Technologies for today's mine emergency responders

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Abstract: Historically, underground mine rescue teams have only received training in the course of actual emergencies, or in simulated mine environments, usually on the surface, with placards to identify objects and hazards. Also, while US Federal Regulations require all underground miners to walk escapeways and conduct fire drills every 90 days in a smoke-free environment, this does not fully prepare them for the conditions that will be encountered in real escape situations. This paper describes technology and realistic training simulations that have been identified for the general workforce and mine emergency responders. Of all the technology evaluated by underground personnel, laser lights and lifelines were most beneficial in leading personnel to safety and out of the mine in smoke-filled passageways. These technological advancements can improve the state of readiness for rescue personnel and increase the chances of survival for personnel escaping from underground emergencies.

Keywords: Emergency response; underground smoke training; mine rescue simulations; response technology.

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1 Introduction

Mine rescue teams are often called upon to save lives during an underground emergency such as a fire, explosion, roof fall, or water inundation. It is extremely important that team members are provided with adequate exploration and recovery equipment and be properly trained in the use of that equipment. Cooperative agreements were established between the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (PRL) and state agencies and several mining companies to increase the operational effectiveness of mine rescue teams for coal and metal/non-metal mines and to evaluate new and emerging technology for emergency responders. Over the past several years, NIOSH has developed, conducted and evaluated mine rescue training simulations, in-mine smoke training exercises, and mine emergency response drills (MERD) at its Lake Lynn Laboratory (LLL) near Fairchance, PA and at operating mines. These training simulations allowed rescue personnel to train under realistic conditions and focused on fire fighting, ventilation, searching for 'victims', mapping, etc. For example, in one area of the LLL mine, a kerosene heater was used to simulate a fire and reduce the oxygen concentrate to 18%. In another area, a 1.5% methane zone was established. Handheld sensors carried by the rescue team members alarmed when they entered these areas, alerting them to the 'hazardous' condition [1,2].

This paper is structured to emphasise the importance of early warning to alert all underground personnel of an emergency event and looks at devices that may assist personnel during their escape from smoke-filled passageways. The various technological devices used by the emergency responders during the training simulations are discussed. It also focuses on technology that can assist responders during exploration and recovery operations. For example, identifying personnel and materials in smoke, vision enhancement (seeing through the smoke) and effective communications.

These research efforts have resulted in improved disaster recovery training drills for mine rescue teams, fire brigades, first responders, and miners in general and the development of new technology such as new team lifelines and inflatable devices for fire suppression and personnel escape [3–5]. Existing technologies were identified to help responders during exploration and recovery operations. These included various chemical lightshapes, strobe lights, light vests, and laser pointers to identify team members. Most of these devices may be used to mark underground areas and certain mine materials. Also, strobe lights were used for mapping out escapeways and lasers were used to negotiate travel through smoke. Thermal imaging systems allow rescue personnel to see in darkness and through dense smoke and easily locate missing or trapped personnel and heated areas. A hands-free communication system showed potential for enhanced communications between team members, the fresh air base, and command centre.

The NIOSH, PRL's LLL, formerly a limestone mine, is now a multipurpose research facility used to conduct mining safety and health research [6]. The new entry dimensions of the underground mine range from 1.8 to 2.4m high and from 5.3 to 6.3m wide. The average dimensions are 2.1 and 5.8m, for an average cross-sectional area of $12m^2$. The underground configuration of the new entries covers approximately $95km^2$, with an overburden ranging from 50 to 100m. The unique nature of the facility allows it to be readily adapted for elaborate training simulations in smoke-filled entries for emergency responders.

2 Through-the-earth signalling and communications

It is imperative during an underground emergency that all personnel, no matter where their location is, can be notified of the event. The LLL has installed such a device, a wireless signalling system that transmits an emergency warning, which can quickly reach every underground miner. The low-frequency electromagnetic field can penetrate kilometres of soil and rock to reach the most remote shaft or tunnel, which makes it ideal for underground signalling and paging. This system consists of a low-frequency transmitter that can be strategically placed to create an electromagnetic signal that can completely envelop most mines without the use of repeater systems. The transmitter loop antenna is on the surface, and a receiver/transmitter loop antenna is underground. The person-wearable receivers are small, lightweight modules incorporated into the miner's caplamp assembly. Upon receiving an emergency or paging signal, the caplamp begins to flash, which in turn alerts the miner to evacuate the mine or call the surface for a message, depending on which signal is received. The system can also turn devices such as strobe lights on or off. Additional information on wireless signalling systems and medium frequency radio communication systems for mine rescue can be found in [7,8].

A successful evacuation of miners during the Willow Creek mine fire, that occurred in Helper, Utah, on November 25, 1998, was attributed to a similar system, the Personal Emergency Device (PED) [9,10]. This system displays a message on a LCD display after the caplamp flashes. The paging system was activated when one miner saw flames and telephoned the dispatcher to evacuate the mine. The PED system allowed a mine-evacuation plan to be safely carried out before the mine passageways filled with smoke. All underground miners escaped in approximately 30 minutes.

