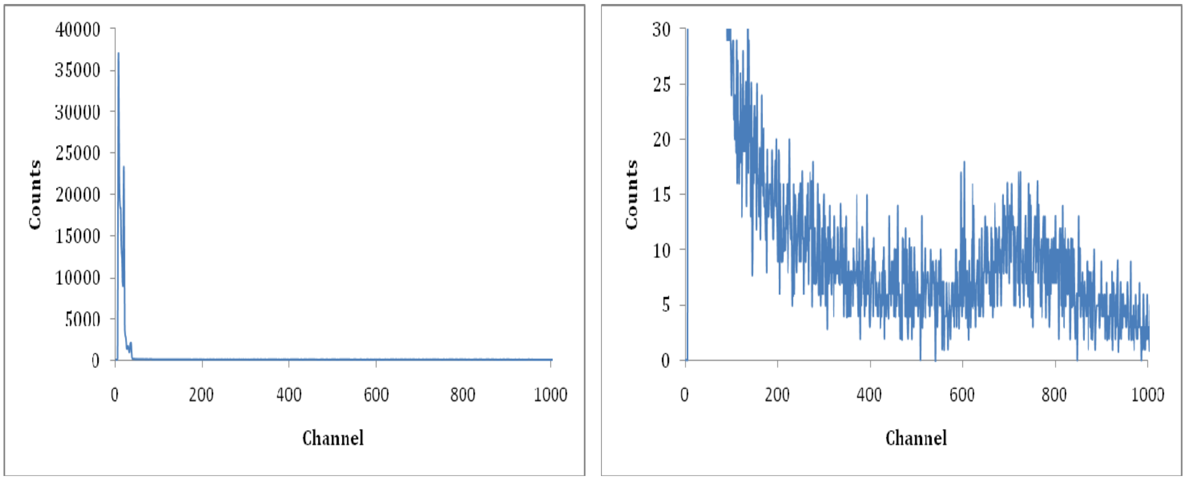


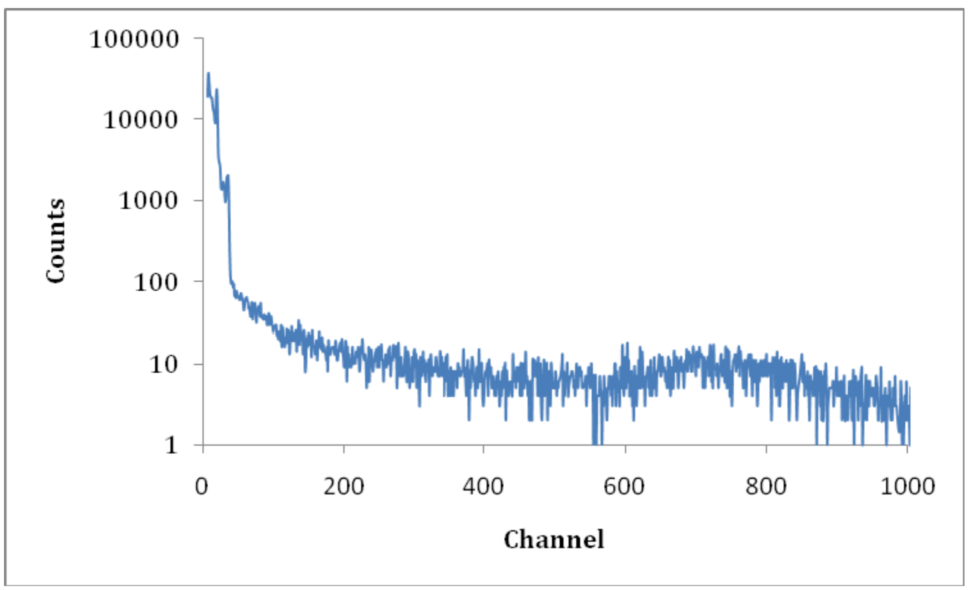
Figure 3. Energy calibration of NaI(Tl) detector at 535V

Surface measurements, each 10-minutes in duration at an operating voltage of 375V, were conducted at 3 locations in and around PNNL building 331G. The first measurement was performed on a tabletop inside 331G. The 1024 channels correspond to an energy range of 0 to ~90 MeV. Results are shown below (Figures 4a and 4b). The cosmic “peak” appears at channel ~720.

