# EVALUATION OF DEVICES TO ENHANCE MINER SELF-ESCAPE IN SMOKE-FILLED ENTRIES

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## Abstract

The Department of Health and Human Services (HHS), National Institute for Occupational Safety and Health (NIOSH), Office of Mine Safety and Health Research (OMSHR), with the assistance of cooperating underground mining operations and state agencies, has conducted research exploring devices and technologies that could be used to assist miners navigating through smoke and dust resulting from a fire or explosion. Recent events in mines confirm that smoke and dust can enter and contaminate mine escapeways creating an atmosphere with severely reduced visibility. This reduced visibility results in substantially increased escape times, possible disorientation or confusion, and increased stress levels, and may prevent evacuation altogether.

Tools or devices that assist miners in navigating through smoke-filled areas void of lifelines could make the difference in successful escape from the mine. This paper presents the results of OMSHR research to identify and evaluate tools and devices that could provide meaningful information to evacuating miners in areas with limited visibility and without the benefit of a lifeline.

## Background

On June 15, 2006, the 109th Congress passed the Mine Improvement and New Emergency Response Act (MINER Act), amending the Federal Mine Safety and Health Act of 1977 to improve the safety of mines and mining. Section 6, Subsection (a)(h)(3) of the Act states that the Office of Mine Safety and Health "shall be responsible for research, development, and testing of new technologies and equipment designed to enhance mine safety and health" (MINER Act 2006).

In 2006, tragedies at the Sago Mine, Aracoma Alma Mine No.1, and Darby Mine No. 1 resulted in the deaths of 19 miners and raised serious concerns about the safety of underground coal mines. In response, sweeping changes were made in federal and state legislation. As a result of the MINER Act of 2006, several federal regulations were revised, including requirements for a continuous durable directional lifeline or equivalent devices to be installed throughout the entire length of each escapeway in coal mines. As a result, miners working on active sections now have a directional guide to help them navigate from the section, through smoke- and dust-filled mine entries, to the surface in the event of a fire or explosion.

In 2007, OMSHR researchers touring the Safety in Mines Testing and Research Station (SIMTARS) in Queensland, Australia, with Martin Watkinson, Principal Mining Engineer, observed a hand-held electronic sonar device a.k.a. Miniguide being tested as a possible navigational aid for a mine escape vehicle. The Miniguide is designed to provide distance information to a visually impaired traveler supplementing information provided by other aids such as the long cane or guide dog. Initial observations indicated that the device might also help underground miners navigate though smoke- or dust-filled mine entries.

To determine the suitability of the Miniguide for navigating in emergency situations, OMSHR researchers conducted a study to identify and evaluate new and existing technologies that could provide miners with useful navigational information when traveling through areas with limited visibility from smoke or dust. Three devices, including the Miniguide, were selected for this study and were subsequently evaluated by miners navigating in (simulated) smoke-filled underground mines. Travel times, positive and negative aspects of the devices, and comments by the miners were recorded. Of the participating miners, approximately one-fourth navigated the smoke-filled entry without the assistance of any device to establish a baseline for comparison. This paper presents the results of this research.

The U.S. Code of Federal Regulations (CFR), Title 30, Part 75, Section 75.380 [30 CFR 2010] requires coal mine operators to provide two separate and distinct escapeways from each working section. Each escapeway must be maintained in a safe condition to always ensure passage, including by disabled person(s), and be clearly marked to show the route and direction of travel to the surface. Metal/non-metal mine operators are required to follow similar regulations; however, current regulations do not require those mines to install directional lifelines as is required in underground coal mines.

In coal mines, the current regulations greatly enhance the ability of most coal miners to escape the underground workings in an emergency situation. However, underground mining operations also have employees that are responsible for establishing new sections, pumping mine water, conducting airway examinations, hauling supplies, and maintaining the infrastructure of the underground operation. These employees do not regularly work on active sections and may not have immediate access to a lifeline. Additionally, miners working in the face area may be required to find their way to an established meeting place, don self-contained self-rescuers (SCSRs), and travel to the emergency escapeway in zero or near-zero visibility.