There are currently 17 PED systems installed in US coal mines and one in a metal/non-metal mine.

3 Identifying team members

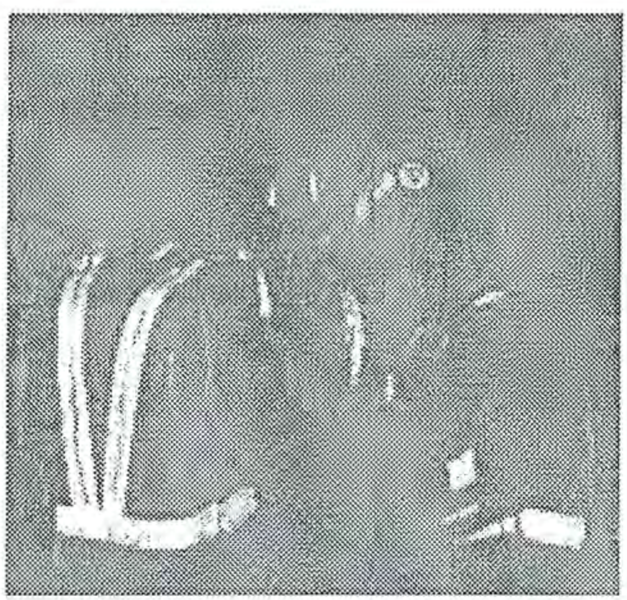
NIOSH attempted to address several issues raised by rescue team members that participated in the simulations. One of the main concerns of the rescue teams was identifying other team members and marking locations, such as crosscuts, brattice curtain, cribbing, and other items that may be found in the smoke-filled entries, or just maintaining a reference point. Chemical lightshapes (lightstick, lightrope and lightdisc), a technology that has been around for years, were found to be a valuable tool for underground rescue teams. The lightshapes are non-flammable and not a source of ignition, and they are weatherproof, maintenance free, and non-toxic. Infrared (IR) lightsticks are also available. To activate, just remove a lightshape from the package, bend, snap, and shake. Instantly, a source of light exists that can vary in intensity and duration. The brightest lightstick lasts five minutes; the least brightest, 12 hours. Team members assessed the cylindrical lightsticks during the simulations, both in white non-toxic smoke and black toxic smoke produced from conveyor-belt fires. Four lightstick colours were evaluated; clear, green, red, and yellow. Team members attached these lightsticks to the back of their helmets with plastic ties. They can be also placed on the floor at various critical locations and on obstacles during exploration or may be used to mark supplies and materials. Of 403 members participating in the white non-toxic smoke training simulations, 80% identified green as the most dominant colour seen, 9% identified red, 7% yellow, and clear was the least visible colour. Out of the 90 rescue team members that participated in fighting the conveyor-belt fire, 85.4% felt that green was the most dominant colour; red was the least visible colour. Team members also evaluated other lightshapes. Lightropes were mounted on the back and around the brim of the helmet, and chemical circular lightdiscs were mounted on the back of the self-contained breathing-apparatuses (SCBAs). The lightdisc was helpful; however, the lightrope was found to be ineffective. Lightsticks are now a crucial component for these team members. Other chemical lightshapes and intensities are currently being considered.

In other smoke training exercises, the lightstick was effectively used to negotiate travel through a smoke-filled passageway. The participants turned off their caplamp and held a green lightstick out in front of them, about waist high.

3.1 Light vest

Personnel working around moving equipment in low light areas are always placed at risk due to their poor visibility to the operator. The light vest is a new technology, developed by LiveWire Enterprises, Inc., that uses a blue/green electro-luminescent fibre and a 0.5mm copper wire coated with a semiconductor material. It is safe, non-toxic, flexible, impact and water resistant, portable and produces no heat. An AC or DC power source is used depending upon its application and/or length; and current consumption may be as low as 0.3 mA/m. For example, two AA batteries could power the vest for over 24 hours. The light vests, shown in Figure 1, were modified with Velcro straps to wrap around a mine rescue member, including their SCBA, for 360^0 visibility. Team members felt that it was much easier to see other team members, who were wearing the light vest, in darkness and in smoky entries. Several mines are also considering the use of light vests for personnel working around moving machinery.

Figure 1 Light vest



3.2 *Strobe lights*

Another area examined was utilising high-intensity strobe lights (xenon-white flash tube) strategically located in the entries to map out an escape route for evacuating miners during an emergency. These weather resistant strobe lights, with interchangeable reflective lenses, are compact and lightweight (100 gm) and provide visibility of 180°. The triangular shaped (9 cm each side by 4 cm high), lithium AA battery powered strobe lights could be remotely activated by a wireless through-the-earth signalling system such as the one installed at LLL. Ideally, underground sensors would monitor the gases and smoke in the passageways during a fire. By interfacing these data with a computer, the best escape route could be determined and the appropriate strobe lights remotely turned on.