The observed spectra consist of contributions from many factors. All of the natural radioactivity peaks are below 3 MeV or channel ~30 with the ^{40}K line is at channel ~20. This is consistent with the estimated full scale energy sensitivity of ~90 MeV [chl 1024/~90 MeV = chl x/3 MeV]. The muons deposit energy as minimally ionizing particles, producing the broad peak centered around channel ~720 [chl 1024/~90 MeV = chl x/~70 MeV] in Figure 4b. The rest of the counts below this muon feature arise from other cosmic sources including protons, neutrons, and gamma rays.



a) Indoor spectrum at 375V



b) Logrithmic scale of indoor spectrum at 375V

Figure 4. Indoor spectra

Since not all interacting cosmic rays deposit the average minimally ionizing energy in the crystal, the peak is broad. Since the detector, when set sideways, presents an area of 4″×16″ (10.2cm × 40.6cm), or 0.0413 m^2, to the sky, a 10 minute collection should yield ~4200 muons, assuming each is detected.

$$\left(\frac{170\ muons}{m^2 \cdot \sec}\right)\left(0.0413\ m^2\right)\left(600\ \sec\right) \cong 4200\ muons$$

Table 1 shows integrated counts for several channel ranges shown in Figures 4a and 4b. Red arrows indicate the lower bounds. Energy ranges are approximations. The 3.6 – 90 MeV integrated sum is a factor of ~4.4 times greater than the theoretical 4200 muons found above presumably from the detection of non-muon cosmic radiation. Note that integrating over the energy range ~40 MeV-90 MeV (channels 450-1023) yields approximately the expected muon flux.

Table 1. Integrated counts for several energy limits for data from inside 331G

Channel range	~Energy (MeV)	Sum, counts
40 – 1023	3.6 – 90	18569
92 – 1023	8.3 – 90	8430
400 – 1023	36 – 90	4168
450 – 1023	40 – 90	3854
500 – 1023	45 – 90	3518
557 – 1023	50 – 90	3151

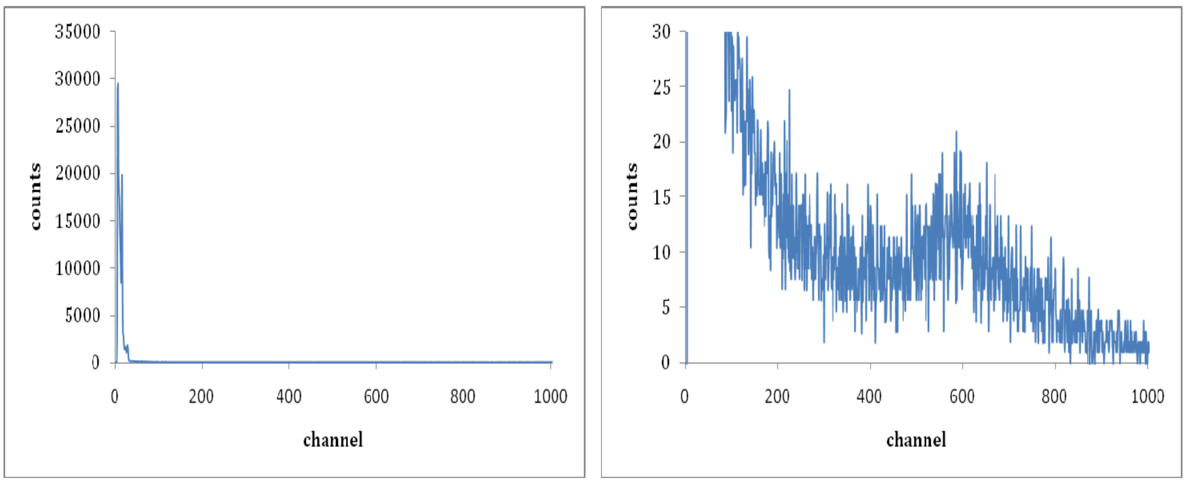


Figure 5. Spectra outdoors at portals (375V). Right hand plot is an expansion of the ordinate.

