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Mine rescue and response

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This paper describes technology and training that has been identified for underground emergency responders. 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 U.S. 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. Therefore, it is extremely important that miners are provided with adequate technology and that training simulations are conducted in a realistic manner.

A series of mine rescue training and mine emergency response development (MERD) exercises, and in-mine smoke training were developed, conducted, and evaluated by state and company teams, and by National Institute For Occupational Safety and Health (NIOSH) personnel. The training exercises were held at NIOSH's Lake Lynn Laboratory (LLL) and operating mines during the past several years. This training 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. 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 allows the user to 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. A new team lighted-lifeline allows for flexibility in movements of team members during routine tasks and allows them to easily find their fixed 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 have improved the state of readiness for rescue personnel and have increased the chances of survival for all personnel escaping from underground emergencies.

Keywords: Emergency response, smoke training, mine rescue, response technology.

Introduction

Over the past several years, NIOSH's Pittsburgh Research Laboratory (PRL) has conducted mine rescue training simulations at its 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 to evaluate new and emerging technology (Conti[1–2]). 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 (Conti[3], Kennedy[4], Weiss[5]). 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 LLL, formerly a limestone mine, is now a multipurpose research facility used to conduct mining safety and health research (Mattes[6]). 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.

Technology escape and emergency responders

Emergency warning systems

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 a device to accomplish this, 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. Figure 1 shows a typical configuration of the wireless system for a mine. 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 signalling systems and medium frequency radio communication systems for mine rescue can be found in Conti[7], Dobroski[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) (Zamel[9]). 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 14 PED systems installed in U.S. coal mines.

Identification and seeing through smoke

NIOSH attempted to address several issues raised by rescue team members that participated in the simulations at LLL. One of the main concerns of the rescue teams was identifying other team members, marking locations and materials, 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 5 min; the least brightest, 12 hrs. 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, as shown in Figure 2, 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. Of 403 members participating in the white non-toxic smoke training simulations, 80 per cent identified green as the most dominant colour seen, 9 per cent identified red, 7 per cent 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 per cent felt that green was the most dominant color; red was the least visible colour. Lightropes were mounted around the brim of the helmet, and chemical circular lightdiscs were mounted on the back of the self-contained breathing-apparatuses (SCBAs). Team members also evaluated other lightshapes. The light-rope was found ineffective. In other smoke training exercises, the participants turned off their caplamps and held a green lightstick out in front of them, about waist high. The lightstick was effectively used to negotiate travel through a smoke-filled passageway. Lightsticks are now a crucial component for many rescue team members as well as underground miners.

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 0.5 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

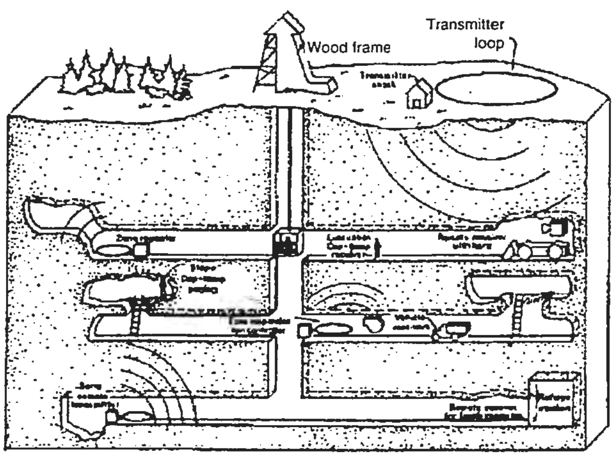

Figure 1. Conceptual representation of a mine, depicting capabilities of the signalling system

Figure 2. Chemical lightsticks attached to the back of miners helmets

length and current consumption is as low as 0.3 mA/m. Two AA batteries power the vest for over 24 hrs. The light vests 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 considering the use of light vests for personnel working around moving machinery.