During the in-mine rescue team simulations conducted at LLL, strobe lights were positioned in the centre of the entry about 1.8m from the floor and in the entry crosscuts predetermined to be the best escape routes. The strobe lights were activated by the wireless, through-the-earth signalling system. Rescue team members were told that a roof fall had occurred and severed the main communication/lifeline. Team members detached themselves from the main communication/lifeline and successfully followed the strobe lights out of the smoke-filled entries to the fresh air base. Team members felt that by keeping their caplamps off, the strobe lights were easier to follow. Two hundred and seventy-one miners evaluated five strobe light colours (red, green, blue, amber, and clear) during the simulations. The most visible colour in the non-toxic white smoke was green and the least visible colour was amber.

A similar simulation was conducted for underground mine personnel in a Western mine. Miners, in groups of five, entered smoke-filled (non-toxic white smoke) passageways and followed strobe lights to the fresh air base. Not only did this exercise allow miners to travel through smoke in their mine (many for the very first time), but also it gave them an opportunity to evaluate the strobe lights as an escape aid. Miners felt that placement of strobe lights at decision points was quite helpful and interfacing these devices with an audio output would enhance the use of strobe lights for mapping escapeways. The miners felt that the coloured reflectors currently mounted in the centre of their entries would not have helped them.

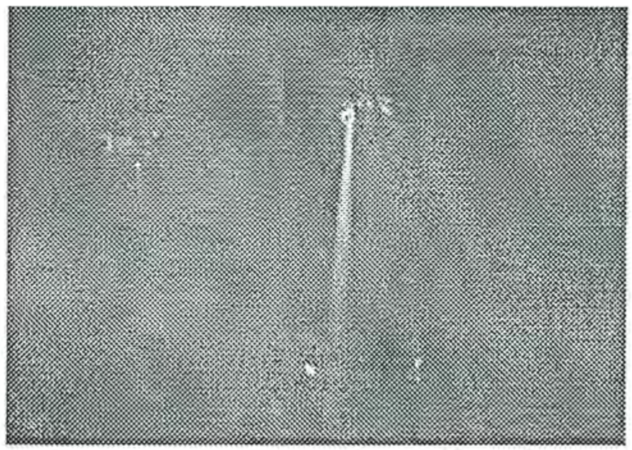
The concept of strobe lights to identify escapeways and marking mine obstacles was successful in experiments at the Lake Lynn Mine and several isolated passageways of a Western mine. In a larger mine, the uncertainties inherent in a complex ventilation system would complicate this process considerably. Additional research would be required to evaluate the feasibility of using these devices in larger mines and incorporating audio output with each strobe light unit.

3.3 *Laser pointers*

Commercial laser pointers are compact, lightweight, affordable, and have high quality beams. They utilise laser diode technology and several of these handheld battery powered pointers have ranges of up to 732m. Rescue team members evaluated two class IIIa laser pointers, red and green. The red laser pointer, with a wavelength of 645 nm and output power of 3-5 mW, can operate continuously for 8 hours. The green laser pointer, with a wavelength of 532 nm and an output power of 1-3 mW, can operate continuously for 2-3 hours. The green wavelength appears brightest to the eye, so a high power is not required. Beam diameters are less than 1mm.

These pointers, shown in Figure 2, are mounted to their caplamps with modified hose clamps. The momentary on/off switch is modified to stay on. The team captain is fitted with the green laser and the tailperson with the red laser. The laser beams were highly effective in the smoke-filled entries, allowing team members to easily determine the location of the captain and tailperson and to stay in better alignment across the entry during exploration.

Figure 2 Laser pointer



During other smoke training exercises, the laser pointer was effectively used to negotiate travel through a smoke-filled passageway. Approximately 25 participants during each exercise travelled 300m in a non-toxic smoke-filled entry, using a lifeline to lead them to fresh air. Visibility ranged from 0.3 to 0.9m and there were no tripping hazards in the entry. Two to three participants entered the smoky entry at 40 to 60-sec intervals, until all participants were headed toward the fresh air base. Another participant followed this group with only the laser pointer to direct them to the other end (no lifeline) and with their caplamp turned off. The beam of the laser pointer was continuously moved up and down and left to right. When the beam hit the rib, roof, floor, or other participants, a spot was seen. The participant with the laser reached the fresh air base at the same time as the first participant who entered the smoke. The concept of laser pointers was successful in experiments at the LLL and an operating mine. Additional research would be required to evaluate the feasibility of using a higher power lasers to identify escape routes in smoke-filled entries or surface structures.

3.4 Caplamp filters

Everyone realises the problem encountered while driving an automobile in foggy conditions at night with high beam headlights on. The same problem is experienced in smoke-filled passageways both by miners attempting to escape and also by rescue personnel. During several training simulations in non-toxic smoke, a coloured lens filter was placed over the caplamps of 121 miners in an attempt to reduce the glare from the white light reflecting off the smoke particles. The colour filters that were evaluated included green, blue, orange, and red. Green was the most visible colour seen by 38% of the miners. Seventy-one percent of the miners felt the lens filters were useful in reducing the glare from the white light and beneficial in travelling through smoke. It has also been suggested that a miner's caplamp can be taken off the helmet and held about waist high to negotiate travel through smoke.

