Underground Research Laboratory Muon Detector Project Progress Report

Spent Fuel and Waste Disposition

Prepared for
US Department of Energy
Spent Fuel and Waste Science and Technology

Jennifer Meszaros, Stefano C. Tognini,
Rose Montgomery
Oak Ridge National Laboratory

Rob Howard, Harish Reddy Gadey
Pacific Northwest National Laboratory

Stylianos Chatzidakis, Junghyun Bae,
Sydney Grahovac
Purdue University

July 30, 2021

PICS:NE Milestone No. M4SF-21OR010310051
ORNL/SPR-2021/2077

SUMMARY

This report documents work performed supporting US Department of Energy (DOE) Nuclear Energy Spent Fuel and Waste Disposition, Spent Fuel and Waste Science and Technology, under work breakdown structure element 1.08.01.03.10, "Technical Support for Underground Research Laboratory Activities." In particular, this report fulfills the M4 milestone, M4SF-21OR010310051 "Experimental Apparatus and Calibration Results" included in Work Package SF-21OR01031005.

This effort is a collaboration among Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Purdue University. This national laboratory and university partnership includes team members with expertise in high-energy particle physics analysis, detector development, and deep geological repository evaluation and design.

This report summarizes a plan to develop a relatively compact, low-power, plastic scintillator cosmic ray muon detector at the prototype level. Ultimately, the project intends to further develop this technology so that it can serve as a new non-destructive assay (NDA) characterization technique and support geologic disposal safety assessments (GDSA). The proposed muon detector apparatus has the potential to:

- provide fast and independent verification of existing geologic characterization data (e.g., overburden and host rock density).
- provide a passive, non-intrusive method to support surveys of potential geological repositories where the associated geology is not well-characterized.

This experimental plan includes detector development and deployment, a description of the detector concept, calibration needs, and various project details (e.g., challenges, tasks, budget, and schedule). The proposed muon detector is to be deployed at the DOE's Underground Research Laboratory (URL). At the URL, muon flux measurements will be taken at various elevations to calibrate the new detector and to measure the rock overburden at various zenith angles. Measured overburden data will be compared to measurements obtained via other means for the purposes of detector validation.

The work described herein serves as the initial phase in the development of this new NDA characterization technique. The DOE URL is a favorable location for development of new characterization techniques because the surrounding geology is well-characterized and sufficient data exists for the purposes of benchmarking new techniques. This report estimates that this first phase of work should be completed by the end of FY2023. Subsequent phases of work will include deployment of the muon detector again at the URL for the purposes of evaluating host rock density. Density measurements, in turn, could be used to provide relevant GDSA characteristics such as host rock porosity, saturation level, and seismic fault information. Detector capabilities could next be expanded to perform 3D imaging of host rock, also known as geo-tomography. Geo-tomography can provide a detailed map of host rock density including identification of voids, seismic faults, and low-density areas.

This page is intentionally left blank.

ACKNOWLEDGMENTS

This research was sponsored by the Spent Fuel and Waste Science and Technology Program of the US Department of Energy (DOE) and was carried out at Oak Ridge National Laboratory under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

The authors would like to thank Kris Kuhlman, David Sassani, and Emily Stein from Sandia National Laboratories and Bob Clark and Tim Gunter from DOE for providing guidance and support to this project.

This page is intentionally left blank.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

CTW	Coincidence time window
DAQ	Data acquisition
DOE	US Department of Energy
EAS	Extensive air shower
FNAL	Fermi National Accelerator Laboratory
GDSA	Geologic disposal safety assessment
MC	Monte carlo
NDA	Non-destructive assay
PMT	Photomultiplier tube
PVT	Polyvinyltoluene
SiPM	Silicon photomultiplier
UI	User interface
UPS	Uninterruptible power supply
URL	Underground Research Laboratory

This page is intentionally left blank.

1 INTRODUCTION

Cosmic rays are energetic elementary particles and nuclei that reach the Earth. They originate from multiple sources—from the Sun to extragalactic events—and their acceleration mechanisms can vary drastically, with some still being open to debate [1]. The hadronic interaction of a cosmic ray with the upper atmosphere produces a set of secondary particles, each of which decaying or interacting with another element. This chain of events is known as an extensive air shower (EAS), and can be divided into three main components: electromagnetic, which encompasses electrons and photons; hadronic; and muonic. Muons represent the largest fraction of charged particles at the surface [2] and, aside from neutrinos, are the only remaining component at significant underground depths. As such, the detection of muons, their associated energies, and their incoming angular distributions can be utilized to determine the densities of the surrounding rock that they penetrate without requiring the drilling of numerous boreholes that would otherwise be required [3].

