Technologies for Today's Mine Emergency Responders

Ronald S. Conti
National Institute for Occupational Safety and Health (NIOSH)
P.O. Box 18070, Pittsburgh, PA 15236
rkc4@cdc.gov
Linda L. Chasko, Physical Science Technician, NIOSH

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Abstract

This paper describes technology that has been identified for underground mine emergency responders. Mine rescue teams are often called upon to save lives during an underground emergency such as a fire, explosion, roof fall, or water innundation. It is extremely important that team members are provided with adequate exploration equipment and that they are properly trained in the use of that equipment. A series of mine rescue training, in-mine smoke training, and mine emergency response development (MERD) exercises, was developed, conducted, and evaluated by the National Institute for Occupational Safety and Health (NIOSH) in cooperation with state agencies and companies. The training exercises were held at NIOSH's Lake Lynn Laboratory and operating mines during 1995 to the present. This effort resulted in improved technology and training for mine rescue teams, fire brigades, first responders, and miners in general. For example, existing technologies were identified to help responders during exploration and recovery operations. These included various chemical light shapes, 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 center. A new team lighted-lifeline allows for flexibility in movements of team members during routine tasks and allows them to easily find their usual position on the lifeline. 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. A positive-pressure inflatable escape device (IED)/airlock, was used to isolate the "hazardous" environment from fresh air and allow rescue team members to traverse through. An inflatable feed-tube partition that can rapidly block large openings, such as underground passageways or tunnels, and simultaneously provide a feed-tube for high-expansion foam generators was also deployed during the simulations. These technological advancements can improved the state of readiness for rescue personnel and increase the chances of survival for personnel escaping from underground emergencies.

Introduction

Over the past several years, NIOSH's Pittsburgh Research Laboratory (PRL) has conducted mine rescue training simulations at its Lake Lynn Laboratory (LLL) near Fairchance, PA. Memorandums of Understanding/Agreement were established between NIOSH and state agencies and several mining companies to increase the operational effectiveness of their coal mine and metal/nonmetal rescue teams and evaluate new and emerging technology [Conti et al. 1998; Conti et al. 1999]. These efforts have resulted in improved disaster recovery training drills and the development of new technology such as new team lifelines and inflatable devices for fire suppression and personnel escape [Weiss et al. 1996; Conti and Weiss 1998; Kennedy et al. 1991]. Existing technologies, such as the use of chemical lightshapes, laser pointers and strobe lights for identifying team members, and thermal imaging equipment were evaluated. Current rescue protocols and strategies were also assessed.

The NIOSH, PRL's LLL, formerly a limestone mine, is now a multipurpose research facility used to conduct mining safety and health research [Mattes et al. 1983]. The new entry dimensions of the underground mine range from 1.8 to 2.4-m high and from 5.3 to 6.3-m wide. The average dimensions are 2.1 and 5.8-m, for an average cross-sectional area of 12-m^2. The underground configuration of the new entries covers approximately 95-km^2, with an overburden ranging from 50 to 100-m. The unique nature of the facility allows it to be readily adapted for elaborate mine rescue team simulations in smoke-filled entries.

Through the Earth Signaling 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 signaling system that transmits an emergency warning which can quickly reach every underground miner. The low-frequency electromagnetic field can penetrate kilometers of soil and rock to reach the most remote shaft or tunnel, which makes it ideal for underground signaling 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 cap lamp assembly. Upon receiving an emergency or paging signal, the cap lamp 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 signaling systems and medium frequency radio communication systems for mine rescue can be found in [Conti and Yewen 1997; Dobroski and Stolarczyk 1982].

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[1] (PED) [Zamel 1990]. This system displays a message on a LCD display after the cap lamp 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 13 PED systems installed in U.S. Coal Mines.

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 nonflammable and not a source of ignition, and they are weatherproof, maintenance free, and nontoxic. 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 5-min; the least brightest, 12-hrs. The cylindrical lightsticks were assessed by the team members during the simulations, both in white nontoxic smoke and black toxic smoke produced from conveyor-belt fires. Four lightstick colors 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

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locations and on obstacles during exploration. Of 403 members participating in the white nontoxic smoke training simulations, 80 pct identified green as the most dominant color seen, 9 pct identified red, 7 pct yellow, and clear was the least visible color. Out of the 90 rescue team members that participated in fighting the conveyor-belt fire, 85.4 pct felt that green was the most dominant color; red was the least visible color. 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 (SCBA's). Other lightshapes were also evaluated by team members. The light-rope was found ineffective. Lightsticks are now a crucial component for these team members. Other chemical lightshapes and intensities are currently being considered.

