MISSOURI S&T

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

Formerly University of Missouri-Rolla

END OF FIRST YEAR PROGRESS REPORT

CENTERS FOR DISEASE CONTROL AND PREVENTION
NATIONAL INSTITUTE FOR OCCUPATIONAL SAFETY AND HEALTH
CDC-NIOSH AWARD NO.: U60OH012350

TITLE: Research, Technological Innovations and Human Factors for Effective Miner Self-Escape from Underground Mine Emergencies

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PERIOD OF PERFORMANCE: 10/01/2021 – 09/30/2022

FUNDING: Per First Year Program Budget

The Curators of the University of Missouri System
On behalf of Missouri University of Science and Technology

EXECUTIVE SUMMARY

This report summarizes the first-year research progress on the CDC-NIOSH U60OH012350 Program in the focus areas (see APPENDIX A). The period of activity is between October 01, 2021, and September 30, 2022. The report provides progress summaries on the focus areas since the funding was awarded to Missouri University of Science and Technology (S&T) and University of Kentucky (UK). The research progress includes research personnel, research environments, interactions with NIOSH personnel and other stakeholders, the creation of the MERIT Center (APPENDIX B), intellectual property, research challenges, and major goals in Year 2.

The U60 Program is advancing research, technological interventions, and training to empower miners for safe self-escape in mine emergencies. The main objectives are 1) advance research in underground wireless communication; 2) study human-robot interactions for safe miner self-escape; 3) study critical ingress/egress mechanisms for refuge alternatives subjected to explosions; 4) evaluate the risks of lithium-ion battery electric vehicle fires; and 5) use a "train the trainer" model to train operators. The Team is pursuing five areas to address the research challenges. These areas include (i) Wireless Communication; (ii) Human Factors; (iii) Mine Explosions and Refuge Alternatives; (iv) Battery Electric Vehicle Fires; and (v) Technology Transfer and Training. The program is carried out under The MERIT (Mine Escape, Research, Innovations and Technology) Center at S&T in collaboration with UK, industry, and NIOSH.

The S&T-UK Team has recruited almost 100% of the research personnel for undertaking the U60 research initiatives. Overall, one Research Manager, three Post-Doctoral Fellows (PDFs), eight PhD students, and two Undergraduate Research Assistants have been hired to assist the research efforts. The PhD researchers are advancing through their respective graduate course completions in all the focus areas. The Teams continue to develop the required research environments for executing the research mandate. The human-robot, explosion test facilities, and the battery fire stations have been set up to carry out the respective research experiments. We are currently setting up the wireless communication environments to carry out demonstration tests for miner self-escape in underground emergencies in the next few weeks. The Team has published eleven refereed journal and conference manuscripts within Year 1.

We have established The MERIT Center with broader research focus to provide leadership and management for the U60 Program. The Center engages stakeholders, and attracts researchers (graduate students, post-doctoral fellows, and research professors) to undertake collaborative initiatives. We have established the Industry Research Advisory Board (IRAB) to provide input into the research substance and directions for the benefit of industry. The IRAB comprises representatives from Arch Resources, Komatsu, Fred Weber, Matrix Design Group, MSHA, Peabody, Prairie State, Vale, and Strata Worldwide. The S&T-UK Team has had several interactions with partners and collaborators including NIOSH, and IRAB. The Team met with IRAB members on January 07, 2022, for discussions on research relevance to industry, and NIOSH on January 11, 2022, for the U60 Kick-Off. The meeting with NIOSH also outlined strategic collaborations by both S&T-UK and New Mexico Tech and NIOSH personnel. Overall, the progress made within Year 1 is very good given the late start of the U60 Program, and the time it took to establish the research environments and hire the researchers.

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1.0 DELIVERABLES

1.1 Highly Qualified Research Personnel Development

The U60 Team includes

- Research Manager (Dr. Muhammad Azeem Raza)
- Seven (7) PhD and one (1) MS researchers, plus one (1) PhD researcher in Spring 2023
- Three (3) Post-Doctoral Fellows
- Two (2) Undergraduate research fellows

1.2 Research Environments

- ***The Wireless Communication (WC) Team*** is creating a Delayed Tolerance Network (DTN) simulation and test-bed environments for efficient communication at S&T Mine.
- ***The Human Factors (HF) Team*** has created a collaborative space on Google Drive, Boston Dynamics Spot robot for research.
- ***The Underground Coal Mine Explosions and Refuge Alternative (UCMERA) Team*** has expanded and dewatered the Wombat Underground Research Facility. The UK team has acquired a high-performance computer for fast computational modeling and a license for Cradle SC/Stream and SC/Tetra software.
- ***The Battery Electric Vehicle (BEV) Fire Team*** has set up a fire station at the S&T Mine to conduct the Li-ion battery fire test. Fourier-transform infrared spectroscopy (FTIR) instrument was also purchased to investigate gas samples from Li-ion battery fires.
- ***The MERIT Center:*** We have established the Center with broader research focus to provide leadership and management for the U60 Program, with highly qualified researchers to undertake collaborative initiatives.
- ***Industry Research Advisory Board (IRAB):*** We have established IRAB to provide input into the research substance and directions for the benefit of industry. IRAB comprises representatives from Arch Resources, Komatsu, Fred Weber, Matrix Design Group, MSHA, Peabody, Prairie State, Vale, and Strata Worldwide.

1.3 Intellectual Property Development

The U60 research team has published 3 refereed journal and conference manuscripts, with 8 accepted for publication (see Section 8.0).

1.4 Quarterly Reports to CDC-NIOSH

Two previous quarterly reports have been submitted to CDC-NIOSH and another submitted to NIH via era Commons.

1.5 Strategic Collaborations

The U60 research team has collaborated effectively among S&T faculty from Mining, Explosives, and Mechanical Engineering, Computer Science, and Psychology, UK faculty in Mining Engineering, NIOSH personnel, Penn State University, University of Maryland, with future collaborations with Colorado School of Mines.