This project proposes development of a relatively compact, low-power, plastic scintillator detector apparatus for the ultimate purpose of developing a new non-destructive assay (NDA) characterization technique. The work described herein reflects the first steps necessary to develop a muon detector that can be deployed as part of geologic disposal safety assessment (GDSA) host rock characterization activities. The proposed muon detector apparatus has the potential to:

- provide fast and independent verification of existing geologic characterization data (e.g., overburden and host rock density).
- provide a passive, non-intrusive method to support surveys of potential geological repositories where the associated geology is not well-characterized.

The proposed detector will first be used to measure muon flux at the US Department of Energy (DOE) Underground Research Laboratory (URL), which is located approximately 100 miles northwest of Las Vegas, Nevada. Muon flux measurements will be used to calibrate the new detector and to measure the rock overburden at various zenith angles. Measured overburden data will be compared to measurements obtained via other means [4] for the purposes of detector validation and to reflect the first effort at utilizing the detector for the purpose of characterizing the rock. Note that simple muon detectors are currently available, such as Cosmic Watch [5]. Of note, the Cosmic Watch does not satisfy the project's needs due to its pulse processing clock being at the kHz level, which is too slow for scintillator coincidence triggering.

The following sections of this report provide a description of the URL site, project planning, the muon detector design, and future work that will be required to further develop the concept of GDSA site characterization via muon detection. This report expands upon the project initial test plan [6] and a follow-on progress report [7].

2 URL SITE

The URL is an approximately 8 km long U-shaped tunnel consisting of successive layers of fine-grained volcanic rock. Access to the URL is provided via a north and south ramp from the surface to approximately 300 m below the surface. The two ramps and the connecting main drift are 7.62 m in diameter [4]. There are eight alcoves within the tunnel that can be used to deploy equipment and instrumentation or serve as safe havens for personnel in the event of degraded environmental conditions.

To estimate the average elevation of the URL, three data points were chosen associated with its elevation. Based on these data, the average elevation was found to be about 1,470 m above mean sea level [4]. Literature has also indicated that the mountain crest near the URL is about 1,700 m above the sea level

[8]. For this report, the base of the URL mountain is assumed to be about 1,350 m above sea level, and the average height of the crest is about 1,700 m above sea level.

3 DETECTOR DEPLOYMENT PLANNING

The initial test plan for this project [6] identified four phases necessary to build and deploy a muon detector at the URL. These phases have been reevaluated; the new phased approach to the project is summarized in Table 1. The full scope of detector development and deployment for the purposes of muon flux/overburden measurement is expected to take 2 years. In this plan, detector assembly and off-site calibration will be complete by the end of FY2022 (Phase I) and calibration/measurement activities at the DOE URL as well as data analysis (Phases II- III) will be completed in FY2023. Estimated costs included in Table 1 account for projected team member time, periodic travel to the URL, subcontract costs, and the material cost of the muon detector (included in the costs associated with Phase I; Section 4.6.3 provides details).

Table 1. Muon detector deployment plan

Phase	Phase description/scope	Projected location	Estimated duration	Estimated cost (USD)
I	Detector and electronics assembly, simulations, and testing	ORNL/PNNL/TBD	6-12 months	$225,000
II	On-site access training, preparation, installation, calibration, initial test period, and measurements	URL	2-3 months	$85,000
III	Data analysis and reporting	ORNL/PNNL	3 months	$75,000

The estimated duration of Phase II has been updated from that previously documented [6] based on additional calculations of the time necessary to obtain statistically significant muon counts. The average overburden at the URL entrance is used in this calculation and is estimated as half the distance between the surface and the crest, or 175 m above the surface, based on the elevations listed in Section 2. In this project, muon data will be collected at the surface and at several locations beneath the surface, in the existing URL tunnels. The approximate required time for collecting 10,000 muons is computed for several example subsurface depths- specifically 860 and 1,260 meter water equivalent (m.w.e.), corresponding to 150 and 300 m below the surface, respectively. As noted in the initial test plan [6], at least 10,000 muons must be counted to achieve a statistical error of 1% or less. Notably, the geology of the URL is not symmetric [4], yielding different fluxes at different directions.

Using a flux adjustment factor of 1.5426 to account for the site's 1,350 m altitude [9], the approximate times for recording 10,000 counts at variable zenith angles are presented in Table 2. For these calculations, a detector surface area of 1 m^2 and distance between detection panels of 10 cm was assumed. Note that times for surface calculations, which will also be obtained, are not included in Table 2 because a statistically sufficient flux is expected to be obtained in less than an hour.