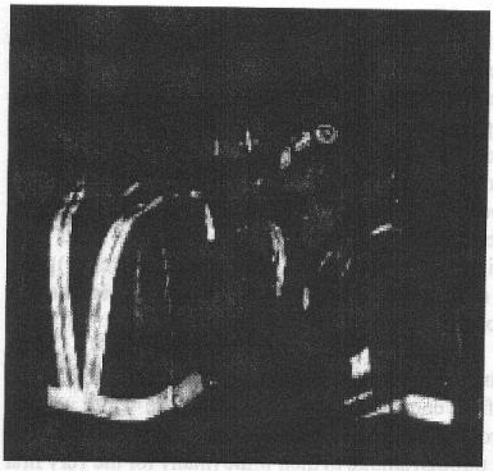

Figure 1.-Mine rescue team member wearing the light vest.

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.

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 electroluminescent fiber and a 0.5-mm 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 length and current consumption is as low as 0.3 mA/m. Two AA batteries could power the vest for over 24-hrs. The light vests, shown in figure 1, were modified with Velcro straps to wrap around a mine rescue member, including their SCBA, for 360 degree 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.

Strobe Lights

Another area examined was utilizing 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 signaling 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 center of the entry about 1.8-m 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 signaling 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 cap lamps off, the strobe lights were easier to follow. Five strobe light colors (red, green, blue, amber, and clear) were evaluated by 271 miners. The most visible color in the nontoxic white smoke was green and the least visible color was amber.

A similar simulation was conducted for underground mine personnel in a Western mine. Miners, in groups of five, entered smoke-filled (nontoxic 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 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 colored reflectors currently mounted in the center 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.

Laser Pointers

Commercial laser pointers are compact, lightweight, affordable, and have high quality beams. They utilize laser diode technology and several of these handheld battery powered pointers have ranges of up to 732-m. Two class IIIa laser pointers, red and green, were evaluated by rescue team members. 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 1-mm.

These pointers, shown in figure 2, are mounted to the side of the miner's helmet with Velcro or to their cap lamps with 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.

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 traveled 300-m in a nontoxic smoke-filled entry, using a lifeline to lead them to fresh air. Visibility ranged from 0.3 to 0.9-m 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 cap lamp 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

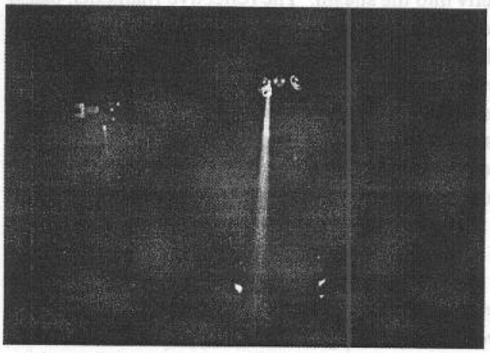

Figure 2.-Laser beam shining through smoke.

surface structures.

Cap Lamp Filters

Everyone realizes the problem encountered while driving an automobile in foggy conditions at night with high beam head lights 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 nontoxic smoke, a colored lens filter was placed over the cap lamps of 121 miners in an attempt to reduce the glare from the white light reflecting off the smoke particles. The color filters that were evaluated included green, blue, orange, and red. Green was the most visible color seen by 38 pct of the miners. Seventy-one pct of the miners felt the lens filters were useful in reducing the glare from the white light and beneficial in traveling through smoke. It has also been suggested that a miner's cap lamp can be taken off the helmet and held about waist high to negotiate travel through smoke.

Lifelines

Very often, rescue team members are attached to a team lifeline or linkline connected to the main communication/lifeline that extends from the fresh air base. Team members are fixed along an 8.5-m length of rope at various distances between the captain and tail-person. Team members have reported that if one person would trip and fall, other team members would be pulled down with the falling team member.

These concerns were solved by using a high-visibility rope with filaments made of reflective material braided directly into the sheath. The reflective filaments, based on glass-bead technology, generate a return more than 1,000 times brighter than plain, white rope. Double-locking snaps were attached to both ends of the rope, with three or more snaps in-between both ends. D-shaped carabineers were then attached to the snaps. 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.

If the rope became entangled around obstacles, finding it was difficult. These concerns were solved by the development of a lighted team lifeline. Four different colored flexible light wires (Live Wire technology, 0.5-mm copper wire coated with semiconductor material) are secured to the rope, extending 2-, 4-, 6-, 9-m, respectively, from the tailperson's position towards the captain's position. The light wires are battery powered and will last 4-hrs. The entire length of the rope is sheathed with clear polyvinyl chloride tubing. Double-locking snaps and carabineers are attached to both ends of the rope, with three moveable snaps in-between both ends. The different colored light wires allow the team members to easily find their usual position along the lifeline when exploring in darkness and smoke-filled passageways.

A few underground mines use a continuous lifeline for escape purposes. This lifeline or rope would most likely be secured to the rib 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 kilometers in length. One manufacturer developed a directional lifeline. It consists of standard spools containing 91-m of 0.64-cm polypropylene rope with directional (cone-shaped) orange indicators installed at every 23-m 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 3-m from a mandoor, etc. This procedure would alert personnel escaping in smoke-filled entries that an obstacle of some sort is nearby.