The second measurement was performed on a plastic picnic table located by the SAIC POV portals ~100 ft (30 m) southwest of 331G. Results are shown in Figure 5. The cosmic "peak" appears at channel ~600.

Table 2 shows integrated counts for several channel ranges shown in Figure 5. Red arrows indicate the lower bounds. Energy ranges are approximations. The 3.6 – 90 MeV integrated sum is a factor of ~3.1 times greater than the theoretical 4200 muons found above, while the range ~40 MeV-90 MeV (channels 450-1023) again approximates the expected muon fluence.

Table 2. Integrated counts for several energy limits outside 331G

Channel range	~Energy (MeV)	Sum (counts)
40 – 1023	3.6 – 90	13191
92 – 1023	8.3 – 90	8952
400 – 1023	36 – 90	4312
450 – 1023	40 – 90	3862

The third measurement was performed on the ground ~40 ft (12 m) south of 331G, under the chained perimeter dividing the 331G racetrack from the adjacent field. Results are shown in Figure 6. The cosmic "peak" appears at channel ~700. Table 3 shows integrated counts for several channel ranges. The 3.6 – 90 MeV integrated sum is a factor of ~4.8 times greater than the theoretical 4200 muons found above, while counts over the energy range ~40 MeV-90 MeV (channels 450-1023) produce the theoretical muon flux.

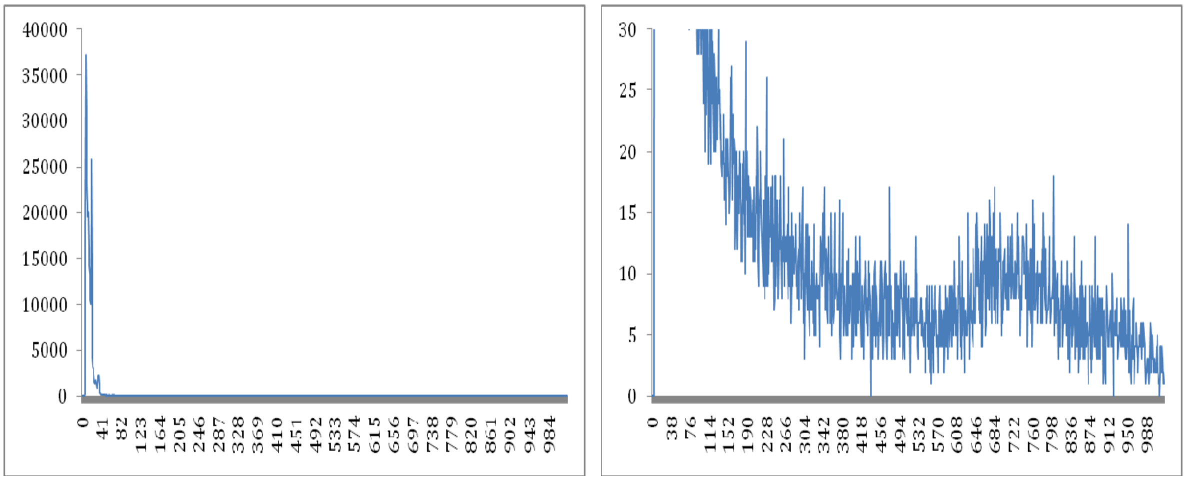


Figure 6. Outdoor spectra on ground (375V). Right hand plot is an expansion of the ordinate.