2.0 RESEARCH PERSONNEL

The U60 research team has successfully recruited a Research Manager (Dr. Muhammad Azeem Raza) that would assist the team in managing the program and he will begin work in January 2023. In addition, we have recruited seven (7) PhD and one (1) MS researchers, three (3) Post-Doctoral Fellows, and two (2) Undergraduate researchers for the U60 Program. An additional PhD researcher will join the Team in Spring 2023 to complete the research personnel, as illustrated in Table 1. The PhD students are progressing through their respective academic and research programs appropriately.

Table 1 Recruited Research Personnel (S&T & UK)

Name of Researcher/Level	Recruitment Date	Research Status
Dr. Muhammad Azeem Raza,	Spring 2023	Research Manager
Emmanuel Atta Antwi, PhD in Mining Engineering	Spring 2022	GRA
Abhay Goyal, PhD in Computer Science	Fall 2021	GRA
Estefania Aramayo, MS in Explosives Engineering	Fall 2021	GRA
Eugene Gyawu, PhD in Mining Engineering	Fall 2021	GRA
Amir Iqbal, PhD in Mining Engineering	Fall 2021	GRA
Kutay E. Karadeniz, PhD in Mining Engineering	Fall 2021	GRA
Dr. Robert Pushparaj, PDF in Mining Engineering	Fall 2021	PDF
Dr. Kelly Williams, PDF in Explosives Engineering	Fall 2021	PDF
Dr. Kelechi Anabi, PDF in Mining Engineering	Fall 2022	PDF
Cyrus Addy, PhD in Mining Engineering	Fall 2022	GRA
Jacob Vandoren, B.S. in Computer Science	Fall 2022	URA
Dustin Peterson, BS in Mining Engineering	Fall 2022	URA
Patrick Nonguin, PhD in Mining Engineering	Spring 2023	GRA

GRA – Graduate Research Assistant; PDF – Post-Doctoral Fellow; URA – Undergraduate Research Assistant

3.0 RESEARCH ENVIRONMENTS

The New Wireless Communication (NWC) Team is creating simulation and test-bed environments for efficient communication inside the S&T Mine. Currently, the Team is working on a test-bed prototype using DTN environment, by programming smart devices to facilitate the development of a testbed inside the Mine for a series of tests and experiments. Human Factors (HF) Team has created a collaborative space on Google Drive, which is a living hub of scholarly and industry information that students and collaborators can access. The team is using the S&T Mine and the Boston Dynamics Spot robot, for experimental tests at the Mine.

The Underground Coal Mine Explosions and Refuge Alternative (UCMERA) Team at S&T focused on the Wombat Underground Research Facility. The Team has expanded the Wombat working space and is permanently dewatering this underground facility. Appropriate electrical power (volts/amps/phase) has been supplied to one of the research labs that houses a crusher. Additional comminution equipment is being acquired to increase sample capacity for explosion tests. We are waiting to see the performance of the UK generated coal dust during full-scale testing before finalizing the acquisition of the second crusher to ensure the sizing is appropriate. The U60 Program funding has also allowed the purchase of equipment, tools, and other consumables

facilitate research initiatives at UK. The UK team has acquired a high-performance computer for fast computational modeling and a license for Cradle SC/Stream and SC/Tetra software.

In addition, the U60 funding has allowed the purchase of equipment, tools, and other consumables for research on mine fires. Funds were used to test diesel fires in underground mines to obtain valuable data. The Battery Electric Vehicle (BEV) Team set up a fire station to conduct the Li-ion battery fire test. The fire station is located at the S&T Mine. Fourier-transform infrared spectroscopy (FTIR) instrument was purchased to investigate gas samples from Li-ion battery fires. The Team also hosted a BEV Fire Safety Workshop in Rolla on June 16, 2022. The workshop was funded by the College of Engineering and Computing and the Department of Mining and Explosives Engineering at S&T, and over 30 people attended in-person, with 40 online attendees. Workshop attendees included vehicle manufacturers, industrial BEV end users, fire safety experts, and university researchers. These efforts will promote S&T to become a research hub in solving the safety issues related to BEV and provide training to the industry.

4.0 PROGRESS ON RESEARCH FOCUS AREAS

4.1 New Wireless Communication (NWC) Research Progress

The NWC Team focused has focused on Task 1.1 (Hybrid Duty-Cycle DTN Architecture). Recent reports by the Mine Safety and Health Administration suggest that several injuries and fatalities could be attributed to the inability to accurately locate miners in case of disasters. Since underground mines have a complicated geometrical layout, it is difficult to predict the location of a miner with no GPS information available, and hence may cause delays and inefficiencies in rescue operations during a disaster. A significant amount of research has been done to capture complex spatio-temporal relationships of movement of the nodes/people/things with time, spatial and temporal features to separately extract these relationships. Although Markov Chains (MC), Recurrent Neural Network (RNN) based methods have been used to predict locations, not all of them specifically mention the spatial locations, their connections and the aggregation techniques which would allow for the actual representations of the trajectory of users (miners).

The principles of energy harvesting, and kinetic energy harvesting were explored in detail for the DTN architecture. Energy harvesting is the process of capturing energy from one or more renewable energy sources and converting them into usable electrical energy. One major issue is the maintenance of the nodes in the network architecture. This is because, in most cases, they are battery powered and often positioned in places with difficult accessibility. One of the main problems in Wireless Sensor Networks (WSNs) is battery life. Battery life poses a real problem in node maintenance in operation due to performance difficulty and the corresponding high cost of maintenance. Energy harvesting is expected to be used as a power source in sensor nodes for WSNs. This is because energy harvesting eliminates the need for periodic battery replacements. In general, an energy storage device is required for an energy harvesting system because the amount of harvested energy is unstable.

In addition, energy storage devices are expected to be charged with small currents and to store energy without leakage for long periods of time in various environments. Sensor nodes represent

most applications powered by batteries or equipped with an energy storage device. In these systems, battery lifetime is a key parameter since it defines the nodal maintenance frequency. Since sensor node maintenance may be an expensive operation, system designers must always find the optimum trade-off between battery capacity, device power consumption, node lifetime and cost. Battery capacity has a direct impact on the cost and size of the device and depends on the power consumption of the electronics equipment. Based on our research investigation, the two major energy harvesting methods for underground mine applications are (i) RF Energy Harvesting; and (ii) Kinetic Energy Harvesting.