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 triangular shaped strobe lights, with interchangeable reflective lenses, are compact and lightweight, powered by a lithium AA battery and provide visibility of 180 degrees. The strobe lights can be activated by the 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 1.8 m from the floor and in the entry crosscuts predetermined to be the best escape routes. Rescue team members were told that a roof fall had occurred and severed the main communication/lifeline. At that time, the strobe lights were remotely activated. 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. Two hundred and seventy-one miners evaluated five strobe light colours (red, green, blue, amber, and clear) during these smoke training exercises. 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.

Another successful device that was evaluated in smoky environments uses laser technology. 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. 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 hrs. 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 are mounted to the miners' 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. Figure 3 depicts the green laser beam cutting through the smoke-filled entry.

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 300 m in a non-toxic 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 lamps 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.

Additional experiments were conducted with Class IIIa yellow, orange, and green Helium-Neon lasers with wavelengths of 594 nm, 612 nm, and 643.5 nm, respectively. The output power and beam diameters were similar to the laser pointers. The 110 VAC powered lasers were mounted at graduated heights in an entry, approximately 1 m from the rib, starting at 100 cm from the floor. The three-coloured laser beams were adjusted to maintain the same distance and height ratio from the rib and floor, 300 m away. The three laser beams showed up well in dark areas. However, test results with thick smoke indicated that these lasers were ineffective, with the beams not visible 3 m from the laser sources. In comparison, the

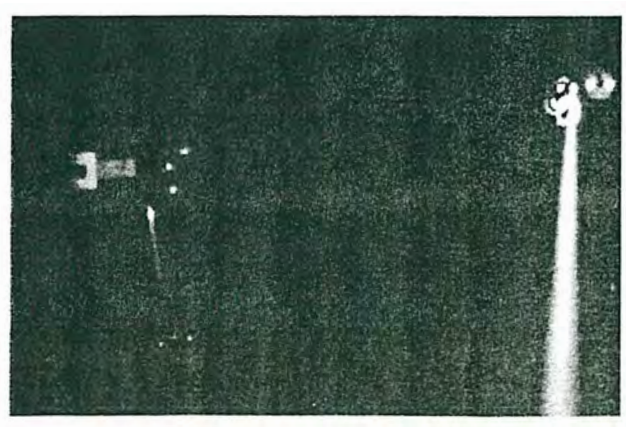

Figure 3. Green laser beam shining through smoke

beam from a laser pointer (laser diode technology) was visible to 10 m from the laser. The concept of laser pointers was successful in experiments at the LLL and an operating mine. Additional research is needed to evaluate the feasibility of using a higher power laser to identify escape routes in smoke-filled underground passageways and in surface structures where community firefighters have become disoriented or lost.

Everyone realizes 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 cap lamps 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 per cent of the miners. Seventy-one per cent 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 cap lamp can be taken off the helmet and held about waist high to negotiate travel through smoke.

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 8.5 m length of rope at various distances between the captain (lead person) and tail-person. Team members have reported that if one person should trip and fall, other team members would be pulled down with the falling team member. If the rope became entangled around obstacles, finding it could be difficult.

These concerns were solved by the development of a lighted team lifeline, shown in Figure 4. Four different coloured flexible light wires (Live Wire technology, 0.5 mm copper wire coated with semiconductor material) connected in series, pass through a 0.64 mm diameter hollow single braided polypropylene rope (336 kg tensile strength). The light wire extends 0–2.1 m (blue), 2.1–4.3 m (orange), 4.3–6.4 m (green), and 6.4-8.5 m (red), respectively, from the captain's position toward the tail-person's position and has 360 degree visibility. The light wire is battery powered and will last a minimum of 4 hrs. 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 tail-person, with three movable 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.

Figure 5 illustrates mine rescue team members attached to an earlier version of a high-visibility team lifeline (Conti[10]). In this prototype, a high-visibility 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.