Table 3. Integrated counts for several energy limits on the ground outside 331G

Channel range	Energy (MeV)	Sum (counts)
40 – 1023	3.6 – 90	19998
92 – 1023	8.3 – 90	9017
400 – 1023	36 – 90	4329
450 – 1023	40 – 90	3669
536 – 1023	50 – 90	3361

The underground measurements were made at night and over the course of a weekend to avoid construction crews and other personnel. Thus, the measurement times varied from 7 to 33 hours; the results were all scaled to 10 minutes. Measurements were made at four locations with an operating voltage of 375 V corresponding to an estimated ~90MeV full scale sensitivity.

The first underground location was on the ground in the shaft. The shaft is a rectangular vertical opening to the sky that is about 15 feet by 20 feet (4.6 m × 6.1 m). The muon flux observed at this location should be much larger than other sites in the underground laboratory. The results from this measurement, time corrected, are shown in Figures 7a and 7b. The cosmic "peak" appears around channel 700. Table 4 shows the integrated counts for the channel ranges chosen.

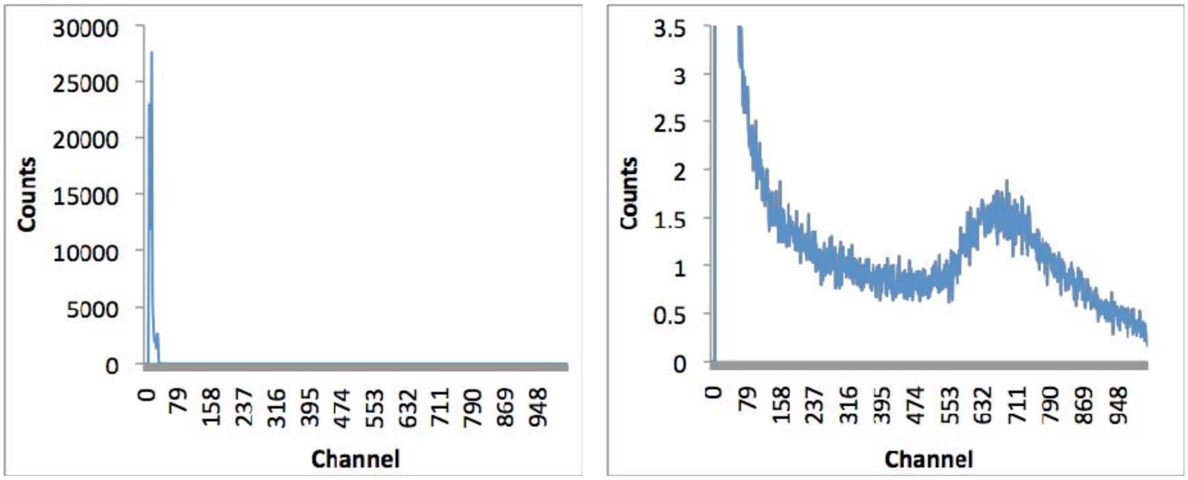


Figure 7. a) Underground spectrum in shaft (375 V); b) Magnified underground spectrum in shaft (375 V)

Table 4. Integrated counts for several energy limits in the <u>shaft</u> at the underground laboratory.

Channel range	~Energy (MeV)	Sum (counts)
40 – 1023	3.6 – 90	2659
92 – 1023	8.3 – 90	1679
450 – 1023	40 – 90	989
572 – 1023	51 – 90	851

The second underground location was near the West wall. Measurements were acquired over the course of 14 hours and time corrected to get the number of counts recorded in 10 minutes. The results from this measurement are shown in Figures 8a and 8b. The cosmic “peak” appears around channel 770. Table 5 shows the integrated counts for the channel ranges selected based on the features of the spectra in Figures 8a and 8b.