3.5 Lifelines

When emergency personnel are searching for missing personnel or exploring a hazardous smoke-filled environment in underground mines, rescue team members are attached to a team lifeline or linkline. This team lifeline is then connected to the main communication/lifeline that extends from the area that needs to be explored to the fresh air base. Usually, five team members are fixed along an 8.5m length of rope at various distances between the captain (lead person) and tail-person. Team members have reported that if one person were to trip and fall, other team members would be pulled down with the falling team member. If the rope became entangled around obstacles, finding it was difficult.

These concerns were solved by the development of a lighted team lifeline [11]. Four different coloured flexible light wires (Live Wire technology, 0.5mm copper wire coated with semiconductor material) connected in series, pass through a 6.4mm diameter hollow-single braided polypropylene rope (336 kg tensile strength). The light wires extend 0–2.1m (blue), 2.1–4.3m (orange), 4.3–6.4m (green), and 6.4–8.5m (red), respectively, from the captain's position toward the tailperson's position and has 360-degree visibility. The light wire is battery powered and will last a minimum of four hours. The entire length of the braided rope is sheathed with clear polyvinyl chloride tubing. Double-locking snaps and D-shaped carabineers are attached to both ends of the rope for the captain and tailperson, with three moveable snaps and carabineers in-between both ends for the remaining team members. Team members attach the carabineers to their mine belt and have freedom of movement to slide between the captain and tail-person, providing flexibility of motion to do activities such as carry supplies, erect temporary ventilation controls and construct roof supports. This also alleviates tripping and falling problems. The different coloured light wires allow the team members to easily find their usual position along the lifeline when exploring in darkness and smoke-filled passageways.

In an earlier version of a high-visibility team lifeline, a rope with filaments made of reflective material braided directly into the sheath is used. The reflective filaments, based on glass-bead technology, generate a return more than 1,000 times brighter than plain, white rope. Team members attach to the line with the carabineers as previously described. This lifeline requires some light so that the reflective material can be seen.

Typically, during exploration at underground intersections in smoky conditions, the tailperson is anchored to a corner of a crosscut, while the team members explore the intersection and the captain locates the opposite corner. Most of the time, the team is restricted by the length of the 8.5m linkline, and would swing back around to the tailperson, missing the opposite corner and causing great delays. During the training simulation, two of the rescue teams evaluated the use of a retractable line (6.1m in length) in addition to the linkline. This new concept greatly reduced the time that team members explored the intersection, because the captain is able to add extra length to the linkline during exploration in intersections.

A few underground mines use a continuous lifeline for escape purposes. This lifeline or rope would most likely be secured to the rib or roof of the mine starting at the working section and leading to the exiting portal. Depending on the configuration of the mine, the lifeline could be many kilometres in length. One manufacturer developed a directional lifeline. It consists of standard spools containing 91m of 0.64-cm polypropylene rope with directional (cone-shaped) orange indicators with green reflective tape installed at every 23m interval. Due to the complexity of mine entries that contain crosscuts, mandoors, overcasts, etc., it is suggested that two directional indicators be mounted together on the lifeline approximately 2 to 3m from a mandoor, etc. This procedure would alert personnel escaping in smoke-filled entries that an obstacle of some sort is nearby.

4 Communications

Communication is a major issue and concern of rescue teams. Team members are often unable to hear other members, and at times the communication signal to the fresh air base is also faulty. This can be very frustrating to team members, especially in high stress situations.

The sound powered communication/lifeline system, developed in 1946 by the former US Bureau of Mines, is the most typical system in use today. Although this type of system tends to be reliable, it does have problems. It requires the use of large cable reels (304m of cable) and the communication usually gets scrambled as the electrical contacts in the cable reel wear. Also, good electrical connection to and along the lifeline cable is necessary. The current practice is that the tailperson, who has the earphones and microphone, talks to the fresh air base.

To address the communication concerns of mine rescue teams, the voiceducer two-way communication device was evaluated at LLL. The voiceducer, combined with a two-way radio, provides hands free two-way communications from a small device worn in the ear. Although it looks like an ordinary earphone, the earpiece contains both an accelerometer microphone and miniature receiver component. The ear microphone detects speech-induced bone vibrations via direct contact with the ear canal wall. The miniature earpiece leaves the hands free and face unobscured when worn by rescue personnel with breathing apparatus. When in high ambient noise, suitable earmuffs can be worn. The user consequently is afforded a much greater degree of freedom than has previously been possible with two-way radios.

At LLL, a radiating transmission line, base station and repeater system along with two-way radios are used for daily communications between employees. The in-mine transmission line leaks a controlled amount of radio frequency energy over its full length so that two-way radio communication can be maintained for a considerable distance through the mine passageways and to the surface. Experiments with rescue teams at LLL indicated this system and the voiceducer showed potential. Both the captain and tailperson could communicate with the fresh air base. However, the earpiece slipped out of the ear canal at times and background noise was also a problem.