In addition to miners in remote locations, miners traveling in designated escapeways may encounter obstacles or debris from an explosion that requires travel outside the designated escapeway to an alternate escape route to reach the surface. In such circumstances, underground miners are trained to seek out common mine features such as mine track or rails, water lines, cables, conveyor belt structure, etc. to help them navigate through smoke-filled mine entries in areas where lifelines do not exist. A general knowledge of the mine layout and familiarity with the locations of infrastructure items can greatly increase the chances of successfully evacuating the underground mine workings. In areas absent of these features, miners face the challenge of relying on their own internal sense of direction to evacuate, which can be hampered in areas of low visibility.

## Research Plan

### *Research Partners*

OMSHR has working agreements with coal mine operators and state agencies to conduct research in mine emergency response. These collaborations have resulted in technology development and the successful development of reliable and respected methods for conducting mine rescue team simulations and smoke evacuation exercises (Bealko et al., 2010; Conti et al., 1999; Conti 2001). Two mine operators and a state agency allowed OMSHR to recruit miners from their workforce to participate in this research to evaluate devices that could assist miners navigating through dense smoke. Experience levels for the recruited miners ranged from less than a month to 43 years. The research was conducted at two separate test sites: an active underground coal mine in the western United States and the OMSHR Bruceton Experimental Mine (BEM) located in the eastern United States. A research protocol was approved by the Centers for Disease Control and Prevention (CDC) Human Subjects Review Board (HSRB).

To summarize the current approach to training its miners, Mine Operator A, located in the western United States, takes a pro-active approach in meeting the annual SCSR expectations training requirement. Underground coal miners are required to complete training that includes donning and transferring an SCSR in simulated theatrical smoke and breathing through a realistic training unit that provides the sensation of SCSR airflow resistance and heat as outlined in the U.S. Code of Federal Regulations, Title 30, Part 75, Section 75.1502 [30 CFR 2010]. In addition to the minimum requirements, this training involves miners navigating through 183 m (600 ft) of mine entry filled with theatrical smoke, encountering common underground objects and obstructions while wearing the SCSR training unit. This training not only familiarizes the miners with the feel of the SCSR, but allows them to gain experience in evacuating the underground mine should an actual fire or explosion occur. The goal is to build the skills and confidence of miners for navigating in a smoke-filled environment.

For this study, Mine Operator A gave OMSHR researchers access to an underground location to construct a test area for conducting the research on the navigational devices. As the miners completed the mandatory SCSR expectations training exercise, they were then assembled in an underground briefing room and asked to participate in the research program. Volunteers were given information on the research objective, the devices being evaluated, and the design of the test area.

Operator B is a state agency located in the eastern United States. Annual expectations training for this workforce is conducted at the BEM. Operator B consists of inspectors and related mining professionals. Prior to beginning their annual training exercise, the workforce was given information regarding the training exercise and the subsequent research effort to evaluate devices for possible use during evacuation of underground mines. Volunteers who agreed to participate in the research effort completed the mandatory expectations training in the BEM, and then traveled through the mine to a briefing room where they received information on the devices being evaluated and the design of the test area.

Mine Operator C, located in the eastern United States, conducts mine rescue and fire brigade training exercises at the OMSHR BEM. Prior to donning their mine rescue and fire brigade gear, miners were given information regarding the training exercise and the subsequent research effort to evaluate devices that could possibly be used to assist miners evacuating smoke-filled underground mine works. Volunteers who agreed to participate in the research completed their training exercise, removed their self-contained breathing apparatuses and fire fighting gear, and then assembled in the underground briefing room. At this location, the volunteers received information on the devices being evaluated and the design of the test area.