Another product is LiteLine 360. The lighted line offers an illuminated path to safety for rescue personnel or firefighters working in darkness or smoke-filled

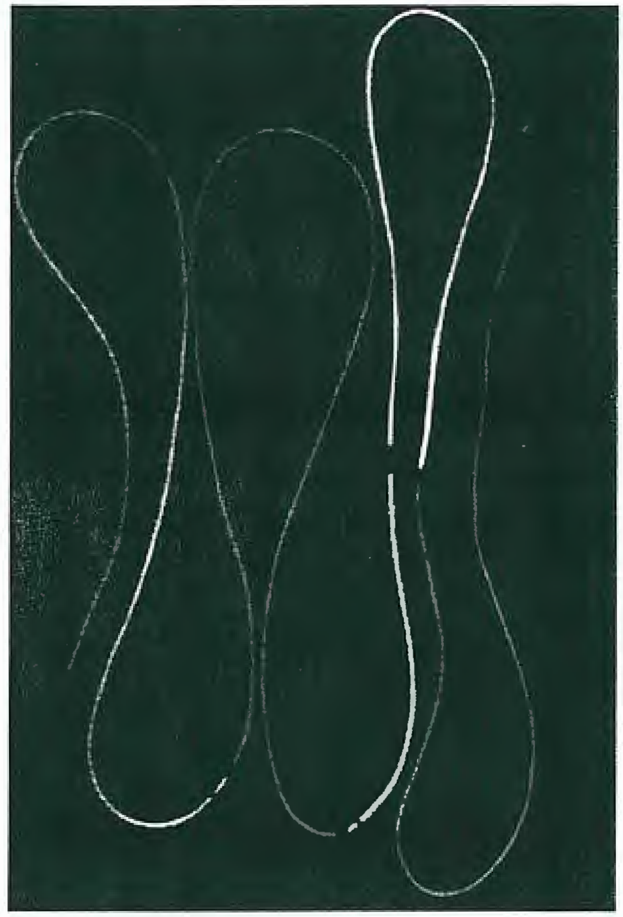

Figure 4. Lighted team lifeline

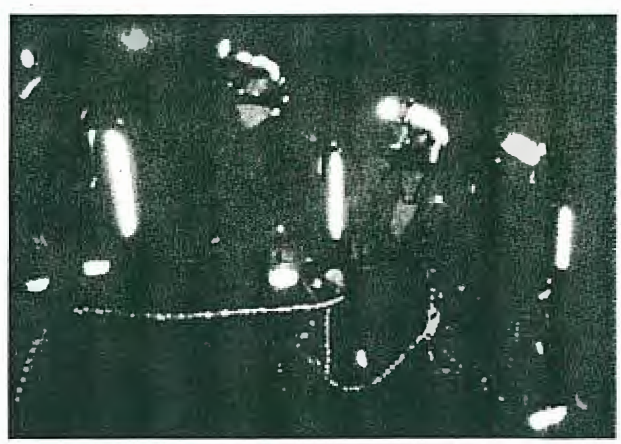

Figure 5. Rescue team members attached to the high-visibility team lifeline

environments. The LiteLine furnishes moderate ambient light level everywhere it is deployed. Rather than a limited 'point-and-beam' light source, it is a continuous strand of omni-directional light in 30 to 90 m lengths. It is lightweight, flexible, easy to deploy and requires 120 VAC power.

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.

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. Figure 6 shows a mine rescue team member with a thermal imaging camera. 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[11]). In 1995, Cairns & Brother Inc. introduced the first commercially available hands-free helmet-mounted IR imaging systems. 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 mins of continuous, uninterrupted use at ambient temperature.

The first demonstration of the Cairns IRIS in an underground mine was conducted at LLL 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 in-mine simulations suggested that new protocols should 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; 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, colour images, and storage capabilities. The spectral range is 3.6 to 5.0microns 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 image, shown in Figure 7, can be downloaded to a computer for analysis or interfaced directly to a monitor for debriefing members at the command centre. IR cameras may also be used for preventive measures: such as to fire boss underground areas prone to fires, like belt drives and power centres.

A Flir System called FireFLIR, is used in conjunction

Figure 6. Rescue team member wearing the FireFLIR thermal imaging camera

Figure 7. A thermal image of a conveyor belt structure

with SCBAs 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 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 view either IR or visual viewing modes and 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. Argus recently introduced the next generation camera that features a remote wireless video transmission system. During experimental tests at LLL, the video signal from the camera was successfully transmitted from inside a metal and concrete block fire gallery to an outside remote receiver station. The remote receiver, located 60 m away, was positioned in the direct line of sight to the camera. Command centre or fresh air base personnel could use this feature to better direct rescue efforts.