Table 2. Time estimates for collecting 10,000 counts at variable depths and zenith angles

Zenith (º)/ Depth (m.w.e.)	0	30	60
860	18.58 h	25.56 h (1.07 d)	106.78 h (4.45 d)
1,260	60.56 h (2.52 d)	87.24 h (3.64 d)	479.24 h (19.97 d)

4 DETECTOR CONCEPT

The muon detection system consists of multiple components interfacing with each other. A schematic describing the general components of a detector is included in Figure 1. When photons and charged particles interact with a scintillation medium, optical photons are generated. These optical photons are subsequently sensed by devices that convert these photons into current signals (labeled "SiPM" in Figure 1). The current signals are routed through pulse processing electronics ("DAQ" or data acquisition in Figure 1), which digitize the detector response. A user interface (UI) enables controlling variable aspects of the detection system such as energy threshold and offsets. The steps in the detection chain are detailed in the following subsections.

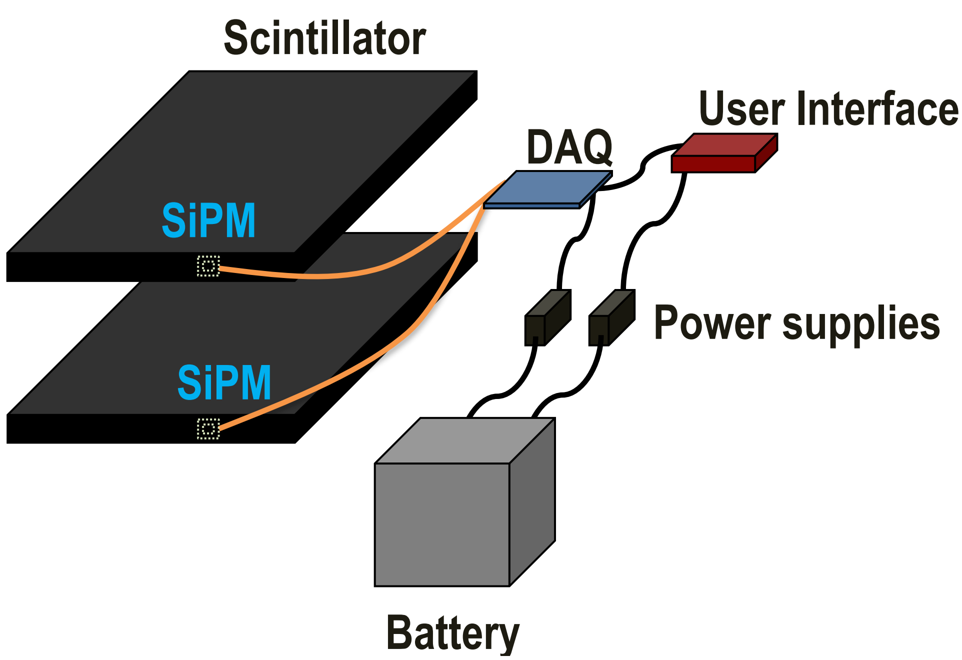

Figure 1. Components of the suggested detection system.

4.1 Scintillation Medium

As charged particles travel through a medium, they undergo energy loss due to several phenomena, including ionization, bremsstrahlung radiation, and multiple scattering [10]. Most of these interactions result in the production of photons. In the case of scintillators, most of these are optical photons, with their intensity being directly proportional to the energy deposited in the medium [11]. This process can be accomplished by either using organic or inorganic scintillators. For this work, organic scintillators (plastic scintillators) were chosen because of their relatively easy machining and scintillator development properties. Additionally, organic scintillators can be manufactured in large sizes (over 10,000 cm^2) with relative ease, while inorganic scintillators (e.g., sodium iodide) are restricted by the size to which the crystals can be grown. Inorganic scintillators are also relatively brittle and expensive compared with their organic scintillator counterparts.