### *Theatrical Smoke*

For training purposes, theatrical fog machines have been successfully used to simulate smoke in underground mine works. Water-based fog dispersion is achieved by pumping a food grade glycol/water mixture through a heat exchanger. This vaporizes the fluid as it passes through the hot unit. The vaporization of the fluids forces the hot mixture through the output nozzle. When mixed with ambient air, the vapor forms an opaque aerosol, i.e. fog or "theatrical smoke" (herein referred to as smoke). To realistically simulate conditions that could be encountered during a mine fire or explosion, fog machines will maintain smoke density so that visibility is limited to approximately 0.4 m (15 in). For information on measuring and controlling smoke density, see Appendix A.

### *Evaluation Areas*

A preliminary full-scale test area was set up in the BEM to determine the overall logistics and anticipated travel times for miners. Information obtained during the test was used to develop the research protocol. Twenty-one OMSHR employees traveled through the smoke-filled test area in an average total time of 192 sec. Minimum travel time was 66 sec and maximum travel time was 510 sec. Based on the knowledge gained from this preliminary experiment, it was determined that most miners should be able to complete the course in less than 600 sec.

The two research test areas were designated as Evaluation Area 1 (EA1) and Evaluation Area 2 (EA2). EA1 was located in the underground workings of Mine Operator A. It consisted of a straight mine entry 6 m (20 ft) wide by 2.7 m (9 ft) high and 61 m (200 ft) long. Three 20-cm (8-in) diameter pipe lines were installed along the roof line adjacent to the left rib. Under ideal evaluation conditions, the pipes would not be in this entry; however, this was the only area available for the operator to conduct the training. Therefore, the decision was made to proceed with anticipation that the simulated smoke would mask the location of the pipes. The crosscuts within this area contained stopping walls, mine curtains, or barricades to prevent miners from traveling into adjacent entries. Rib spall was minimal. Check curtains at the inby and outby ends were used to contain the smoke in EA1. Smoke density was relatively consistent throughout this area and was maintained by monitoring the visibility at two locations using obscuration meters. A section of lifeline was installed in a manner consistent with practices at the operation, starting at the entrance to EA1 and extending a distance of 7.6 m (25 ft). The end of the lifeline inside EA1 was cut and draped to the floor to indicate that the lifeline was no longer useable.

Evaluation Area 2 (EA2) was located inside the BEM. The mine entry at this location was 6 m (20 ft) wide by 1.8 m (6 ft) high and 61 m (200 ft) long, with a concrete floor. Unlike EA1, this area did not contain common mine infrastructure such as water pipes, and miners were required to navigate from one entry to the adjacent entry though a connecting crosscut. All other crosscuts were blocked with mine curtains to prevent miners from traveling outside EA2. Smoke density was monitored by two obscuration meters. A lifeline was also installed in a similar fashion to that in EA1.

To minimize the impact on mine operations, miners were permitted to travel through the evaluation area only one time. Before entering an evaluation area, each miner was read a set of instructions and issued an identification number. As the miner entered the EA, an OMSHR researcher at the exit end of the EA was notified by two-way radio "Miner No. [xxx] is ready to enter the EA area with [type of device or control]". The OMSHR researcher at the exit end recorded on the data collection form the miner's number and the device being tested. Each device used in this research was also issued an identification number. Once this data was recorded, the OMSHR researcher at the exit would give the miner the signal to begin and would record the start time. Only one miner was permitted to travel through the EA at a time. Two OMSHR researchers were stationed within the EA to respond if miners needed assistance. A thermal-imaging camera was used to monitor the progress of the miners as they navigated through the smoke-filled environment.

Approximately 2% or seven of the 315 miners became disoriented and were not able to successfully navigate the entire course without the assistance of an OMSHR researcher. Three of these miners had less than one year of experience, two had 5 years of experience, and two had over 34 years of mining experience. Since some of these miners required assistance from the OMSHR researchers to evacuate the EA, the amount of time spent in the EA by those miners was not equivalent to that of miners who successfully navigated the EA on their own. Therefore, the data was recorded for these miners but not included in the research database. For all others, the OMSHR researcher recorded the time that the miner arrived at the end of the EA, verified the ID number, and collected the device. At this point, the miners were then provided an opportunity to write comments on the form regarding their experience with or without the device. The completed form was returned to an OMSHR researcher.