Additional research efforts could include inserting a wire antenna into the main line that extends from the fresh air base or wrapping the main communication line with a wire antenna. The latter example could serve as a back-up communications system. During exploration, team members would have the antenna with them and can use the voiceducer. By having several channels on the radios, communications between team members or the fresh air base can be controlled.

Another new concept which will be evaluated by rescue teams is the head-contact microphone [12]. It is a hands-free radio microphone that can either be strapped onto the forehead or incorporated into a helmet headband. A rescue member need not speak into this microphone; it gathers sounds from vibrations transmitted through the skull and works whether the rescue member is wearing an SCBA or not. The microphone picks up little background noise, so rescue members need not shout. Ear speakers are suspended on the helmet and a gloved hand can easily activate the system by touching a sensitive on/off switch.

The m-Comm communications system, developed in the UK [13] was also evaluated with mine rescue teams at LLL. The m-Comm system is intrinsically safe and designed specifically for confined space and rescue applications. This system employs advanced low frequency (single wire) guide propagation techniques to achieve flexibility and dependability. The system consists of three handsets, a portable base unit, a dispenser reel holder, and lightweight guide wire that are available in various sizes. The guide wire is payed out on entering a confined space. A button on the clip-on handset is pressed to talk. The handsets receive and transmit from any point along the guide wire. It has a range of 8km and the guide wire could be deployed from the fresh air base (FAB) to the surface command centre, so that everyone can hear the whole story simultaneously. This would eliminate repeating messages and everyone would be ready for decision making.

Experiments with mine rescue teams indicated exceptional quality of speech when one handset was used at distances of 300m. However, when three handsets were used within the 8.5m length of a rescue team, quality and reception degraded. The small size guide wire easily tangled, frayed, and broke when used as intended. The same occurred when the guide wire was taped to the main team lifeline. For all practical purposes, the small guide wire cannot replace the present lifeline for US coal mine rescue teams. Perhaps a guide wire with a higher tensile strength like stainless steel or other material could be used. Additional research is being conducted to see if the wiring from the current sound powered communication/lifeline system can be used for this system. Other emergency rescue personnel can still use the present system in its current design.

5 Vision enhancement

Fire fighting and similar emergency response activities often impair vision due to dense smoke or darkness. Vision enhancement in such circumstances is a profound benefit for completing the assigned task. Infrared (IR) thermal imaging enhances the user's vision when visible light is inadequate. Thermal imaging both restores vision and also provides significant additional information to the user that would otherwise be impossible to obtain. This technology increases the responder's understanding of the environment, thus enhancing safety and the ability to accomplish the task. The first documented civilian life saved with thermal imaging technology occurred during a 1988 fire in New York City.

Recent improvements in the sensitivity and resolution of uncooled IR imaging sensors have provided the major enabling technology for the development of a practical helmet-mounted IR vision system [14]. In 1995, Cairns & Brother Inc. introduced the first commercially available hands-free helmet-mounted IR imaging systems [15]. Firefighters can use the Cairns IRIS to see through dense smoke and darkness in structural fires allowing 'size-up' of the situation to be faster and more effective. The system processes the signal and displays a black and white image that shows the hottest areas as white, the coldest as black and the temperatures between as varying shades of grey. It can detect 0.3^0C differences in temperatures. The sensor is a specially coated 15mm Germanium lens that filters out everything except 8 to 14-micron infrared radiation. The helmet-mounted IR imaging system weighs 4.8 kg. A rechargeable nickel cadmium battery pack provides 30 minutes of continuous, uninterrupted use at ambient temperature.

The first demonstration of the Cairns IRIS in an underground mine was conducted at Lake Lynn Laboratory on 8 February 1996. The capabilities of the hands-free thermal imaging camera in the smoke-filled mine passageways suggested that it indeed had merit for reducing the time required for mine rescue exploration. However, the simulations suggested that new protocols need to be developed when mine rescue teams explore with these IR devices, because the team member with the thermal imaging camera can travel smoke-filled entries much more rapidly than other team members. A drawback of the Cairns IRIS is the weight of the helmet-mounted system. Due to its weight, the system cannot easily be passed on to other team members and could not be used in low coal mine seams. Cairns IRIS recently introduced the Cairns-Viper, a lightweight hand-held thermal imager and video transmitter. It offers superior image quality, and the innovative, 180^0 rotating display provides comfortable viewing from any position. It enables the user to see from 0.9m to infinity. The camera uses intelligent colour to help locate the seat of the fire more quickly. Burning solid materials radiating energy greater than 480^0C is displayed in red and slightly less radiant objects or gases are displayed in shades of yellow.