3.1.1 RF Energy Harvesting

RF energy can be used either to directly power ultra-low power battery-free devices, or to charge the batteries of low energy battery-powered devices. This energy can be used for maintenance charging of several devices, sensors, and consumer electronics. Depending on the power demand and the operating system, the power can be sent continuously, on scheduled basis, or on-demand. This can prevent, or greatly reduce, the cost of labor, decreasing future maintenance efforts and the cost to replace the batteries, and ultimately allowing ubiquitous IoT and WSN deployments. While RF energy is very pervasive, allowing energy transfer with out-of-sight sensing devices, the main drawback is that the efficiency of the power transfer is very low, and for this reason, it is restricted to low energy devices. In a typical power transmission at 900 MHz in free space, the received power is about −30 dB of the transmitted power within 1 meter, with a decay of −20 dB every 10 meters. The amount of stored RF energy in a battery depends on several parameters, such as the transmitted power, the gain of both the transmitting and receiving antenna frequency of the transmitted RF signal, distance between the RF transmitter and the efficiency of the RF harvester.

3.1.2 Kinetic Energy Harvesting

Kinetic Energy Harvesting (KEH) converts the ambient motion/vibration energy into electrical energy to power the IOT sensor nodes. The Power Management Unit (PMU) is used to manage the harvested energy to power a load or a node. The harvested energy is stored in an energy storage unit (i.e., capacitor/battery) which is used to power a sensor node. The harvested energy is consumed by various hardware components within the sensor node including the sensor module, Analog-to-Digital Converter (ADC), microcontroller, and transceiver to sample the physical attribute as well as its transmission to the destination. To harvest the maximum power, the transducer must operate in the Maximum Power Point (MPP). This is the operating point in the system when the internal impedance of the transducer is equal to the load impedance.

3.1.3 Further Progress on Wireless Communications

Addressing these concerns, we develop a first-of-its-kind end-to-end system entitled Miner-Finder to predict the future location of the miners by incorporating Long and Short-Term Memory (LSTM) for trajectory information with Graph Autoencoder (GAE) for spatial environmental information representing the node connectivity. In addition, our approach will combine the miners' previous trajectories and daily repetitive patterns enhancing the prediction robustness. In addition, this brings forward a semi-supervised learning method of prediction which could run in a plug-and-play. This method has not been modelled in real-time underground mining research. We

evaluated Miner-Finder over synthetic dataset to analyze the structure and location topology of an underground mine compared with foreground locations. Our model outperforms state of the art models and achieves an AP score ranging from (0.62 - 0.68) and Receiver Operating Characteristics (ROC) ranging from (0.63-0.68) with increasing percentage of prominent locations (most visited) to 50%. The next stage is to demonstrate this with real-world experiments in the S&T Mine. We are currently working on designing and performing these experiments.

3.1.4 Conclusion

In conclusion, energy harvesting in IOT Sensor augments the battery life and acts as an alternate source of power. Some of the practical energy harvesting techniques in the underground mining would be RF Energy Harvesting and Kinetic Energy Harvesting. RF Energy Harvesting method generated a maximum voltage of 2300mV @60cm distance after 9000sec and 82 microAmp @60cm distance after 9000 sec. Kinetic Energy Harvesting method generated a maximum power of 5mW @1000mV shaker input operating at 2300mV MPP voltage. The Team is currently preparing to set up a wireless communication demonstration experiments to test the capability and capacity of a wireless communication network in underground mining environments.

4.2 Human Factors (HF) Research Progress

The Team worked on submitting the order for Boston Dynamics' Spot robot. The Team completed all the paperwork to justify a sole-source purchase and successfully signed a purchase order with Boston Dynamics on Dec. 15, 2021. The Team received delivery of the robot in the first quarter of 2022. Once the robot arrived, the Team conducted a series of focus group sessions to elicit different uses from miners. As per the proposal, the goal for the first year was to assess miner attitudes and perceptions about the deployment of dynamic, highly mobile robots to facilitate self-escape and to assist other miners in danger during an emergency. The research team decided to use a focus group survey with groups of miners to elicit miner attitudes and perceptions about deployment of dynamic, highly mobile robots to facilitate self-escape. The research team designed a rigorous focus group interview and applied for IRB approval. The University of Missouri IRB granted an exception for the study. Table 1 shows the focus group sessions conducted by the research team. The research team is in the process of collating the focus group results to draw conclusions on miner perceptions and attitudes.

Table 2 Summary of Focus Group Sessions

#	Date	Industry Sector	No. of Participants
1	9/15/2022	Coal	4
2	9/27/2022	Metal/non-metal	4
3	9/28/2022	Metal/non-metal	7
4	9/28/2022	Coal	6
5	10/11/2022	Coal	3
6	10/25/2022	Coal	5
Total			**29**

4.3 Underground Coal Mine Explosions and Refuge Alternatives (UCMERA)

The UCMERA Team at S&T completed an expansion to the main drift in the Wombat portal to create an underground test site. This site allows full-scale testing of coal dust and methane explosions in straight entries and testing on crosscuts. Figure 1 shows the Wombat drift expansion. Additionally, the Team at UK will expand their explosion tunnel facilities and examine the following:

- Optimal set-back distances for structures subjected to side-on pressures (e.g., BIP RA walls, stoppings, communication equipment, etc.)
- Determination of a potential negative phase and its significance (if any)
- Optimize mine design or design features to minimize explosion effects

The testing facility at UK is utilized for full-size and scaled tests of coal and methane explosions above ground. These tests focused on scaled tests of different mine layouts and testing of mine communication systems' durability. Numerical modeling was conducted using the data collected from the tests and tests developed at the Lake Lynn Experimental Mine (LLEM). Figure 2 displays the current UK test facility.