***Test Devices***

Three devices (Figure 1) were selected for the research project. The least complex device was a safety cane constructed from 19-mm diameter (¾-in) PVC rigid electrical conduit. The finished product weighed 400 g (14 oz). Strips of 25-mm-wide (1-in-wide) adhesive reflective tape were applied to make the device easier to locate in the smoke-filled entry in the event the cane was dropped by the miner. The purpose of the cane is to assist a person to locate the rib or floor in conditions of poor visibility [Galvin 2008]. Miners using the (device) were given ~ 3-5 minutes to become familiar with the device before entering the EA.

The second device was a handheld laser pointer. The unit is powered by two AAA batteries, has a 5 mW output, and an operating life exceeding 3 hr. The laser emits a green beam focused by a glass lens. The unit weighs 70 g (2.5 oz). Previous research conducted by OMSHR indicated that the green laser beam was able to penetrate deeper into the theatrical smoke compared to other tested colors [Conti et al., 2005]. Miners using the green laser were given ~3-5 minutes to practice before entering the EA.

The third device was the Miniguide Ultrasonic Mobility Aid herein referred to as a Miniguide, manufactured by GDP Research, Adelaide, Australia. This unit is a hand-held electronic sonar device designed to provide distance information to a visually impaired traveler supplementing information provided by other aids such as the long cane or guide dog. The device emits an ultrasonic sound, measures the time for the echo return, and provides tactual feedback by vibrating more rapidly as one approaches an object. The device can also provide sound feedback through an earphone, although this feature was not used in this evaluation. The device was previously tested by SIMTARS as a possible navigation aid for a driver of a mine escape vehicle to assist in maintaining the vehicle in the center of the entry in limited visibility conditions. Preliminary tests revealed that a more powerful fixed unit was required for the mine escape vehicle application [Harrison 2009].

The Miniguide weighs 60 g (2 oz). Two sensors, one for transmitting and one for receiving, are located at the front of the device. The sensors are circular in shape with a fine mesh covering. There is a single on/off switch located near the front of the Miniguide. The device has five range settings: 0.5-m (1.5-ft), 1-m (3-ft), 2-m (6.5-ft), 4-m (13-ft), and 8-m (26-ft). The setting selected by the user depends on the surroundings. A person using the Miniguide inside a home may require the device to vibrate when he or she is within 0.5 m (1.5 ft) of an object. When the device is used outdoors or in larger rooms, higher settings would be useful to locate landmarks at greater distances. For this research study, the 4-m (13-ft) setting was used on the Miniguide. This setting allowed miners to use the device to locate and maintain travel in the center of the mine entry or locate and walk parallel with the closest mine rib to maintain direction of travel. Miners using the Miniguide were given ~ 3-5 minutes to practice before entering the EA.

The Miniguide provides useful information regardless of smoke or dust density in the atmosphere. Bench tests were conducted on the Miniguide confirming that it functioned as well in dust as in glycol fog. The device depends on the operator having some degree of spatial perception which is the ability to perceive or otherwise react to the size, distance, or depth aspects of the environment. Normally, learning the many subtle nuances of spatial perception is a continuous self-oriented or individual learning process and extends over a long period of time [Kay 2004]. Introductory training on the use of the Miniguide is offered through organizations that specialize in rehabilitation of the visually impaired. As an example, the Seattle Lighthouse for the Blind offers a course designed to train individuals on the use the Miniguide [Johnson 2010]. The training is designed to provide the user with the basic operational skills. The user will gain proficiency by continuing to use the device on a routine basis. While training of this magnitude may not be required for using the device as an escape aid, it does indicate that some level of training and practice in a mine setting would be required for the user.