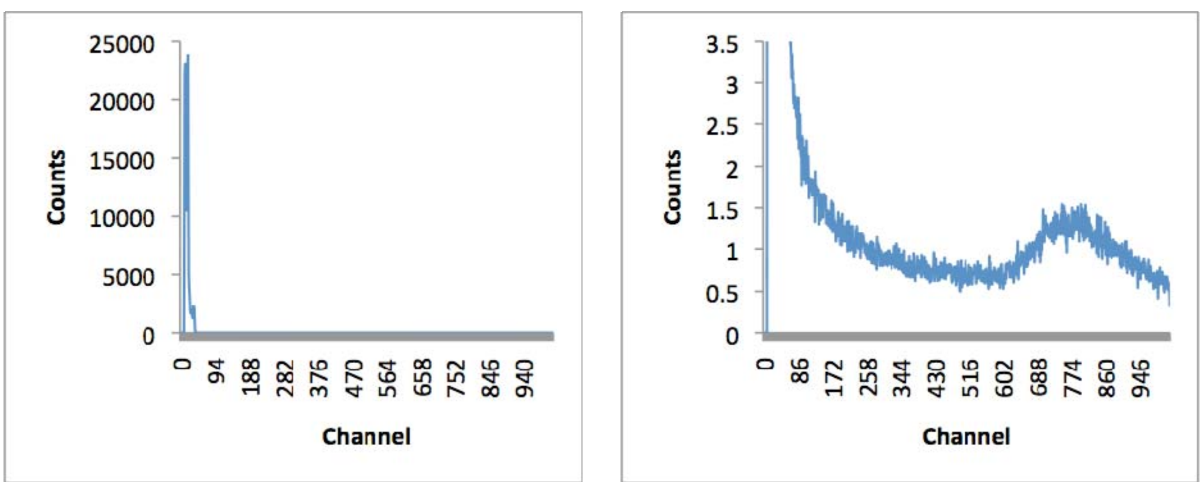


Figure 8. a) Underground spectrum near west wall (375 V); b) Magnified spectrum near west wall (375 V)

Table 5. Integrated counts for several energy limits made near the west wall.

Channel range	~Energy (MeV)	Sum (counts)
40 – 1023	3.6 – 90	1231
92 – 1023	8.3 – 90	976
450 – 1023	40 – 90	549
498 – 1023	45 – 90	510

The third underground location was made with the detector located in the middle of the room. Data were collected over 16 hours. The results from this location, time corrected, are shown in Figures 9a and 9b. The cosmic "peak" occurs around channel 745. The integrated counts for the channel ranges selected shown in Table 6.

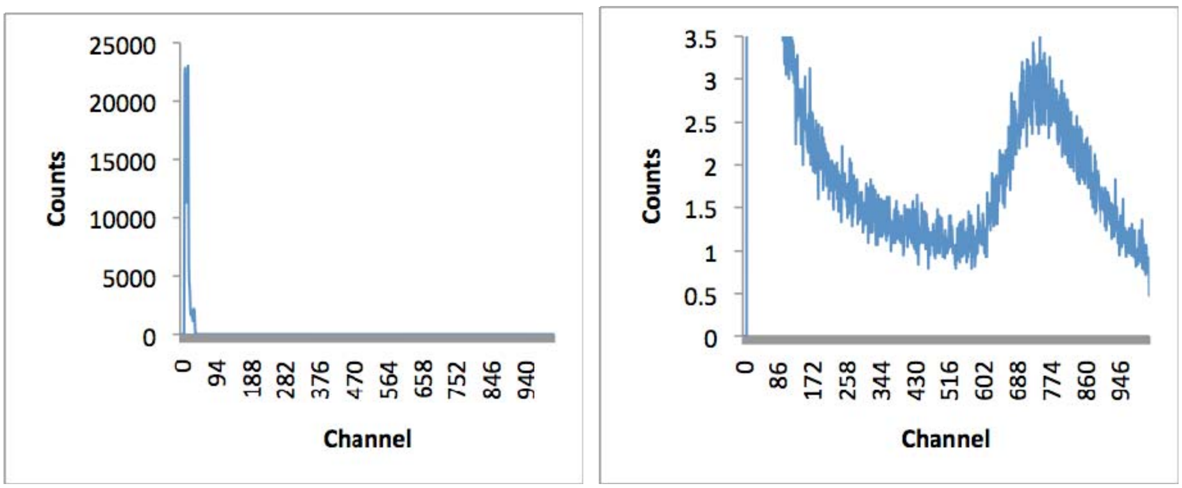


Figure 9. a) Underground spectrum center of room (375 V); b) Magnified spectrum center of room (375 V)

Table 6. Integrated counts for several energy limits in the middle of the underground laboratory.