Two organic scintillator manufacturers (Saint-Gobain and Eljen Technology) were contacted to understand the preliminary feasibility of the design. Based on the inputs provided by the manufacturers, a light guide was included in the design to improve the optical light collection efficiency. The scintillation medium will be wrapped with a Polytetrafluoroethylene (Teflon) or equivalent reflector material. The plastic scintillator slabs will be held in place by a mechanical holder that is under development. This holder allows the user to move the detector orientation both in the zenith and azimuthal direction. The dimensions of the detection system are envisioned to be about $132 \times 81 \times 5.08$ cm^3. The area was chosen to closely match some of the standard sizes produced by the scintillator manufacturers. These plastic scintillators are made of Polyvinyltoluene (PVT). PVT has a density of about 1.032 g/cm^3 and a stopping power (-dE/dx) of about 1.956 MeV cm^2/g [12]. Multiplying these two quantities results in an energy loss of about 2 MeV per cm traversed in the scintillator by the muon. Considering the geometry of the proposed detection system, an energy deposition of about 10 MeV is expected for a muon passing vertically (zenith angle: 0°). Therefore, for any muons passing at a zenith angle greater than 0°, the energy deposition is expected to be greater than 10 MeV. The light yield of PVTs is about 60% of anthracene [13]. Using this information and the energy deposition, about 104,000 photons are expected to be produced in each muon interaction. Taking these factors into consideration, an energy threshold of about 2 MeV is proposed to distinguish background from muon interactions. Moreover, this threshold is high enough to safely eliminate background beta emissions. This threshold was originally proposed for this project in the 2020 progress report [7]. Similar thresholds have also been used in some previous muon experiments [14], [15]. Using two plastic scintillator slabs and operating in coincidence also provides confidence that the detector signal is indeed a muon interaction. Figure 2 illustrates a cylindrical plastic scintillator.

Figure 2. Example of a plastic scintillator under UV light (used with permission from Eljen Technology) [16].

4.2 Optical Photon Sensing Devices

The next step in the detection chain involves using an optical photon-sensing device, which is responsible for converting the optical photons into current signals. The current signal generated is a function of both the intensity and frequency of the optical photons impinging on the device. Therefore, to improve the overall efficiency of the system, matching the emission peak of the scintillator and the sensitivity peak of the photon-sensing device is desirable. Broadly speaking, two device classes are available in the market for sensing optical photons—photomultiplier tubes (PMTs) and silicon photomultipliers (SiPMs). This section discusses these devices and explores some of the advantages and drawbacks.

PMTs in their most basic essence are vacuum tubes that amplify the initial number of photoelectrons generated in the photocathode and output a respectable current signal. These devices have been around for several decades and have been successfully used in several projects. A significant advantage of using PMTs is the extensive experience that has been accumulated by both researchers and detector manufacturers in handling, mounting, and experimenting with these devices. However, PMTs also have considerable shortcomings, namely high voltage operation (750–1,500 V), relatively fragile structures compared with SiPMs, susceptibility to electromagnetic fields, and rigid form factors. These devices generally cost between $500 to $1,000, require a high-voltage power supply, and consume below 50 mW for operation.

SiPMs are the second option for sensing optical photons. These are relatively new technologies that use the semiconductor properties of silicon to measure the intensity of the optical photons. Each SiPM consists of thousands of reverse-biased photodiodes that operate in the Geiger mode (like GM tubes). When a photon interacts with a microcell, it results in a fixed discharge. A reset mechanism is inbuilt in the SiPMs, which enables it to be ready for sensing the subsequent photon. Some significant advantages include the low-voltage operation (below 30 V), mechanical rigidity compared with PMTs, small form factor, and nonsusceptibility to external electromagnetic fields. Interestingly, both SiPMs and PMTs have similar quantum efficiencies. The drawbacks of using SiPMs for this project are relatively less experience of manufacturers in mounting the SiPMs on the scintillator surface and challenges with respect to connecting the summed anode with the readout electronics. The peak power consumption of an SiPM was found to be about 0.45 W.

4.3 Pulse Processing Electronics

Pulse-processing electronics are used in the next step in the detection chain. They are responsible for reading pulses from the photon detectors and identifying if a muon interaction has occurred in coincidence. This procedure can be accomplished either using a partial analog and digital system or completely realized using real-time coincidence identification in the digital domain. Notably, recording this data in the digital domain provides more flexibility because it offers the capability to save the individual pulse data as opposed to just providing the muon count rate.

In the analog domain, the PMT/ SiPM pulses are initially routed through the preamplifier. After this step, the preamplifier output is read by the amplifier, which is responsible for producing a Gaussian shape signal using a mix of resistor/capacitor (low-pass) and capacitor/resistor (high-pass) filters. This signal is then read by the single channel analyzer to determine if the interaction is indeed a muon. Usually, a high discriminatory level is set to reject any background events interacting with the detector. As soon as the voltage signal from the detector exceeds a preset user-defined threshold, the system considers the event to be a muon interaction. When two such detectors are operating in coincidence, a coincidence logic unit is employed to identify such events. Although this system is successful in identifying muon count rates, it is unable to record muon interaction pulse shapes, which is essential to constructing a muon energy spectrum. As for power consumption, each individual nuclear instrumentation module consumes about 50 W of power. Therefore, if the analog detection system is employed, it would require about 150 W.