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 looking at them with the naked eye. It is imperative that personnel using these devices be properly trained.

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 tail-person, 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 tail-person 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 lifeline communication system that extends from the team to the fresh air base. The latter example could serve as a backup communications system. During exploration, team members would have the antenna with them and could 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 may be used by rescue teams is the head-contact microphone (Pittsburgh Post-Gazette[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 United Kingdom was also evaluated with mine rescue teams at LLL. The m-Comm system, shown in Figure 8, 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

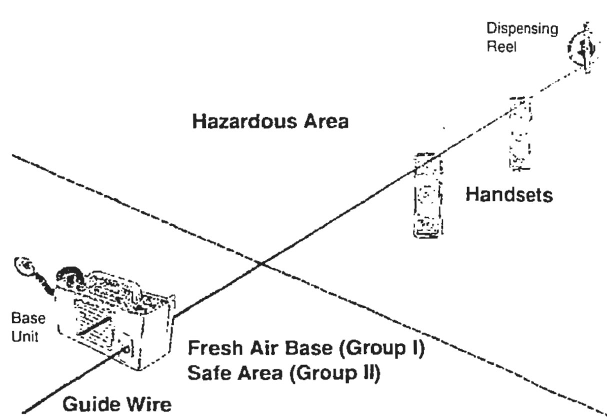

Figure 8. Diagram of the m-Comm communication system

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 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 indicate 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. Other emergency rescue personnel can still use the present system in its current design.

Inflatable devices for fire suppression and personnel escape

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[13], Havener[14]). 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[15]).

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 an underground training 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[16-17]) was developed. The IFTP is a lightweight, inflatable rectangular bag. The device can rapidly block large openings (within 15 mins), 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 other 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 per cent 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[18], Conti[19], Bird[20]).

Another conceptual use of an inflatable bag is a positive-pressure, inflatable walk-through escape device (IED), shown in Figure 9. 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 to 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

Figure 9. Rescue team members entering the IED

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[20]). The use of a fan for inflation, however, would require that the fan remains 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. 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.

Underground smoke training exercise

One hundred and twenty-seven miners participated in a smoke training exercise in a Western underground coal mine. The average age of the participants was 37 years and average number of mining experience years was 12. Miners in groups of five traversed more than 300 m of mine passageways filled with non-toxic 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 centre 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, etc.) evaluated in the non-toxic smoke, green was the most visible colour seen by most of the miners.

Figure 10 illustrates the responses of the miners for the two most beneficial devices for identifying other people in smoky passageways. The two devices chosen by the miners participating in the study were the light vest and lasers. These miners also felt that the lasers and lifelines, responses shown in Figure 11, were most beneficial in leading then 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 per cent of the miners who participated in the training reported that they have travelled through smoke at some time in their mining career.

Training simulation modules for mine rescue teams

During the simulations conducted in the LLL Experimental Mine, rescue team members donned self-contained breathing apparatuses and generally traversed more than 305 m of mine passageways filled with non-toxic smoke. Visibility is controlled and usually ranges from 0.3 to 0.5 m. The IED is used by rescue team members to enter the 'smoke-filled' passageways from a fresh air base. Depending on the scenario and objectives, the mine environment can be modified. For example, in one area of the mine, a kerosene heater was used to simulate a fire and reduce the oxygen concentration to 18 per cent. This area has also been heated so that the temperature is more than 38°C. In another area, a 1.5 per cent methane zone was established. Handheld sensors carried by the rescue team members were activated when they entered these areas, alerting them to the 'hazardous' conditions.