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 U.S. 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 (304-m 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 backup 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 that will be evaluated with rescue teams is the head-contact microphone [Pittsburgh Post-Gazette 1998]. 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. Little background noise is picked up by the microphone, 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 United Kingdom [Operators Manual for m-Comm System 1998] 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 is 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 8-Km and the guide wire could be deployed from the fresh air base (FAB) to the surface command center, 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 300-m. However, when three handsets were used within the 8.5-m 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 U.S. 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. The present system in its current design can still be used by other emergency rescue personnel.

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 not possible 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 [Miller 1997]. In 1995, Cairns & Brother Inc. introduced the first commercially available hands-free helmet-mounted IR imaging systems [Cairns IRIS 1995]. 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 gray. It can detect 0.3 °C differences in temperatures. The sensor is a specially coated 15-mm 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-min 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 February 8, 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 it's 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 hand-held thermal imager. It offers superior image quality, and the innovative, 180-degree rotating display provides comfortable viewing from any position. It enables the user to see from 0.9-m to infinity.

The Agema 550 System is a high-performance handheld IR camera. It has digital voice recordings, color 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 center.

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 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 color. Advanced optics and display offer natural depth perception and orientation. It is also designed to easily view either IR and visual viewing modes. The FireFLIR is quickly and easily handed off to other team members.

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.

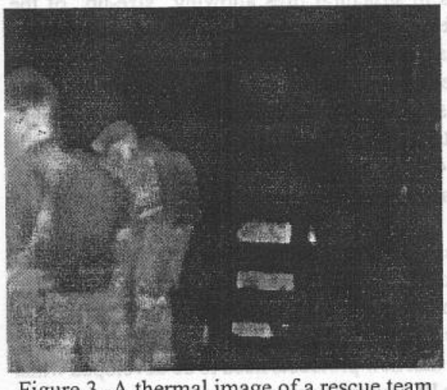

Figure 3.-A thermal image of a rescue team in dense smoke after building a roof support.

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.

Underground Smoke Training Exercise

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 300-m of mine passageways filled with nontoxic smoke. Visibility ranged from 0.5 to 3-m. One objective of the exercise was to evaluate technology that could be used for escape purposes, while giving the miners an opportunity to travel through smoke-filled entries at their mine. The various devices were mounted on the roof in the center of the entry, placed on the floor or secured to the rib. Of all the devices (chemical light shapes, strobe lights, laser lights, light vests, cap lamp, reflective materials, thermal camera, lifeline, other) evaluated in the nontoxic smoke, green was the most visible color 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 vest 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 realized 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 traveled through smoke at some time in their mining career.

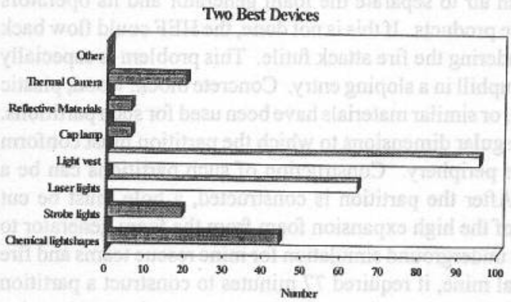

Figure 4.-Most beneficial devices for identifying other personnel in smoky passageways.

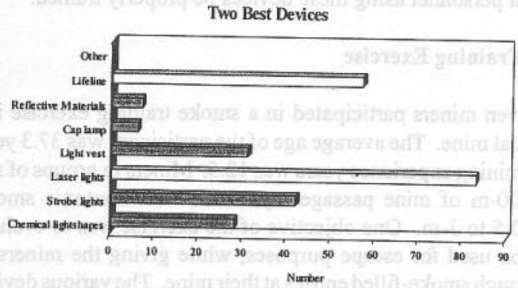

Figure 5.-Most beneficial devices for leading personnel to safety and/or out of the mine in smoke.

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 [Conti 1994; Havener 1975]. 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 [Nagy 1960].

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) [Conti and Lazzara 1995; Conti 1994] was developed. The IFTP is a lightweight, inflatable rectangular bag. The device can rapidly block large openings (within 15-min), 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 (0.076-mm 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 2.1-m-high by 5.8-m-wide, the IFTP would take the shape of a slightly oversized rectangular bag approximately 2.6-m-high by 6.1-m-wide and 3.1-m-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 245-m through an entry 2.1-m high by 5.8-wide with a 4.3 pct 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 [Mitchell 1996; Conti 1995; Conti et al. 1998; Bird et al. 1999].

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 light weight 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 [Baldwin 1996]. 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 5 to 10 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 an Open Industry Briefing on Mine Fire Preparedness held at Lake Lynn Laboratory and an operating coal mine. 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.

Summary

This cooperative 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 evaluate new and existing technology that may be used for underground mine emergencies. For example, rescue teams have identified green as the most visible colored 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 signaling 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 color in white smoke.

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 are more flexible to do activities such as carrying supplies, erecting stoppings and constructing roof supports. The team lifeline also alleviates tripping and falling problems. The electroluminescent fiber 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. Utilizing 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. Utilizing 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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