In the digital domain, the pulses from the PMT/SiPM are initially converted into a voltage signal. This is generally followed by employing an analog-to-digital converter to digitize the pulses. The digitized pulses are usually saved onboard a PC or computer. Internal clocks in the digital domain allow the electronics to identify coincidence events between two channels (detectors). The user can select various coincidence time windows (CTWs). The CTW is usually the amount of time in between when both the detectors are expected to trigger. Generally, the shorter the CTW, the lower the probability of unwarranted background interactions being recorded as legitimate muon counts. Several companies and universities including CAEN Technologies, XiA LLC, ORTEC, Fermi National Accelerator Laboratory (FNAL), and the Massachusetts Institute of Technology were contacted to evaluate the capabilities their systems offer and the requirements of the muon detection system. Various factors, including the analog-to-digital converter clocking frequency, CTW adjustment capability, coincidence pulse data (waveforms/energy) recording, cost, and power consumption were considered while exploring the options. Most of these real-time digital data acquisition systems (XiA LLC/CAEN Technologies) generally consume between 20 to 35 W.

4.4 User Interface or Supplemental Software

Several functions need to be controlled, including energy threshold, pulse offsets, CTW, and voltage power supply to the SiPMs/PMTs. Ideally, all these features will be controlled using a personal computer UI. This interface is also responsible for recording data (pulse shape/energy) that can be used at a later stage for data analysis. All the digital systems identified in Section 4.3 provide a set of software packages or UIs that can be used to control the hardware on board.

4.5 Power Supply

At the DOE URL facility, no power supply is expected to be readily available to power the detectors and supplementary equipment. Therefore, portable power supplies will need to be carried on-site. A battery power station (e.g., Jackery, NinjaBatt, Goal Zero) is proposed to power the equipment. Each portable power station provides about 2,060 Wh and at least two such battery power stations are anticipated to be required. As highlighted in Table 2, the measurements may take up to 19 days. Since no proposed power supply can run for such an extended period, an uninterruptible power supply (UPS) from APC (a division of Schneider electric) is also proposed to provide the required time to swap batteries and not disrupt the power supply to the detection systems. The proposed system provides an 8 h run time at a 100 W load. The discharged battery power station can thus be charged while the other station is powering the detector. This process can be repeated until the required amount of data is collected. The battery capacity as a function of charging cycles has also been explored. Based on the technical specifications of the battery power station and the duration of the experiments that are currently proposed, the battery capacity is not expected to significantly degrade.

4.6 Detector Assembly Options

The exploration of various components led to two possible design options for realizing the muon detection system. These options are detailed in the following sections along with a table summarizing the components, cost, and power requirements for each component.

4.6.1 Option 1

The first proposed detection system uses a plastic scintillator in conjunction with a light guide from Eljen Technology or Saint-Gobain. For optical photon readout, SiPMs are proposed because of the associated low-voltage operation. For pulse processing, the QuarkNet DAQ circuit board is proposed [17]. This hardware is planned to be leased from FNAL. As for portable power supply, at least two Jackery Explorer 2000 portable power stations are proposed. Also, estimating additional costs like detector holder fabrication is currently in progress, though total project cost estimates included in Table 1 allow for this uncertainty.

4.6.2 Option 2

The second possible option includes using the Saint-Gobain/Eljen Technology plastic scintillators along with the light guide and interfacing them with SiPMs. Based on the SiPM style that is intended to be used (ball grid or printed circuit board), the power supply is required to be adapted. As for the pulse processing, XiA's Pixie Hybrid is suggested for both identifying coincidence events and recording pulse data. The same portable power station or equivalent as described above (Jackery Explorer 2000) will be used in this detector setup as well. Other support systems such as detector holders will also be required to be used in this setup.

4.6.3 Summary

Table 3 summarizes some of the observations and options explored in realizing the detection system and provides the detection components, anticipated power requirements, and approximate cost for both the options.