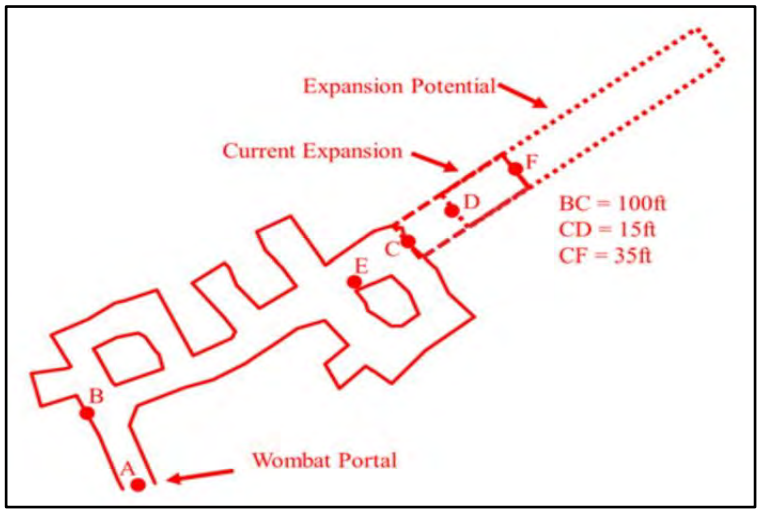

Figure 1 S&T Wombat Expansion

With the Wombat extended and a permanent dewatering solution in progress, methane/coal dust explosions will continue with pressure monitoring throughout the mine at points of interest. Two doors from Kennedy Metal Products and Aurora Manufacturing's CAD geometries have been imported into ANSYS Workbench's Static Structural tool for a preliminary static loading. Following this initial step, the geometries were also imported into the ANSYS Explicit dynamic analysis tool. The imported geometries have been preliminarily subjected to a 15-psi explosion pressure, and the mesh models have also been checked for finite element error in dynamic analysis.

Coal dust for explosion testing will be processed on-site at the S&T Mine, using a two-stage crushing/grinding circuit. Coal chunks, with a maximum size of 3 inches, will be fed into the primary crusher, a lab-scale jaw crusher. This is not something S&T currently has, so an LC-28 crusher from Gilson Global will be purchased for this purpose. The cost will be $9,950 if purchased

directly from the manufacturer. The product of this crusher, with a p50 of ¼", will be fed directly into the non-sparking lab scale ball mill that is already on site, which should produce a product with a p50 of 50 microns, to match the product that UK used in their testing. The ball mill run time, loading ratios, and media size will be adjusted as needed to meet this size. Both crushing and grinding will be run as concurrent batch processes.

Figure 2. UK Test Facility

The work at UK on the CFD models has focused on reducing the computational time with accurate results. Multiple approaches have been developed to accomplish this objective, which consider different methodologies (total pressure boundaries, bursting balloon, etc.), and the use of different software (SC/Tetra, SC/Stream). To advance the project, 1000 pounds of processed coal dust has been produced to be used for explosive testing.

4.4 Emergency Response to Battery Electric Vehicle (BEV) Fires

The BEVF Team started designing the large size battery test facility (Figure 3). The facility comprises electric heater, commercial Li-ion battery (about 10 cylindrical cells pack), heat resistant hood, smoke duct, video camera, thermocouple, and fan. The fire station is covered with metal roof to avoid fire and it is about 3-5 m in length and 2-3 m in height. There will be two windows on the left and right to exhaust excess fire or smoke out of the chamber. The smoke duct is 10 cm in diameter and 2-3 m long. The batteries are wired and placed on the burner with a 16kW. This process will be executed in a single burning item that was used in previous literature. Also, we will conduct this fire test for different state of charged batteries (SOC is 0-100%).