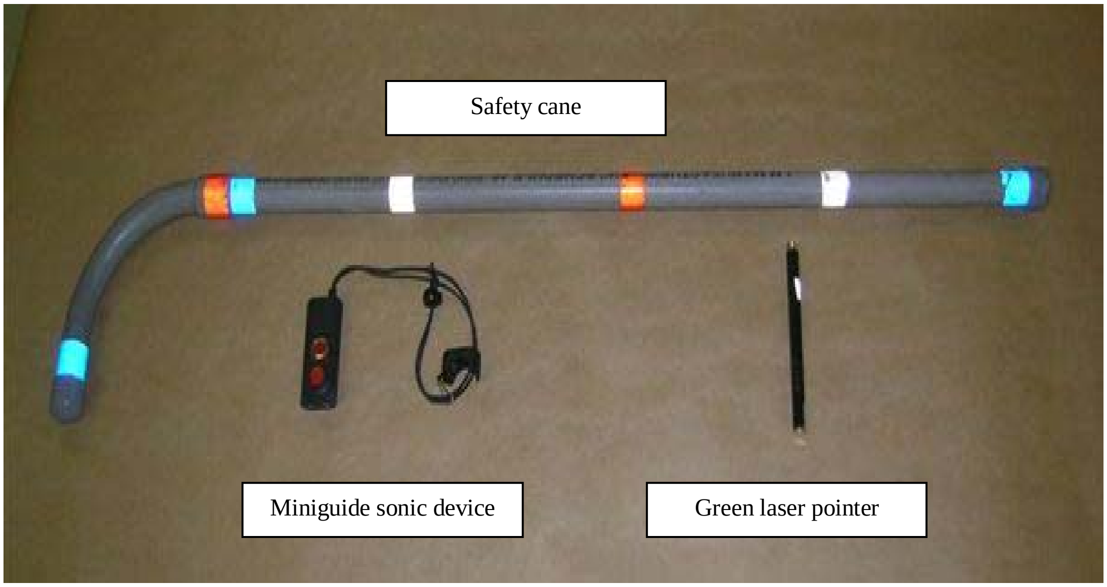


**Figure 1.** The three navigational devices evaluated to enhance miner self-escape in smoke-filled entries.

## Data Analysis

All study data was collected using a report form completed by the OMSHR researcher and the miner. The name of the miner was not recorded on the form. All information recorded on the report form was entered into a spreadsheet. Data inconsistencies, i.e. conflicting responses recorded on the forms by miners, were resolved before the spreadsheet was imported into statistical analysis software.

Initially, the data was analyzed to determine if the information for the two EA locations should be combined into one dataset or analyzed individually. Based on the average age, length of service at that operation or agency, and years of mining experience of the miners in the two groups, a determination was made that there were significant differences in the data sets. Therefore, the data for each EA location was analyzed separately (Table 1).

**Table 1.** Mean Values for Miners Based on Age, Length of Service, and Mining Experience

| Variable | EA1 | EA2 |
|---|---|---|
| Age, yrs | 34.4 ± 10.5 | 48.6 ± 12.5 |
| Length of Service, yrs | 5.1 ± 6.4 | 12.9 ± 10.8 |
| Mining Experience, yrs | 7.1 ± 9.7 | 22.4 ± 14.4 |

A one-way Analysis of Variance was performed for each EA dataset to determine if any of the selected devices provided the miners with sufficient information to reduce the time required to travel through the smoke-filled EA. The total time to navigate each EA was analyzed by dividing the data into four groups; i.e., one group for each of the three devices and one for the control group or group without a device. Although it was anticipated that at least one of the devices would expedite travel through the smoke-filled entry, the analysis in Table 2 indicates that the devices do not decrease average travel time. The analyzed data in Table 2 also indicates that a longer average travel time was required for EA2. This was expected due to the added navigation though an open crosscut between two entries. Transit time for the miners using the Miniguide is nearly the same as for the control group in EA1. However, in EA2, the transit time using the Miniguide is much longer than for the control group and by comparison to the other two devices.