Table 3. Proposed detector setups, power consumption, and cost estimates

	Component	Power Consumption (W)	Approximate Cost (USD)
Option - 1	Scintillator (x2)	N/A	$7,700 each
	Non-recurring Engineering Fee	N/A	$3,500
	QuarkNet DAQ (FNAL)	≤ 12	$700 for five-year lease
	13" MacBook Air/ Raspberry Pi 4 (B)	~3.5[1]/ 4.59[2]	$1,000/ $35
	Additional Equipment	N/A	$6,396
	Total		**$26,996/ $26,031**
Option - 2	Scintillator (x2)	N/A	$7,700 each
	Non-recurring Engineering Fee	N/A	$3,500
	XiA Pixie Hybrid	30	$10,200
	13" MacBook Air/ Raspberry Pi 4 (B)	~3.5[1]/ 4.59[2]	$1,000/ $35
	Additional Equipment	N/A	$6,396
	Total		**$36,496 / $35,531**

[1] Based on 49.9 Wh battery and 15 h wireless web browsing.
[2] Assumed voltages of 5.1V and average current consumption of 0.9A (mean between bare board and maximum).

Under "additional equipment" in Table 3, the following items are included:

1. A UPS system from APC (a division of Schneider Electric) costs $1,198.
2. A portable power station from Jackery (Explorer 2000) costs $2,099; two are included in the Table 3 "additional equipment" cost.
3. A conservative estimate of the detector holder is about $1,000. This holder would provide mobility along the zenith, azimuthal, and linear directions.

5 DETECTOR CALIBRATION AND VALIDATION ANALYSIS

Detector calibration plays an important role in estimating the muon energy deposition in the scintillation medium, as well as correctly recording such data across different detector channels. This is especially true when the energy deposition is close to the threshold of the detection system. For this project, the detector calibration is intended to be carried out using gamma check sources like ^{137}Cs or ^{22}Na. The number of counts observed by each scintillation panel as a function of the position of the source with respect to the detector will be obtained. This provides an opportunity to perform gain matching between the two scintillation panels which is essential in setting thresholds. In addition to the calibration that will be performed in the lab, the manufacturer will also be performing initial calibration tests and shall provide performance reports for future reference and analysis.

Once the detection system is characterized in a lab environment, the aim is to use this system to observe the overburden at the DOE URL. This facility was chosen for this project because of its well-characterized geology, which provides an excellent opportunity to validate the apparatus and test the methodology. Multiple data acquisition campaigns are planned, covering both surface and different depths of the URL, at variable zenith and azimuth angles. The detector validation entails comparing muon flux data collected at URL with analytical predictions and existing geological surveys of the site. Ground measurements should match the expected flux at the surface level, which can be described using a parameterized equation that considers the muon production from pion and kaon decays [2]

$$\frac{dN}{dEd\Omega} \approx \frac{0.14\, E_\mu^{-2.7}}{cm^2.s.sr.GeV} \times \left[\frac{1}{1+\frac{1.1E_\mu \cos\theta}{115\,GeV}} + \frac{0.054}{1+\frac{1.1E_\mu \cos\theta}{850\,GeV}}\right]$$

adjusted to the URL's altitude. Underground, the observed muon intensity should be in accordance with

$$I(X) = I_0 \frac{\epsilon^{1-\gamma}}{\gamma-1} e^{-(\gamma-1)\beta X}\left(1-e^{\beta X}\right)^{1-\gamma} \approx A\left(\frac{X_0}{X}\right)^{\eta} e^{-\frac{X}{X_0}},$$

where X is the rock's slant depth traversed by the muons, $X_0 = \beta(\gamma-1)^{-1}$, and $\eta \equiv \gamma - 1$. Experimental values for these parameters can be found in [18]. The expected depth X depends on the location and direction in which the detector is pointing and can be retrieved from existing geological surveys of the mountain.

Additional cosmic ray analyses that can be completed with data obtained during this portion of the project, independent of the scope of work described herein, are included in Appendix A.

6 CONCLUSIONS AND PATH FORWARD

This report presents progress made toward designing a low-cost detector to count muon flux at the DOE URL. This effort is a collaboration among Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Purdue University. This national laboratory and university partnership includes team members with expertise in high-energy particle physics analysis, detector development, and deep geological repository evaluation and design.

The work scope described herein will demonstrate the feasibility of deploying a low-cost muon detector at the DOE URL and performing a basic evaluation of overburden surrounding the existing tunnels. It is expected to be completed by the end of FY2023. As noted above, the muon detector concept can be advanced beyond the work scope described here such that it may be used along with existing geologic characterization techniques (e.g., borehole drilling, seismic imaging, ground-penetrating radar, and gravity methods) to gain a wider understanding of various geology for the purposes of GDSA. The DOE URL is a favorable location for development of new characterization techniques because the surrounding geology is well-characterized and sufficient data exists [4] for the purposes of benchmarking new techniques.