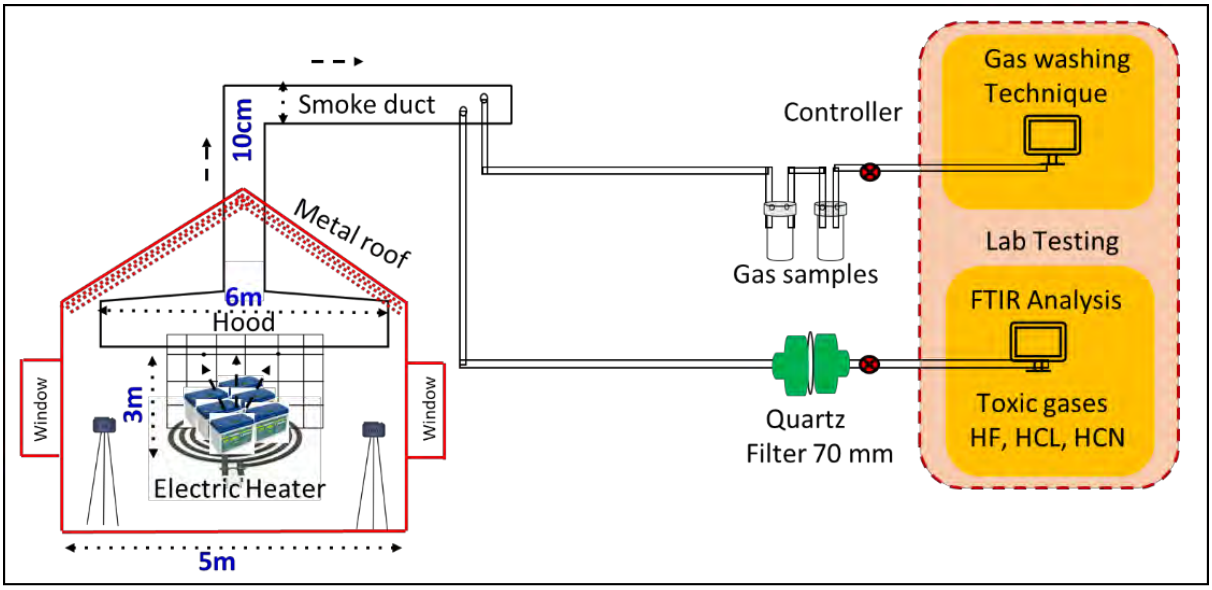

Figure 3 Full size battery test chamber

Additionally, Dr. Guang Xu secured about $40,000 internal support from S&T to organize a BEV fire safety workshop to be held in June in Rolla. The purpose of the workshop was to leverage the U60 Program funding and expand the research to broader BEV safety considering infrastructure design, novel battery cell development, and firefighting strategies and training. We brought experts and stakeholders from government, industry, and academia to identify the needs and research directions for improved BEV fire safety. Regarding the small and large-scale battery fires, Aamir and Robert set up the primary fire station. The outlook seems good to conduct the fire test, but we still need proper analytical tools, such as the FTIR instrument. Several abstracts were submitted to reputable national and international conferences. These include the international conference of the Society of Mining, Metallurgy, and Exploration and the North American Mine Ventilation Symposium. The first-ever workshop on battery fire was conducted at the Kennedy Experimental mine of the S&T that researchers and engineers from the industry attended.

5.0 INTERACTIONS WITH STAKEHOLDERS

The S&T-UK U60 Program researchers had considerable interactions with NIOSH and other collaborators on several initiatives. Within the first year, the S&T-UK Team also met with the Industry Research Advisory Board (IRAB) on January 07, 2022, to discuss research progress and directions. On January 11, 2022, the Team had a kick-off meeting with CDC-NIOSH Team including George Luxbacher, Cassandra L. Hoebbel, María Sofía Lioce, Paul Schmidt, and the New Mexico Tech (NMT) Team. Presentations by the S&T-UK and NMT Teams focused on research progress and directions. The S&T-UK Team also hosted a NIOSH Team (consisting of Dr. Eranda Perera, Marcia L. Harris, and David S. Yantek of the Ventilation & Explosion Prevention Team), on September 08, 2022. The aim of this visit was to allow the NIOSH Team to tour S&T's explosives and ventilation facilities for potential expanded collations in these areas.

The New Wireless Communication (NWC) research team focused on setting up its research environments and recruiting researchers per the requirements of the U60 Program. NWC is exploring extensive collaborations with NIOSH, and Colorado School of Mines in Year 2. The Human Factors (HF) research team has had extensive interactions with multiple NIOSH researchers including Dr. Cassandra Hoebbel, Paul Schmidt, David Yantek, and the VR Mine team. The HF team has sought input from the NIOSH team on survey design, recruiting participants for surveys, designing human subject tests for refuge alternatives, and for doing purge tests for refuge alternatives. The NIOSH team also arranged for our researchers to visit the MSHA Academy in Beckley, WV and to meet with Chembio representatives to discuss collaboration on human subject testing for designing better signage for refuge alternatives. The team is currently working with NIOSH researchers to conduct tests to evaluate how the environment is affected by humans entering refuge alternatives without purging to evaluate how refuge alternatives can be used as way stations during an evacuation.

The S&T and UK UCMERA Team has had several meetings to discuss research progress and the way forward. Although each of the two universities has its own specific research agenda, they are working in parallel to achieve the overall research goals. The BEV Fires Team has had several NIOSH researchers actively involved on many fronts with critical inputs, including:

- Dr. Liming Yuan and Mr. Thomas Dubaniewicz attended the BEV Fire Safety Workshop in Rolls in June 2022
- An online meeting with NIOSH contacts (Dr. Liming Yuan and Mr. Thomas Dubaniewicz). Dr. Xu and his group give presentations and Dr. Yuan and Mr. Dubaniewicz provided feedback.
- Interactions with the Ventilation & Explosion Prevention Team from NIOSH on September 08, 2022. Dr. Xu's group gave presentations on their research, had a lab tour, and discussed possible collaboration work.

The BEV Fire Team visited NIOSH, Penn State University, and the University of Maryland within October 24 and 28, 2022. Dr Ashish Kumar, Assistant Professor in the Department of Energy and Mineral Engineering at Penn State University, and Dr Precht in Mechanical Engineering at the University of Maryland hosted the BEV Fire team and discussed future collaborations.

6.0 INDUSTRY RESEARCH ADVISORY BOARD

As part of the research administration for effective engagement, the S&T-UK Team created the Industry Research Advisory Board (IRAB) to provide input into the research substance and directions. The IRAB has been instrumental in shaping the research directions for the U60 Program. Our first meeting on January 07, 2022, focused on progress of the research initiatives, The MERIT Center as a vehicle to advance initiatives, and the strategic future of the Center. Below are the members of the IRAB.

1. John Drexler, Chief Operating Officer, ARCH Resources, Inc.
2. Tom Barnes, Sr. Mgr., Global Service Excellence, KOMATSU

3. Justin Higginbotham, General Manager, Fred Weber, Inc.
4. Tracy Hayford, Dir. of Technology, Matrix Design Group, LLC
5. David L. Weaver, Reg. Mgr., South-Central Division, MSHA
6. Bryan Galli, Grp. Exec./Chief Marketing Officer, Peabody
7. Lane Hendricks, Safety Manager, Prairie State Generating Co.
8. Tom Michaud, Chief Technical Officer, Strata Worldwide
9. Luke Mahony, Global Head of Engineering, Technology & Innovation, Vale Base Metals

7.0 RESEARCH CONSTRAINTS

The main constraints within Year 1 included (i) delays in acquiring the robot for human factor-robot research due to supply chain issues; and (ii) difficulty in recruiting focus group participants.