Channel range	~Energy (MeV)	Sum (counts)
40 – 1023	3.6 – 90	1521
92 – 1023	8.3 – 90	921
450 – 1023	40 – 90	523
616 – 1023	55 – 90	407

The final underground location was at the East end of the room. Data in this trial were collected over 33 hours. Figures 10a and 10b show the results from this location corrected for time and with the same axis scales as the other underground measurements. The cosmic "peak" occurs around channel 775. Table 7 shows the integrated counts for the channel ranges based on the features of the spectra in Figures 10a and 10b.

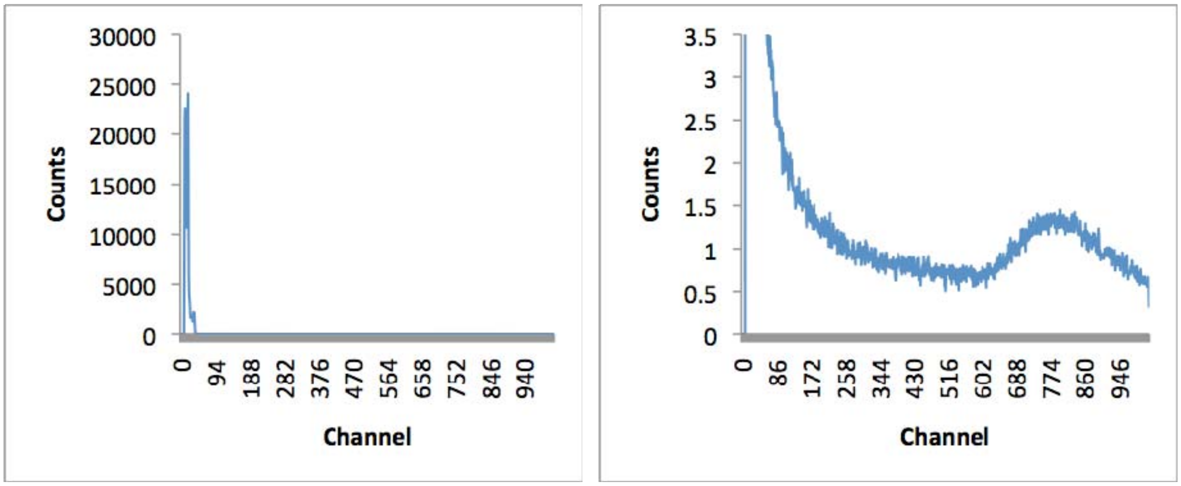


Figure 10. a) Underground spectrum near east wall (375 V); b) Magnified spectrum near east wall (375 V)

Table 7. Integrated counts for several energy limits at the east end of the underground laboratory.

Channel range	~Energy (MeV)	Sum (counts)
40 – 1023	3.6 – 90	1774
92 – 1023	8.3 – 90	945
450 – 1023	40 – 90	532
616 – 1023	55 – 90	415

5. Discussion

Table 8 summarizes the data obtained at each location for the energy region spanning ~40-90 MeV (Channels 450-1023). This range encompasses the muon "peak" for all locations. It can be seen that this muon peak appears to move. Some of this motion can be attributed to differences in the spectrum caused by shielding. The spectrum underground is 'harder,' as indicated by the average channel location of the muon peaks, ~763, measured at the East, middle and West , compared to the above ground values that ranged from ~600-720 (average of 673). Shifts may also occur because of temperature changes.