Subsequent phases of work will include deployment of the muon detector for the purposes of determining directionally dependent densities of the geology surrounding the URL. Density measurements, in turn, could be used to provide relevant GDSA characteristics such as host rock porosity, and saturation level. Seismic faults in the area may also be characterized in this work. The detector could further be deployed within the URL to evaluate time-dependent behavior, such as how water from a heavy rainfall infiltrates the surrounding rock. Detector capabilities could next be expanded to perform 3D imaging of host rock, also known as geo-tomography. Geo-tomography can provide a detailed map of host rock density including identification of voids, seismic faults, and low-density areas.

7 REFERENCES

[1] E. W. Grashorn, “Astroparticle Physics with the MINOS Far Detector,” 2008. doi: 10.2172/1415813.

[2] P. A. Zyla et al. (Particle Data Group), “Progress of Theoretical and Experimental Physics,” *Prog. Theor. Exp. Phys.*, vol. 2020, no. 8, 2020, doi: 10.1093/ptep/ptaa104.

[3] Z. X. Zhang, T. Enqvist, M. Holma, and P. Kuusiniemi, “Muography and Its Potential Applications to Mining and Rock Engineering,” *Rock Mechanics and Rock Engineering*, vol. 53, no. 11, pp. 4893–4907, Nov. 2020, doi: 10.1007/s00603-020-02199-9.

[4] U.S. Department of Energy, “Yucca Mountain Repository License Application- General Information (DOE/RW-0573, Update No. 1),” 2008.

[5] P. Przewłocki and K. Frankiewicz, “Cosmic Watch.” http://cosmicwatch.lns.mit.edu/ (accessed Jul. 22, 2021).

[6] S. Chatzidakis and R. Howard, “Initial Test Plan for URL Muon Scoping Experiment (ORNL/SPR-2020/1591),” 2020.

[7] S. Chatzidakis, R. Howard, H. Gadey, and A. Farsoni, “Progress Report-Development of URL Muon Scoping Experimental Apparatus and Simulation Results (ORNL/SPR-2020/1728),” 2020.

[8] C. W. Hansen *et al.*, “Overview of Total System Model Used for the 2008 Performance Assessment for the Proposed High-Level Radioactive Waste Repository at Yucca Mountain, Nevada,” *Reliability Engineering and System Safety*, vol. 122, pp. 249–266, 2014, doi: 10.1016/j.ress.2013.06.001.

[9] “Snowmass 2001: Quarknet Teachers take the Berkeley Detector to Colorado and Virginia.” https://cosmic.lbl.gov/SnowMass/main.html (accessed Jun. 16, 2021).

[10] CERN, “Lecture: Particle Interactions with Matter.” 2012. Accessed: Jun. 16, 2021. [Online]. Available: https://indico.cern.ch/event/145296/contributions/1381063/attachments/136866/194145/Particle-Interaction-Matter-upload.pdf

[11] P. J. Griffin, “Nuclear Technologies,” in *Aspects of Explosives Detection*, Elsevier, 2009. doi: 10.1016/B978-0-12-374533-0.00005-2.

[12] D. E. Groom, N. v. Mokhov, and S. I. Striganov, “Muon Stopping Power and Range Tables 10 MeV–100 TeV,” *Atomic Data and Nuclear Data Tables*, vol. 78, no. 2, Jul. 2001, doi: 10.1006/adnd.2001.0861.

[13] Saint-Gobain, “BC-400, BC-404, BC-408, BC-412, BC-416 Premium Plastic Scintillators.” https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/bc400-404-408-412-416-data-sheet.pdf (accessed Jun. 16, 2021).

[14] F. E. Gray, C. Ruybal, J. Totushek, D.-M. Mei, K. Thomas, and C. Zhang, “Cosmic Ray Muon Flux at the Sanford Underground Laboratory at Homestake,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 638, no. 1, May 2011, doi: 10.1016/j.nima.2011.02.032.

[15] W. H. Trzaska *et al.*, “Cosmic-Ray Muon Flux at Canfranc Underground Laboratory,” *The European Physical Journal C*, vol. 79, no. 8, Aug. 2019, doi: 10.1140/epjc/s10052-019-7239-9.

[16] Eljen Technology, “Pulse Shape Discrimination EJ-276 & EJ-276G.” https://eljentechnology.com/18-products/plastic-scintillator?start=4 (accessed Jun. 16, 2021).