**Table 2.** Mean Travel Times of Miners with Devices Compared to Those without Devices

| Device | EA1 | | EA2 | | Normalized Results | |
|---|---|---|---|---|---|---|
| | No. of Miners | Time sec | No. of Miners | Time sec | EA1 | EA2 |
| Control / No Device | 53 | 153 ± 37 | 16 | 168 ± 73 | 1.00 | 1.00 |
| Safety cane | 57 | 167 ± 68 | 19 | 207 ± 130 | 1.09 | 1.23 |
| Green laser | 69 | 178 ± 68 | 17 | 215 ± 95 | 1.16 | 1.28 |
| Miniguide | 62 | 154 ± 93 | 15 | 226 ± 92 | 1.01 | 1.35 |

The data questionnaire completed by the miners included Likert Scale statements pertaining to the use of the devices. Miners were asked to rate the statements in Table 3 on a scale of 1 to 4: 1 - strongly disagree, 2 - disagree, 3 - agree, and 4 - strongly agree. Table 3 lists the results obtained using a nonparametric Kruskal-Wallis test[1] to compare values among the devices.

**Table 3.** Mean Likert Scale Statement Responses

| Statement | Device Evaluated | | |
|---|---|---|---|
| | Safety cane | Green laser | Miniguide |
| The tool or device helped me in avoiding obstacles. | 3.2 | 2.8 | 3.0 |
| The tool or device prevented me from tripping. | 2.9 | 2.3 | 2.3 |
| The tool or device increased my confidence that I can get out quickly and safely. | 3.0 | 2.8 | 2.8 |
| I would routinely carry this device or tool. | 2.4 | 3.0 | 2.8 |
| I would like the mine to have an underground cache of the tool or device. | 2.9 | 3.0 | 2.9 |

## Discussion

The devices selected for investigation did provide miners with various degrees of information and confidence as they navigated through dense smoke in the EA. Miners primarily used the devices to maintain contact with the coal rib and to identify tripping hazards and items blocking their path as they navigated. However, despite generally positive opinions about the devices, none resulted in measureable improvements to travel times in smoke.

The safety cane is the least expensive device tested (~ $4 material cost). Miners found it simple to use and it received a higher rating in providing usable information to avoid obstacles and tripping hazards. A battery or power source is not required to operate the safety cane and the density of smoke or dust in the atmosphere does not impact its ability to provide information. However, the safety cane, as tested, would be cumbersome to routinely carry as identified by the comments provided by the miners. Commercially available fold-up safety canes would be more adaptable for miners to routinely carry. The cost of a fold-up safety cane is ~ $50. The safety cane is limited to providing information on objects or the surroundings within the physical reach of the device and the miner's outstretched arm ~ 2 m (80 in). The length of the safety cane could be increased but that could make it awkward to use. About 31% of the 53 miners navigating through EA1 without the assistance of any device experienced tripping incident(s). By comparison, of the 57 miners using the safety cane to aid navigation through EA1, 19% experienced tripping incident(s). Canes (walking sticks) are provided near caches of self-rescuers at some Australia mines to assist persons to locate the rib or floor by sound or touch as they walk through conditions of poor visibility [Galvin 2008]. Safety canes strategically stored underground, to be used in conjunction with the lifeline in an escape scenario, can aid the miner in locating tripping hazards, drop offs, or other obstacles in the escapeway that would not be visible in dense smoke.

The non-permissible, green laser pointer is able to project a fixed green dot on a solid object up to two miles away. At 30 m (100 ft), the laser produces a spot size of 36 mm (1.4 in) and is modestly priced at ~ $62. For use in areas with permissibility requirements, a more robust permissible laser pointer is available for ~ $900 per unit. Depending on the level of smoke or dust in the atmosphere, the green laser can provide information on objects or conditions at greater distances than the safety cane or Miniguide device. The unit is easily carried and equipped with a spring loaded on/off switch, requiring the operator to keep pressure on the switch for the laser to operate. Minimal instruction is needed to be proficient at using the device in smoky conditions. During testing, some miners swung the laser back and forth in 180-degree arcs to detect location of mine ribs or obstructions, while others kept the laser beam focused on the closest mine rib to maintain direction of travel. About 31% of the miners navigating through EA1 without the assistance of any device experienced tripping incident(s). By comparison, of the 69 miners using the laser to aid navigation through EA1, 30% experienced tripping incident(s). The effectiveness of the green laser beam is limited by the concentration of dust or smoke in the atmosphere. As smoke or dust levels increase, the beam is more visible, but its ability to penetrate the atmosphere decreases. Also, the laser may not be able to penetrate the atmosphere sufficiently to provide useful information in the heavy smoke- or dust-filled atmospheres that could be encountered by miners during a fire or explosion.