8.0 INTELLECTUAL PROPERTY DEVELOPMENT

As part of the U60 Program undertaking, the following refereed journal and conference manuscripts have been developed by the researchers.

a. Abhay Goyal, Sanjay Madria and Samuel Frimpong, MinerFinder: A GAE-LSTM Method for Predicting Location of Miners in Underground Mine, in ACM SigSpatial, 2022, USA.
b. Abhay Goyal, Sanjay Madria and Samuel Frimpong, A DTN-based Spatio-temporal Routing using Location Prediction Model in Underground Mines, under review in 5th International Workshop on Emergency Response Technologies and Services (EmeRTeS 2023).
c. Karadeniz, K. E., Nowak, S., Guner, D., & Sherizadeh, T. (2022). Evaluation on Underground Refuge Alternatives and Explosion Survivability: a Review. Mining, Metallurgy & Exploration, 1-21. https://doi.org/10.1007/s42461-022-00682-1
d. Karadeniz, K.E., Nowak, S., Guner, D., & Sherizadeh, T., (2022). Dynamic Response Analysis of a Reinforced Concrete Structure in Underground Coal Mine Environment with Various Strata Conditions. Mining, Metallurgy & Exploration (Under Review)
e. Karadeniz, K.E., Guner, D., & Sherizadeh, T., (2023). Effect of Roof and Floor Strata on Explosion Resistance of Reinforced Concrete Wall for an Underground Coal Mine. Proceedings of the 2023 SME Annual Conference and Expo.
f. Aramayo, E., Petrov T., Silva, J. 2022. "Computational fluid dynamics (CFD) modeling of methane explosions development in underground coal mines." To be presented at the SME Annual Conference 2023.
g. Robert Ilango Pushparaj, Guang Xu, Amir Iqbal, and Salami Oluwafemi, "Identification of toxic gas from large size battery packs fire experiment", NAMS-2023-Accepted
h. Aamir Iqbal, Guang Xu, Robert Ilango Pushparaj, Salami Oluwafemi, "Analysis of toxic fumes emitted during small-scale Li-ion battery" NAMS-2023-Accepted
i. Salami Oluwafemi, Guang Xu, Ashish Kumar, Robert Ilango Pushparaj, Aamir Iqbal, "Experimental and Numerical studies of the interactive Influence of ventilation and fire size on fire characteristics and tenability" NAMS-2023-Accepted
j. Aamir Iqbal, Guang Xu, Robert Ilango Pushparaj, Salami Oluwafemi "Battery Electric Vehicles Fire, Toxic Fumes and Fire protection; A Critical Review", SME-2023-Accepted

k. Salami Oluwafemi, Guang Xu, Analysis of Crew Evacuation Time during different fire scenarios in underground confined space using agent-based modeling," SME-2023-Accepted

9.0 SUMMARY AND CONCLUSIONS

The U60 research team has successfully recruited a Research Manager that would assist the team in managing the program, eight (8) PhD researchers, three (3) Post-Doctoral Fellows, and one (1) Undergraduate Student for the U60 Program. An additional PhD researcher will be recruited in Spring 2023 to complete the research personnel. The PhD students are progressing through their respective academic sand research programs appropriately. The NWC team is creating simulation and test-bed environments for efficient communication inside the S&T Mine. The HF team has created a collaborative space on Google Drive, which is a living hub of scholarly and industry information that students and collaborators can access. The team is using the S&T Mine and the Boston Dynamics Spot robot, for experimental tests at the Mine. The UCMERA team at S&T focused on the underground research facility named the Wombat. The UK team has acquired a high-performance computer for fast computational modeling and a license for Cradle SC/Stream and SC/Tetra software. U60 Program funding also allowed the purchase of equipment, tools, and other consumables for research on mine fires. The Battery Electric Vehicle (BEV) Team set up a fire station to conduct the Li-ion battery fire test. Fourier-transform infrared spectroscopy (FTIR) instrument was purchased to investigate gas samples from the Li-ion battery fire.

The Research Teams worked on research tasks under APPENDIX A within the focus areas. ***The NWC Research Team*** focused on Task 1.1 (Hybrid Duty-Cycle DTN Architecture). The team explored the principles of energy and kinetic energy harvesting in detail for the DTN architecture. The Team established that the two major energy harvesting methods for underground wireless communications are (i) RF Energy Harvesting; and (ii) Kinetic Energy Harvesting. They also established that energy harvesting will be used as a power source in sensor nodes for WSNs. The team is currently preparing to test a demonstration for wireless communication at the Mine. ***The HF Team*** has secured the Boston Dynamics' Spot robot. Once the robot arrived, the Team conducted a series of focus group sessions to elicit different uses from miners. The research team designed a rigorous focus group interview and applied for IRB approval. The University of Missouri IRB granted an exception for the study. The team is in the process of collating the focus group results to draw conclusions on miner perceptions and attitudes.

The UCMERA Team at S&T has extended and currently dewatering the main drift in the Wombat portal to create an underground test site. Methane/coal dust explosions will continue with pressure monitoring throughout the mine at points of interest. Two doors from Kennedy Metal Products and Aurora Manufacturing's CAD geometries have been imported into ANSYS Workbench's Static Structural tool for a preliminary static loading. Following this initial step, the geometries were also imported into the ANSYS Explicit dynamic analysis tool. The imported geometries have been preliminarily subjected to a 15-psi explosion pressure. ***The UCMERA Team*** at UK on the CFD models has focused on reducing the computational time with accurate results. Multiple approaches have been developed to accomplish this objective, and the use of different software (SC/Tetra, SC/Stream). To advance the project, 1000 pounds of processed coal dust has been produced to be used for explosive testing. ***The Battery Electric Vehicle Fires (BEVF) Team*** started on the design of the large size battery test facility. The Team also secured $40,000 support from S&T to organize a Battery Electric Vehicle Fire (BEV) Safety Workshop in June 2022 in

Rolla. The purpose of this workshop was to leverage the NIOSH funding and expand the research work to broader BEV safety research considering infrastructure design, novel battery cell development, and firefighting strategies and training. ***The U60 Research Team*** also had an IRAB Meeting on January 07, 2022 to discuss progress and seek input into the research directions.

10.0 MAJOR GOALS FOR YEAR 2

The S&T-UK U60 Program has outlined major goals Year 2 to achieve the outlined research goals, complete the tasks defined in Appendix, and achieve the associated milestones, as outlined below.