Objectives of the mine rescue team simulations and MERD exercises focused on fire fighting and ventilation techniques; moving the fresh air base; confined space rescue; using thermal imaging cameras; a backup team rescuing the exploration team; rescuing and controlling a hysterical miner lost in smoke; and dealing with the sudden loss in communications to the surface command centre, FAB, exploring team and backup team due to a massive roof fall caused by an explosion. During the simulations, all problem tasks completed by the teams are tracked. At the end of each simulation, all participants answered a series of

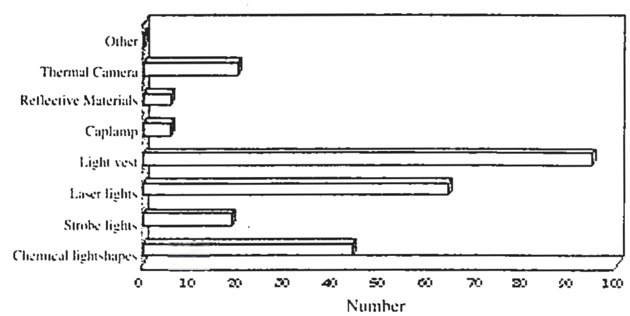

Figure 10. Most beneficial devices for identifying other personnel in smoky passageways

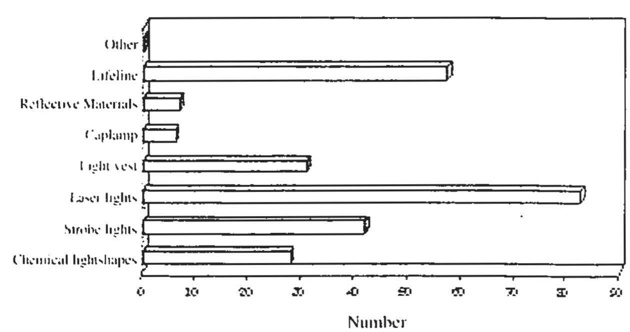

Figure 11. Most beneficial devices for leading personnel to safety and out of the mine in smoke

questions. These included demographics; usefulness of the fresh air base briefing; how the team members, FAB and command centre personnel made decisions; anxiety levels and physical demands of the rescue operation; and any issues that may arise during the exercise. The rescue teams, command centre and observers as a whole were then debriefed. This open forum offers an excellent opportunity for all participants to engage in some lively conversation about the simulation. For example, how was the strategy developed for exploring the entries, and how good was the communication between team members, the fresh air base and surface command centre.

During the MERD exercises, the team members voiced several concerns regarding the command centre's perceptions about solving tasks in smoky passageways. While personnel in command centres are generally very knowledgeable in their own areas, a key element to remember is that inexperienced command centre personnel do not fully understand the basic principels of the mine environment, how the team explores in smoke and communicates with the fresh air base.

Several recommendations are offered for personnel who may be stationed in command centres. Command centre personnel should spend some time underground at the fresh air base during the MERD exercises. They need to tag along with the rescue team and observe how teams explore and complete tasks. These personnel need to evaluate teams in smoke-filled passageways from an observation area; for example, how teams travel from point A to point B, set-up roof support or incorporate ventilation controls. Observers may utilize thermal imaging cameras to do this. Their abilities to participate in or lead the command centre would be enhanced after they complete these basic underground requirements. They need to be opened-minded for input from others and flexible in decisions when circumstances change.

Team members, company personnel and Government officials all agreed that the simulations are extremely beneficial. The programme offers a unique opportunity to develop and conduct realistic training simulations for mine rescue teams and command centres at Lake Lynn Laboratory and operating mines and evaluate technology for mine rescue operations.

Conclusions

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 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 in white smoke.

By using the new-lighted team lifeline, team members have freedom of movement between the captain and tail-person. They can see the rope and their own positions 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 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. Several mines are considering the use of light vests for personnel working around moving machinery.

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 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.

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

Since the onset of rescue team training simulations and MERD exercises at Lake Lynn Laboratory and operating mines, some rescue teams, who trained in smoke for the first time, were so confused that they gave up and had to be rescued. Several team members have decided that rescue work was not for them and quit the team. During another exercise in a low coal, seam height 0.8-m, another member not only quit the team but also the mining industry. Overall, the strengths of the team and its members have improved since their initial exercise. For example, confidence levels have increased, and members are now working as a team, thinking through the problem together. Teams are successfully accomplishing their goals by replacing contest rules and placards with realistic hands-on-training exercises.

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