The non-permissible, battery-powered Miniguide is lightweight, compact, and allows the miner to locate items at a greater distance than the safety cane. The Miniguide is able to convey two important pieces of information to the operator: whether a solid object is located within a maximum radius of 8 m (26 ft), and whether the operator is getting closer or farther away based on the speed of the pulses. Miners in the EA1 commented that slowly moving

[1] Kruskal-Wallis test[1] is a non-parametric method for testing equality of population medians among groups.

the Miniguide in a horizontal arc back and forth between the coal ribs increased their ability to remain in the center of the mine entry as they navigated through the smoke. This can reduce tripping and falling hazards associated with walking through rib roll or spall. About 31% of the miners navigating through EA1 without the assistance of any device experienced tripping incident(s). By comparison, of the 62 miners using the Miniguide to aid navigation through EA1, 19% experienced tripping incident(s). The device requires the miner to focus some attention on the speed of the pulses to determine if the distance to an object is increasing, decreasing, or remaining constant. The unit has five selectable range settings up to 8 m (26 ft). However, the operating manual states that the device can only detect large objects such as solid fences or walls at 4 m (13 ft) or beyond. The device cannot detect drop-offs, such as curbs and low height objects, or objects that absorb the ultrasonic beam [GDP Research 2010]. The cost of a non-permissible unit is ~ $370. The costs to design, manufacture, and obtain permissibility approval would substantially increase the cost of the Miniguide.

It should be noted that the three devices tested are not capable of providing directional information to the user as to the proper travel route out of the mine. This kind of directional information is critical to self-escape. However, as the test results show, the use of any one of the three devices has the potential to aid in the navigation of miners traveling though familiar areas while in dense smoke or dust as long as the miners can locate known landmarks, lifelines, or similar directional information. While traveling in unfamiliar areas, miners using these devices in dense smoke or dust will not greatly increase their chance of successful navigation due to the lack of known landmarks to provide directional information.

## Conclusion

Once the decision is made to evacuate, miners must choose a direction of travel and navigate the chosen pathway to escape the underground mine works. If miners are able to find their way to an intact lifeline system, the escape pathway should be as simple as following the lifeline to the surface. However, if miners have to travel though dense smoke, dust, or some other condition that severely limits visibility without the assistance of a lifeline system, disorientation can occur quickly because common mine features normally used to determine location and direction are no longer visible.

OMSHR researchers identified three devices that could provide miners with useful navigational information when traveling through areas with limited visibility created by smoke or dust. The simplest device was a safety cane which could assist miners to locate the rib and floor by sound or touch. The second device was a hand-held laser pointer which emits a green beam focused by a glass lens. The third device was the Miniguide which is designed to provide distance information to a visually impaired traveler supplementing information provided by other aids such as the long cane or guide dog.

To evaluate the devices, test areas were set up in two underground mines. Miners were given an introduction to each device and were asked to use one of the three devices to navigate through a smoke-filled mine entry 61 m (200 ft) long. Following this, participating miners were asked to fill out a questionnaire about their experience using the device and the assistance it provided.

The devices selected for investigation did provide miners with various degrees of information and confidence as they navigated through dense smoke, but none resulted in measureable improvements to travel times in smoke. The safety cane was the least expensive device tested and miners found it simple to use, but it would be cumbersome to routinely carry and is limited to providing information on objects or the surroundings within the physical reach of the device. Safety canes strategically stored underground, to be used in conjunction with the lifeline in an escape scenario, could aid the miner in locating tripping hazards, drop-offs, or other obstacles in the escapeway that would not be visible in dense smoke.