9.1 Major Goals for NWC Research

The NWC team will focus on the DTN test-bed implementation in the Mine in the second year and improve the current research to make them more efficient and usable in the test-bed environment. We plan to deploy the testbed in the mine for real-time testing and experiments. Research will also focus on advancing the wireless power transfer (WPT) – radio frequency (RF) energy harvest circuit for efficient power transmission and miner localization during emergencies. We also intend to advance collaborations with NIOSH personnel and our external collaborators.

9.2 Major Goals for HF Research

The goals for Year 2 include (i) catalog robotic missions that a trapped miner can use legged robots to accomplish and document the challenges and characteristics of such missions; and (ii) develop object identification algorithms using infrared images to autonomously identify humans in a post-mine disaster environment.

9.3 Major Goals for UCMERA Research

Reduced scale explosion testing will commence in Year 2. The goal is to identify zones of amplification or reduction based on different types of mine geometries. The quality-checked finite element models of the doors are currently being created to make them ready to calibrate just after the testing of these doors at our Experimental Mine Facility of Missouri University of Science and Technology. Upon the calibration of the numerical models, the extensive simulations will start covering both global door models and sub-models for small components like doorknobs, and hinges. The next steps for **UK** in collaboration of **S&T** are use the CFD modeling for more complex geometries and optimize the computational time (Three entries explosions), calibrate the model with more LLEM tests and compare results with scaled models (UK) and tunnel testing (S&T). When successful, a better understanding of design features, placements, orientations, etc. of critical infrastructure will be gained resulting in greater overall safety for miners.

9.4 Major Goals for BEV Fire Research

The BEV Fire team will focus on fire extinguishing agents in Year 2. Limited studies exist on suitable extinguishing agents for battery fires and uncertainty regarding appropriate fire-fighting systems. Thermal and fire propagation of multiple Li-ion batteries will be studied in Year 2. Subtasks include synthesizing novel fire-retardant materials, evaluating various fire extinguishing techniques, exploring their impact on heat and gas generation, and the risk of battery re-ignition.

APPENDIX A PROJECT TASK SCHEDULES AND MILESTONES

Table A-1 shows the tasks, durations, and milestones for the CDC-NIOSH U60OH012350 Program. Even though the Federal Award Date was August 19, 2021, the official notification to Missouri S&T was October 01, 2021. Thus, the research program earnestly began within the last quarter of 2021. Thus, we have adjusted the start date from Table A-1 from the start date of third (3^{rd}) quarter to 4^{th} quarter of 2021.

Table A-1 Project Tasks, Durations and Milestones (Contract No: 75D30120CO8913)

Research Tasks	2021		2022				2023				2024				2025			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.1: Hybrid Duty-Cycle DTN Architecture																		
Task 1.2: WPT-RF Energy Harvest Circuit																		
Task 1.3: DV-Hop Sensor Localization																		
Task 1.4: Enhanced DTN Testbed Experimentation																		
Task 2.1: Human Factor & Miners' Ability to Deploy Robots																		
Task 2.2: Robotic Missions within a Mine																		
Task 2.3: Miner-Centered Robotic Interface																		
Task 2.4: Tech Transfer																		
Task 3.1: Full-Scale Explosion Propagation Testing																		
Task 3.2: Reduced Scale Explosion Propagation Testing																		
Task 3.3: Numerical Modeling																		
Task 3.4: Risks Assessment																		
Task 4.1: LIB Battery Cell Fire Tests																		
Task 4.2: Respirators' Protection Efficiency in LIB Fires																		
Task 4.3: Fire Suspension Techniques																		
Task 4.4: LIB Fire Emergency Evacuation Model																		
Missouri S&T Research Meetings: Regular																		
Board Meeting: Periodic Meetings on Research Directions																		
CDC-NIOSH Interactions: Quarterly Report																		
CDC-NIOSH Interactions: Annual Contract Status Reports																		
CDC-NIOSH Interactions: Submission of Final Report																		

APPENDIX B
MERIT (Mine Escape Research, Innovation and Technology) CENTER

A collaborative effort among Mining and Explosives Engineering, Computer Science, Psychology and Mechanical and Aerospace Engineering
(https://mining.mst.edu/research/meritcenter/)

Director
Samuel Frimpong, PhD, PEng
Professor and Robert H. Quenon Endowed Chair
Director, Heavy Mining Machinery Research Center
Interim Chair, Department of Computer Science

Assistant Director
Kwame Awuah-Offei, PhD, PE
Union Pacific-Rocky Mountain Energy Professor
Interim Program Director of Mining & Explosives Engineering

1. Name of the Center

MERIT (Mine Escape Research, Innovations and Technology) CENTER

2. Research Focus of the MERIT CENTER

The Center will focus on seven (7) integrated initiatives under the 2006 MINER Act as follows.

- Intelligent Communications for Efficient Self Escape
- Self-Escape and Human Factors
- Refuge Alternatives in Self-Escape
- Underground Mine Fire Emergency Evacuation Optimization
- Impact of Explosions on Self-Escape Strategies
- Technology transfer and training
- Other related research opportunities

3. Names and Titles of the Faculty in the Center

- ***Samuel Frimpong,*** Professor and Robert H. Quenon Endowed Chair, Director, Heavy Mining Machinery Research Center and Interim Chair, Department of Computer Science
- ***Kwame Awuah-Offei,*** Professor and Union Pacific-Rocky Mountain Energy Professor & Interim Director, Mining and Explosives Engineering
- ***Sanjay Kumar Madria***, Curator's Distinguished Professor, Computer Science
- ***Guang Xu,*** Associate Professor, Mining and Explosives Engineering
- ***Kyle Perry,*** Associate Professor, Mining and Explosives Engineering and Graduate Coordinator of Explosives Engineering
- ***Catherine Johnson,*** Assistant Professor, Mining and Explosives Engineering
- ***Taghi Sherizadeh,*** Assistant Professor, Mining and Explosives Engineering
- ***Lana Alagha,*** Associate Professor, Mining and Explosives Engineering, Graduate Coordinator of Mining Engineering
- ***Denise Baker,*** Assistant Professor of Psychology
- ***Venkata Sriram Siddhardh (Sid) Nadendla,*** Assistant Professor, Computer Science