The Agema 550 System is a high-performance handheld IR camera. It has digital voice recordings, colour images, and storage capabilities. The spectral range is 3.6 to 5.0-microns and weighs 2 kg. It can easily be passed on to other team members or a small display can be added to the camera for all team members to view. The major advantage is that the images, shown in Figure 3, can be downloaded to a computer for analysis or interfaced directly to a monitor for debriefing at the command centre.

A Flir System called FireFLIR, is used in conjunction with SCBA's and is easily attached to the underside brim of most standard firefighting helmets for hands-free operations. It is a completely self-contained viewing apparatus with no external cables or components to catch or to impair movement. The spectral range is 8 to14-microns. The device weighs less than 2 kg and images can be viewed in either black and white or colour. Advanced optics and display offer natural depth perception and orientation. It is also designed to easily view either the IR or the visual viewing modes. The FireFLIR is quickly and easily handed off to other team members.

Figure 3 A thermal image of a rescue team in dense smoke after building a roof support

The Argus Thermal Imaging Camera (TIC) can also see through smoke and darkness. It is ergonomically designed for comfort and utility, is handheld, and has an angled viewfinder. Moreover, the TIC accommodates a variety of users' positions from standing to lying prone. In low coal exploration, the innovative design reduces potential neck strain and, when used in a stooping position, helps to prevent the back of the helmet from hitting the SCBA, which can occur with the helmet-mounted version. It can easily be passed on to other team members for viewing the thermal image.

Seeing through infrared cameras is different than with natural vision. IR images are thermal interpretations of objects and those interpretations do not appear the same as the objects appear when you look at them with the naked eye. It is imperative that personnel using these devices be properly trained.

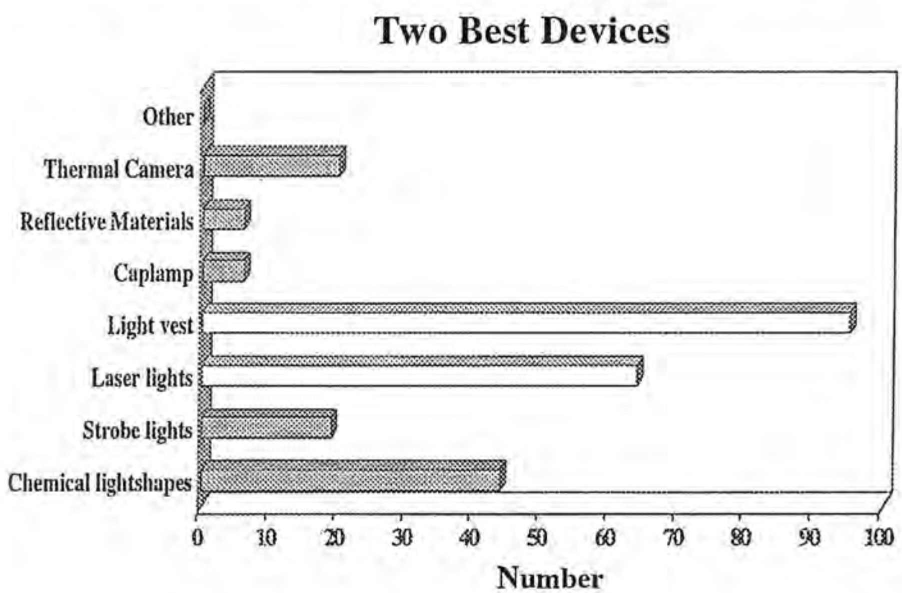
6 Underground smoke training exercise

To better prepare miners to escape from underground smoke-filled environments a series of smoke training exercises were developed and evaluated by NIOSH. The objectives of the exercise were to evaluate present escape methods, existing technology, and new technology that could be used for escape purposes, while still giving the miners an opportunity to travel through smoke-filled entries at their mine. At the end of each training segment, miners completed a questionnaire, which included both forced-choice and open-ended questions, such as demographics (age, mining experience, special training, etc), anxiety levels, usefulness of the exercise and technology, most visible colours seen in smoke and underground firefighting experience.

One hundred twenty-seven miners participated in a smoke training exercise in a Western underground coal mine. The average age of the participant was 37.3 years and average number of mining experience years was 12.5. Miners in groups of five traversed more than 300m of mine passageways filled with non-toxic smoke. Visibility ranged from 0.5 to 3m. The various devices were mounted on the roof in the centre of the entry, placed on the floor or secured to the rib. Of all the devices (chemical lightshapes, strobe lights, laser lights, light vests, caplamp, reflective materials, thermal camera, lifeline, other) evaluated in the non-toxic smoke, green was the most visible colour seen by most of the miners.