As indicated previously, the expected muon flux at the surface is ~4200 counts in 10 minutes. The energy range chosen (~40-90 MeV) gives an average gross count value of 3795 counts above ground. The average value of the three locations underground is 532 gross counts. The value in the shaft is seen to be intermediate between the underground and above ground values, as expected. The ratio of these average gross counts below ground to above ground is ~14%. A similar comparison can be performed for net counts, where a flat background is subtracted. These net counts produce a ratio of ~16%, so there is little difference between the two approaches.

Table 8. Summary of counts for each location for energies of ~40-90 MeV (Channels 450-1023).

Location	Peak Centroid	Gross Sum	Net Sum
331G Inside	720	3854	1527
331G Outside	600	3862	1535
331G on Ground	700	3669	1641
Average Above Ground	**673**	**3795**	**1568**
Shaft	700	989	416
East	775	532	262
Middle	745	523	236
West	770	549	246
Average Below Ground	**763**	**532**	**248**

A number of assumptions need to be made, if only a simple analysis is to be performed. First, we will assume the gross counts found in the region of interest are from muons, which tends to overestimate the flux at the surface. Second, we ignore any potential surface contributions originating from non-collimated sources that result from variations in the azimuthal angle when comparing the above ground and underground values. This overestimates the surface counts that are within the small angular distribution that survive to the underground location relative to the surface. Both of these factors tend to overestimate the depth of the facility. We also assume a simple model is valid for shallow depths, though it was developed it was developed for measurements at deeper locations. In order to use these data to determine an effective depth for the underground facility, a formula is needed for intensity as a function of depth. We use the equation given by Barbouti and Rastin [Grieder 2001, p 486] for intensity as a function of depth:

$$I = \frac{Ke^{-\beta X}}{(X^{\alpha} + a)(X + H)}$$

where K=270.7 hg/cm^2, a=75, H=200 hg/cm^2, α=1.68, β=5.5x10^{-4} cm^2/hg, and X is in units of hg/cm^2 (which is approximately the same as meters water equivalent (mwe)). The resulting intensity (I) is in units of $cm^{-1}s^{-1}sr^{-1}$. The depth is measured from the top of the atmosphere and sea level is at a depth of ~1000 g/cm^2 (10 hg/cm^2).

Table 9 provides results from this formula of the intensity as a function of depth (in mwe) expressed as the ratio of the result relative to the result at 10 hg/cm^2 (~sea level).

Table 9. Muon intensity as a function of depth

X (mwe)	Ratio to Sea Level (10 mwe)
0	1.730
5	1.403
10	1.000
15	0.706
20	0.511
25	0.381
30	0.293
35	0.232
40	0.187
45	**0.153**
50	0.128
55	0.108
60	0.092
65	0.080
70	0.069

With these results and the assumptions stated, the equivalent depth of the facility is ~45 mwe from the top of the atmosphere (representing a "depth" of 10 mwe), or ~35 mwe shielding from the ground (which has ~15% of the surface flux compared to 14-16% from the experimental results).

6. Conclusions

The result of the measurement indicates that the maximum depth of the underground facility (Building 3425) is **~35 meters water equivalent** from the surface. The specification for the construction of this facility is 30 m water equivalent. The measured value is a maximum, since the measured surface flux has contributions to the spectrum from sources other than muons. This approach results in increased counts at the surface and, thus, overestimates the effect of the depth, since most surface contributions, other than muons, are easily stopped within a short penetration of the soil.

The actual effective depth of the laboratory could be less than the value found here. A more controlled measurement using a detector collimated upward should be used to eliminate a contribution from a large solid angle at the surface. In addition, a surface measurement should be made using a top shield of well-defined effect, such as a concrete block, that is thick enough to eliminate the contributions from cosmic ray charged particles and neutrons. This would then allow a better comparison to the rate observed at the underground location. In addition, a more current theoretical model may be available for muon attenuation at shallow depths, since the model used was developed for deeper applications. The present results thus give an approximate value for the depth and were motivated by rapidly obtaining a first measurement. Having made these measurements will provide the foundation for making a more accurate future measurement.

7. References

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