- ***Douglas Bristow,*** Professor of Mechanical Engineering and Director, Center for Aerospace Manufacturing Technologies

4. Partner University and Member

University of Kentucky, Lexington, KY

- ***Jhon Silva-Castro,*** Associate Professor of Mining Engineering and Director of Graduate Studies in Mining Engineering

5. Mission of the Center

Create a robust, well-equipped, and resourced Center at Missouri S&T to

- Pursue research and innovation in mine emergency response
- Collaborate with industry, government agencies (e.g., CDC-NIOSH and MSHA) and university researchers in the outlined research focus areas
- Provide environment for training and developing undergraduate, graduate, post-doctoral, research assistants and faculty expertise in the focus areas
- Develop and transfer technologies and approaches into industry for improving mine emergency outcomes
- Leverage Center funding using other federal, state and industry funding to multiply the research and technological innovation efforts

6. Vision of the Center

Create a center of excellence in mine emergency research and innovation in collaboration with industry, government agencies, and other relevant stakeholders to improve safety outcomes of mine emergency response

7. Management Structure and Funding

The Center will retain a very skeletal management team comprising a Director, Associate Director and Administrative Staff. The administrative costs of the Center will include $38,500 plus fringe benefits for the administrative staff, two-month and one-month salaries for the Director and the Associate Director, respectively. Additional costs of $5,000 per year will be spent on office and administrative expenses. Much of this cost will be part of the CDC-NIOSH proposals for funding.

8. Research Infrastructure

Missouri S&T's Experimental Mine: The Mine is located about 2 miles from the main campus. It sits on a 19-acre land primarily consisting of two surface quarries, two underground mines, and a large building, which houses classrooms, laboratories, and safety training rooms. In addition to these unique facilities, there is a machine shop on site to aid in the creation and development of tools used for research and instruction, as well as other equipment storage facilities. There are magazines on site to store explosives used for research and instruction. The Mine has a fleet of equipment including CAT excavator, two Bobcat skid steers, Epiroc drill, air compressors, and other pieces to aid in research and instruction. Handheld drills including jacklegs, stopers, and sinkers with all necessary bits, steels and hoses are also available for use.

Energetics Research Facility (ERF) is a material testing lab space developed to enable characterization of explosive materials in terms of their sensitivity to react as well as their reaction performance for gas production and shattering effect. The ERF incorporates BAM Friction, BAM Fallhammer, Time/Pressure and dust explosibility test apparatuses, industry standardized tests to quantify the sensitivity of a material to friction, impact and reaction under confinement.

Energetic Materials, Rock Characterization and Geomechanics Research Center (EMRGe): EMRGe offers office space for Explosives Engineering students and faculty. The EMRGe also incorporates a full workshop with subtractive manufacturing capabilities including conventional mill and lathe as well as a 60 ksi waterjet cutting machine with 2-axis automated CNC control. The EMRGe workshop offers full welding capabilities including metal inert gas, tungsten inert gas, and shielded metal arc welding. This equipment enables fabrication through machining and welding on a range of materials including aluminum, steel, and stainless steel.

Mine Ventilation, Health and Safety Laboratory (MVHSL): MVHSL is equipped with the required equipment for conducting a comprehensive underground mine ventilation survey, including 4 Model 765-16B Digiquartz Barometric Pressure Standard kits, 2 high precision monometers, 3 DO000259-52 Anemometer Kit, and various thermometers and Pitotubes.

Web and Wireless Computing Lab: Sanjay Madria is the director Web and Wireless Computing Lab at Missouri S&T. The lab is 600ft in area and has more than 35 servers, dedicated desktops, and several mobile devices such as smart radio device, tablets. The team will use this facility for developing the Delayed-Tolerant Network (DTN) technology.

In-house Cloud, Big data and Blockchain Environment: This private hybrid cloud has been built using Eucalyptus open source platform to conduct experiments. The cloud is highly compatible with Amazon Web Services, which allows us a hassle-free migration of workloads from our data center to AWS and back. Currently we have 15 powerful machines each having 4 cores, 500 Gb of HDD and 8 Gb of RAM each, connected on a private network, which supports over a Gig per second of data transfer.

Sensor Cloud: We have also built a sensor cloud test-bed for efficient data collection, scheduling and allocation for multiple applications. The sensor cloud uses different types of sensors as well as nodes. We currently have various kinds of motes, including several IRIS motes with IRIS gateways, TelosB, Mica2, and Missouri S&T motes.

University of Kentucky Explosives Research Facilities: The University of Kentucky Explosives Research Team, UKERT, has access to a surface and underground facility dedicated to the research of explosives and explosions in mining. The facilities are in a local quarry operated by a private company. Figures 1 and 2 show the underground and surface facilities operated by UKERT, respectively.

Figure 1: Underground mine with shock tube facility

Figure 2: Surface facility

It is possible to recreate gas and dust explosions (methane and coal dust) in these facilities. It is also possible to perform testing using commercial explosives. Figure shows a test in the surface lab using methane and coal dust.

Figure 3: Methane and coal dust explosion test at UKERT

Both labs have been used for research projects with various agencies such as NIOSH, the Alpha Foundation, and the Department of Defense. The facilities have been designed to achieve the pressure-time curves expected in an underground coal mine explosion. UKERT is a university recharge/service center and operates a fleet of equipment necessary for research undertaken by the team. The fleet includes heavy equipment, trucks, generators, welders, light vehicles, as well as a suite of instrumentation that require frequent calibration and maintenance (Data acquisition systems, high-speed video cameras, etc.). Most of the equipment in the fleet is diesel or gas powered and thus fuel consumption costs must be considered for each project. The UKERT cost center account will be used to incur the costs of managing the fleet and equipment maintenance. This account is funded from the research contracts that utilize the equipment. During the proposal phase, cost estimates for the use of this equipment is included under "other direct costs" in the budgeting.