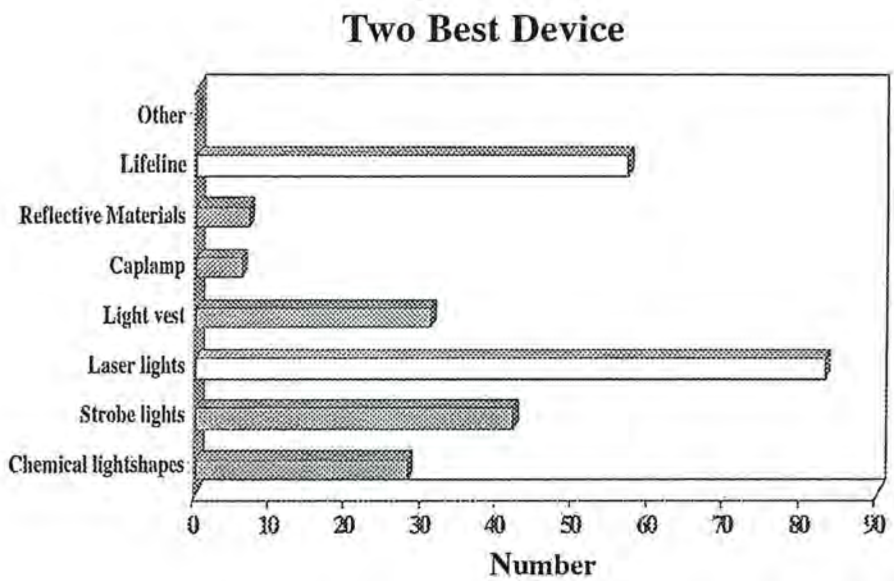
Figure 4 show the responses of the miners for the two most beneficial devices for identifying other people in smoky passageways. The two devices are light vests and lasers. These miners also felt that the lasers and lifelines, responses shown in Figure 5, were most beneficial in leading you to safety and/or out of the mine. Some of the miners were concerned about the durability of lifelines during fires, explosions, and roof falls. When asked about their views on thermal imaging cameras or see-through-smoke devices, they felt that this technology would not apply to escape. This was mainly due to the cost of thermal imaging cameras. However, they realised the importance of using this technology for rescue and recovery operations and felt that every mine rescue team or fire brigade should have access to one. Fifty-six percent of the miners that participated in the training reported that they have travelled through smoke at some time in their mining career.

Figure 4 Most beneficial devices for identifying other personnel in smoky passageways



One of the strong points of the underground smoke training exercise was that miners felt they were better prepared for a real life situation. It gave them a first hand look at what they could be up against by training in non-toxic smoke. They also felt that it gave them a unique opportunity to evaluate devices that can help them navigate through smoke-filled environments.

Figure 5 Most beneficial devices for leading personnel to safety and/or out of the mine in smoke



7 Inflatable devices

When mine fires can no longer be fought directly due to heat, smoke or hazardous roof conditions, high expansion foam (HEF) may be one way to remotely quench the fire. The firefighters and HEF generator can be located away from the immediate vicinity of the fire at a less hazardous underground location. The HEF is a convenient means of conveying water to a fire. It quenches or extinguishes a fire by diluting the oxygen concentration through the production of steam, blocking the air currents to the fire, and blocking the radiant energy from the fuel to other combustibles [16–18].

To effectively use the foam method for remotely fighting fires in underground mine entries, it is often necessary to construct, at some distance from the fire site, a partition or stopping in fresh air to separate the foam generator and its operators from the smoke and toxic fire products. If this is not done, the HEF could flow back over the foam generator, rendering the fire attack futile. This problem is especially acute when the fire is found uphill in a sloping entry. Concrete block, wood, plastic sheeting, mine brattice cloth, or similar materials have been used for such partitions. Often, mine entries have irregular dimensions to which the partition must conform to avoid leakage around the periphery. Construction of such partitions can be a time-consuming process. After the partition is constructed, a hole must be cut through it to allow passage of the high expansion foam from the foam generator to the fire site. During a recent underground simulation for mine rescue teams and fire brigades in an operating coal mine, it required 77 minutes to construct a partition from wood, metal and brattice curtain, and start the foam propagating up the mine entry.

To address the drawbacks of constructing a partition for HEF generators, the inflatable feed-tube partition (IFTP) [16,19] was developed. The IFTP is a lightweight, inflatable rectangular bag. The device can rapidly block large openings (within 15 minutes), such as those in underground mines, and simultaneously provide a feed-tube for high expansion foam. This allows firefighting foam to freely flow to the fire site and control or extinguish the fire.

The portable IFTP can be easily transported to a mine passageway leading to a fire area and then be inflated by a permissible fan/air blower, a compressed air line or an inert gas source (air or inert gas sources must be kept on to compensate for leakage). The IFTP is made from a water and heat resistant, lightweight fabric (0.076mm thick), such as chemically treated, rip-stop nylon. The IFTP could also be fabricated from a material such as Mylar or fire-resistant materials. The shape and size of the IFTP depend on the passageway dimensions in which it may be used. For example, for a mine entry 2.1m high by 5.8m wide, the IFTP would take the shape of a slightly oversized rectangular bag approximately 2.6m high by 6.1m wide and 3.1m long. Experiments in the Lake Lynn Experimental Mine showed that a 2,800 L/s diesel-powered (fixed driving force), high-expansion foam generator with the IFTP could push a foam plug 245m through an entry 2.1m high by 5.8m wide with a 4.3% rise in elevation, before the foam generator failed to push the foam plug further. Additional information on the use of foam, partitions and other inerting methods can be found in the following references [20–23].