The green laser pointer was easily carried, modestly priced, and required minimal instruction for its use. The laser can provide information on objects at greater distances than the safety cane or Miniguide. However, as smoke or dust levels increase, the ability of the laser to penetrate the atmosphere decreases.

The Miniguide is lightweight, compact, and allows the miner to locate items at a greater distance than the safety cane. The Miniguide is able to convey two important pieces of information to the operator, whether a solid object is located within a maximum radius of 8 m (26 ft) and if the operator is getting closer or farther away from an object based on the speed of the pulses. The device requires the miner to focus some attention on the speed of the pulses to determine if the distance to an object is increasing, decreasing, or remaining constant. The device can only detect large objects such as solid fences or walls at 4 m (13 ft) or beyond and cannot detect drop-offs, such as curbs and low height objects.

In very dense smoke or dust, the safety cane and the Miniguide can assist the evacuating miner in locating landmarks within the mine that convey directional information. However, the amount of directional information conveyed by the landmark is dependent on the miner’s knowledge of the mine design and the location of the landmark within the mine. The requirement to install lifelines in emergency escapeways gives miners a directional guide to help them navigate from the section through smoke- and dust-filled mine entries to the surface in the event of a fire or explosion.

Miners had the most favorable opinion of the safety cane for providing assistance in escape, though they would not want to carry one routinely. Reported incidents of tripping were reduced by 39% when using either the safety cane or the Miniguide compared to no device. The safety cane provided in underground caches, in conjunction with the lifeline, can aid miners in locating tripping hazards, drop-offs, or other obstacles in the escapeway that would not be visible in dense smoke.

Although all of the devices tested provide some level of information to the user, none of the devices have the capability of providing location or directional information. Data indicates that the Miniguide can be effective in locating tripping hazards; however, the data also indicates that the Miniguide did not significantly improve travel times in smoke. Therefore, further evaluation or technical development of the Miniguide for use in coal mines is not warranted. Instead, what should be pursued is the development of a true navigational device or interactive tracking system that can properly orient escaping miners in smoke-filled entries and then guide them to safety.

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14. U.S. Congress, 1977, Coal Mine Safety and Health Act of 1977, Public Law 109-236, Section 316.

## Appendix A: Description of procedure used to measure and control smoke density

Before conducting the research in this study, it was necessary to determine the required density of non-toxic fog or smoke to simulate the desired environment. Tests were conducted using a fog machine (LeMaitre G3000[2]) placed in a closed room 6.4 m (21 ft) long, 2.1 m (7 ft) high, and 2.3 m (7.5 ft) wide. The fog machine was operated until the desired smoke density was obtained based on visual observations. Electric fans were used to ensure complete mixing of the smoke into the atmosphere. The goal was to generate a smoke density that would limit visibility to approximately 0.4 m (15 in). To measure optical obscuration, an obscuration meter was constructed which consisted of a laser source and a photovoltaic cell separated by a distance of 1 m (39 in). The laser and photo cell were supported in a rigid frame constructed from 10-cm (4-in) diameter polyvinyl chloride (PVC) pipe with diametrically opposed openings spaced along the length of the pipe. The location of these openings permitted the smoke-filled atmosphere to cross the optical path.

The obscuration meter was located at nine positions in the room with voltage readings recorded for each position to calculate the average obscuration in the room. The amount of fog fluid used to create the required atmosphere was determined by placing fog fluid in a graduated cylinder and recording the levels before and after the test. Atmospheres containing between 600 and 750 $mg/m^3$ (0.0006 and 0.00075 $oz/ft^3$) total glycols would adequately simulate dense smoke that a miner could encounter in the event of a mine fire or explosion. At these densities, the obscuration meter output voltage ranged from 3.6 v to 4.0 v. To maintain a consistent atmosphere underground, a programmable logic controller monitored the output voltage of the obscuration meter and activated the fog machine when the obscuration meter output voltage exceeded 4.0 v. The fog machine continued to operate until the obscuration meter output voltage dropped to 3.6 v.

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