[17] J. Rylander, T. Jordan, J. Paschke, and H.-G. Berns, “QuarkNet Cosmic Ray Muon Detector User’s Manual Series ‘6000’ DAQ, Version 1.1,” 2010. Accessed: Jun. 16, 2021. [Online]. Available: https://quarknet.org/sites/default/files/cf_6000crmdusermanual-small.pdf

[18] J. A. Formaggio and C. J. Martoff, “Backgrounds to sensitive experiments underground,” *Annual Review of Nuclear and Particle Science*, vol. 54, pp. 361–412, 2004, doi: 10.1146/annurev.nucl.54.070103.181248.

[19] D. Heck, J. Knapp, J. N. Capdevielle, G. S C Hatz, and T. Thouw, "CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers," 1998. Accessed: Jun. 11, 2021. [Online]. Available: FZKA 6019

[20] P. Antonioli, C. Ghetti, E. v. Korolkova, V. A. Kudryavtsev, and G. Sartorelli, "A three-dimensional code for muon propagation through the rock: MUSIC," *Astroparticle Physics*, vol. 7, no. 4, pp. 357–368, Oct. 1997, doi: 10.1016/S0927-6505(97)00035-2.

[21] S. Agostinelli *et al.*, "GEANT4 - A simulation toolkit," *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 506, no. 3, pp. 250–303, Jul. 2003, doi: 10.1016/S0168-9002(03)01368-8.

[22] M. A. Acero *et al.*, "Observation of seasonal variation of atmospheric multiple-muon events in the NOvA Near Detector," *Physical Review D*, vol. 99, no. 12, Jun. 2019, doi: 10.1103/PhysRevD.99.122004.

Appendix A
Prospective Muon Flux Calculations

A-1 Validation with Monte Carlo Generators and Simulation Chains

The simulation of the muon flux observed via the proposed detector can be done through a variety of methods. A full simulation of an EAS, muon propagation through the rock, and detector response can be performed or simplifications can be applied to each one of these steps. A direct comparison between data and different simulation chains should provide insights on the accuracy and performance of each approach, which should help future experimental collaborations decide which workflow better fits their needs.

The most computationally intensive and accurate method is a full Monte Carlo (MC) analysis. This method entails simulating EAS using CORSIKA[1] [19], propagating the surviving muons at surface level through the rock using MUSIC[2] [20] or Geant4 [21], and finally simulating the detector geometry in Geant4, which will simulate the muons' deposited energy in the plastic scintillators and the detector response. CORSIKA also provides different high-/low-energy hadronic models, resulting in many different scenarios to be compared with and validated by the data.

The second most intensive chain entails simplifying one of the steps. This can be done by using a randomized distribution of muons at the surface based on experimental data and propagating that via MC (MUSIC or Geant4). Alternatively, it can be done by simulating the muon distribution at the surface using CORSIKA, determining which muons should reach the detector using a parameterized energy loss equation, and propagating the final muons in Geant4.

Finally, the simplest approach only uses Geant4 to simulate the detector geometry and response. It considers a known muon distribution at surface, determines the fraction of muons that reach the detector by calculating the muon energy-loss, and propagates that final distribution through Geant4.

A-2 Observation of Muon Seasonal Variations

Underground muon flux is known to follow a yearly seasonal effect [22] caused by atmospheric temperature variations. A higher/lower muon flux occurs during the summer/winter months due to the change in particle interaction probabilities. Higher temperatures (and thus lower densities) result in lower interaction probabilities, which increase pion and kaon decays and, ultimately, increase the total muon flux. The effect only becomes visible at significant underground depths because underground muons are mostly produced by pion and kaon decays that occur in the tropopause (~15 km of altitude) where daily temperature variations are minimal. Thus, seasonal effect trends are easily tracked. Conversely, low-energy surface muons are produced at lower altitudes in the troposphere, which suffers large daily temperature variations, widening muon flux standard deviations and nulling the effect.

Observing this effect entails taking muon flux measurements at the DOE URL at least two times per year (one run during winter and one run during summer). Longer detector exposure might also be needed to achieve enough statistics to verify the effect, because the seasonal variation should be no more than a few percent of the yearly muon flux average. Nevertheless, this is an interesting result that should provide more visibility to the experiment than a direct single muon flux measurement.

---

[1] Acronym for Cosmic Ray Simulation for KASCADE (Karlsruhe Shower Core and Array Detector).

[2] Acronym for Muon Simulation Code.