Another conceptual use of an inflatable bag is a positive-pressure, inflatable walk-through escape device (IED). This rapidly deployed device, with its 'pass-through' feature, allows extra time for personnel evacuation by isolating a smoke-filled entry from fresh air. The IED would be strategically placed in a mine entry, and then be either manually or remotely deployed during a mine fire. Evacuating miners would enter the IED from the smoke-filled entry and exit into the fresh air side.

To better maintain inflation when the IED doorways are opened, a third generation positive-pressure, inflatable escape device was fabricated and successfully evaluated in the Lake Lynn Experimental Mine. The unit is a rectangular bag constructed from a heat resistant lightweight fabric and is inflated by two fans, one of which is connected to an integral fabric tubing air distribution system. The IED can also be inflated by compressed air. Large C-shaped zippered doorways on both sides of the IED allow easy entry and exit. Because the bag is under positive pressure, it is impervious to outside contaminants, such as smoke, if the air intake remains in fresh air. During a mine fire, the IED would be rapidly deployed to temporarily isolate a smoke-filled entry from fresh air. If the inflating air was clean compressed air, the bag could be used as a temporary shelter [22,24]. The use of a fan for inflation, however, would require that the fan remain in fresh air or that filters be installed on the fan to cleanse the mine air of any contaminants. Mine rescue teams could also use the IED as an airlock system during rescue and recovery operations and it could be rapidly advanced as mine recovery progressed. For this application, an inert gas source could be used to inflate the IED if necessary. The performance of the third generation IED was assessed during mine rescue team training simulations conducted in the Lake Lynn Experimental Mine. The IED was deployed in five to ten minutes and isolated a smoke-filled passageway from the fresh air base. Fully equipped five to seven member mine rescue teams can enter or exit the IED without deflating the unit. The IED has been successfully demonstrated at numerous Open Industry Briefings on Mine Fire Preparedness held at Lake Lynn Laboratory and operating coal mines. Briefing participants and miners walked down a non-toxic smoke-filled entry and passed through the IED to reach fresh air. This device successfully isolated smoke-filled entries from fresh air, and mine personnel effectively passed through the device to the fresh air base or back into the smoke-filled entries.

8 Summary

This cooperative research effort between NIOSH, state agencies, and mining companies offered an excellent opportunity to provide realistic training to mine rescue teams, fire brigades, first responders, and miners in general, and to evaluate new and existing technology that may be used for underground mine emergencies. For example, rescue teams have identified green as the most visible coloured lightshape in both white and black smoke. These teams have now added chemical lightshapes to their cache of rescue team supplies.

Strobe lights were useful for mapping out an escape route for evacuating miners. Activation of the strobe lights by the wireless, through-the-earth signalling system was successful. Additional research would be required to evaluate the feasibility of using these devices in larger mines and to incorporate audio output with each strobe light unit.

During smoke training exercises, red and green laser pointers were effectively used to negotiate travel through smoke-filled passageways. The green laser pointer was the most visible colour seen in white smoke. These realistic training exercises offered the workforce an excellent opportunity to evaluate devices that can help them navigate through smoke-filled environments and better prepare them for real emergencies.

By using the new lighted team lifeline, team members have freedom of movement between the captain and tail-person. They can visually see the rope, their own position and have more flexibility to do activities such as carrying supplies, erecting stoppings and constructing roof supports. The team lifeline also alleviates tripping and falling problems. The electro-luminescent fibre of the light vest allows team members and personnel working in darkness, smoky conditions or around moving machinery in low light areas to be seen more easily.

Escape from complex underground passageways could be improved by using a continuous lifeline. Utilising directional cones and double cones on the lifeline would not only lead personnel escaping in smoke-filled entries in the right direction, but also alert them that an obstacle of some sort is nearby.

The m-Comm communications system shows merit. Utilising the voiceducer, with the present radiating transmission line at Lake Lynn Laboratory, has shown potential for improved wireless communications for mine rescue teams. Additional research is required to incorporate the antenna into the main lifeline.

The thermal imaging cameras have merit for mine rescue exploration and recovery in the smoke-filled mine passageways. However, the simulations suggested that new protocols need to be developed when mine rescue teams explore with these IR devices, because the team member with the thermal imaging camera can travel smoke-filled entries much more rapidly than other team members.

Both inflatable devices have shown merit in providing a relatively rapid method for isolation of a mine fire and use with a foam generator for fire suppression, or for personnel escape and rescue. The inflatable partition can rapidly block large openings, such as those in underground mines, and simultaneously provide a feed-tube for high expansion foam. The inflatable escape device could be used as an airlock system during exploration by mine rescue teams and could be rapidly advanced as mine recovery operations progressed.

These technological advancements can improve the state of readiness for rescue personnel and increase the chances of survival for personnel escaping from underground emergencies.

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