Emerging Technologies: Aiding Responders in Mine Emergencies and During the Escape from Smoke-Filled Passageways

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ABSTRACT

Historically, underground mine rescue teams have received training only 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, this does not fully prepare them for the conditions that may be encountered in real escape situations, such as smoke filled entries. 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.

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. Over the past several years, the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory (PRL), in collaboration with state agencies and several mining companies, 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 operating mines. These training simulations allowed rescue personnel to train under realistic conditions and focused on fire fighting, ventilation, searching for "victims", first aid, mapping, etc. (Conti, et al.1998).

The 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 (Weiss, et al.1996; Conti and Weiss 1998; Kennedy, et al. 1991). 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.

This paper focuses on 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 concentrates on technology that can assist responders during exploration and recovery operations (Conti, et al. 1999). For example, through the earth signaling and effective communications, identifying personnel and materials in smoke, lifelines for escape, vision enhancement and inflatable devices.

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. Signals can be directed to an individual, to a group, or to all underground/surface personnel. Fire brigades and mine rescue teams could be alerted, and key personnel contacted. 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 to identify escape routes. 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 (PED)[1] (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 46 underground miners escaped in approximately 45 minutes. There are currently 17 PED systems installed in U.S. coalmines and one in a metal/nonmetal mine.

Transtek Corp has developed a wireless, two-way cellular communications system for underground mines (Product and Process News). The ComCell technology can be used to reduce communications costs and improve underground productivity. They are also testing a unique Through the Earth wireless system that allows two-way mobile voice and data communications between the underground passageways and above ground sites. There are currently 2 systems installed in underground facilities.

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

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[1] Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health

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 often 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, several devices and systems were looked into (Conti and Chasko 2000). For example the m-Comm communications system, developed in the United Kingdom, shows merit for improved communications for emergency responders. This system is intrinsically safe and designed specifically for confined space and rescue applications. It consists of a single (lightweight) wire on a dispenser reel holder, that is payed out on entering the area to be explored, three handsets, and a portable base unit. 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 to the surface command center.

Other devices such as the Voiceducer and or "head-contact microphone" maybe used if the mine had a radiating transmission line or if the lifeline was also antenna. 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 a miniature receiver component. The "head-contact microphone" is a hands-free radio microphone that can either be strapped onto the forehead or incorporated into a helmet headband. Rescue members need not to 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. Additional research is underway to improve mine rescue communications.

IDENTIFYING PERSONNEL, MATERIALS AND ESCAPE ROUTES

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, light rope and light disc), 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. 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 and the least brightest, 12-hrs. The brightest lightstick is an excellent source of light to administer first aid in smoky environments. Team members assessed the cylindrical lightsticks during the simulations, both in white nontoxic smoke and black toxic smoke produced from conveyor-belt

Figure 1. Chemical lightsticks attached to the back of miners.

fires. Four lightstick colors were evaluated; clear, green, red, and yellow. Team members, as shown in figure 1, 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. The team member, whose duties require mapping the passageways, can use a lightstick to illuminate the map board. Of 403 members participating in the white nontoxic smoke training simulations, 80 pct-identified green as the most dominant color seen and the least visible color was clear. Out of the 90 rescue team members that participated in fighting the conveyor-belt fire, 85 pct felt that green was the most dominant color; red was the least visible color. Lightsticks are an important component for some mine rescue teams.

Team members also evaluated other lightshapes. Lightropes were mounted around the brim of the helmet, and circular lightdiscs were mounted on the back of the self-contained breathing-apparatuses (SCBA's). The lightdisc was helpful, however, the lightrope was found to be ineffective.

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. Some miners have started storing lightsticks in their lunch buckets or having them in their possession for emergency use.

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 technology, developed by LiveWire Enterprises, Inc., that uses a blue/green or orange 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 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.

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. They were also used to mark materials (fire hydrants, cribbing, etc.) in the smoky passageways. These weather resistant strobe lights, with interchangeable reflective lenses, are compact and lightweight and provide visibility of 180°. The triangular shaped, 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 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. Two hundred and seventy-one miners evaluated five strobe light colors (red, green, blue, amber, and clear) during the simulations. 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 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 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.

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 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.

The team captain is fitted with the green laser and the tailperson with the red laser. These pointers are mounted to their cap lamps with hose clamps. 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 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 operating mines. Additional research would be required to evaluate the feasibility of using higher power lasers to identify escape routes in smoke-filled entries or surface structures.

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 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 miners cap lamp can be taken off the helmet and held about waist high to negotiate travel through smoke.

LINKLINES AND LIFELINES

When 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 team lifeline to the fresh air base. Usually, five team members are fixed along the 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 would 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 (Conti and Chasko 2000). Four different colored flexible light wires (Live Wire technology, 0.5-mm copper wire coated with semiconductor material) connected in series, pass through a 0.6.4-mm diameter hollow-single braided polypropylene rope (336 kg tensile strength) 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 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 colored light wires allow the team members to easily find their usual position along the lifeline when exploring in darkness and smoke-filled passageways.

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 8.5-m linkline, and would swing back around to the tailperson, missing the opposite corner and causing delays. During the training simulation, two of the rescue teams evaluated the use of a retractable line (6.1-m 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.

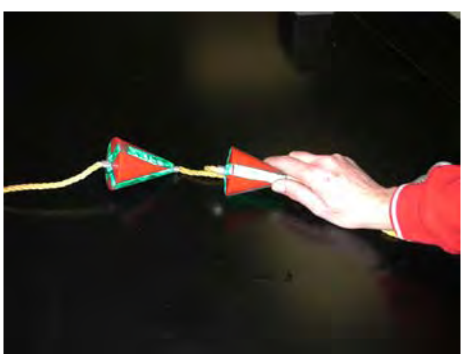

Figure 2. Continuous lifeline for escape.

Underground mines mark their escapeways with reflectors or arrows. Usually two colors are used to represent primary and secondary escapeways. After a period of time, the dust entrained in the airways can collect on the reflectors and decrease their effectiveness, so they may never be seen if the passageways are filled with smoke. 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. Some mines are securing the lifeline near the roof in the center of the entry, at an average height of 2-m from the floor, and lower in lower seam mines. Depending on the configuration of the mine, the lifeline could be many kilometers in length. One manufacturer developed a directional lifeline shown in figure 2. It consists of standard spools containing 91-m of 0.64-cm polypropylene rope with directional (cone-shaped) orange indicators with green reflective tape installed at every 23-m interval. The tapered end of the cone should always point inby, so that escaping miners would never have to take their hand off the line. 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.

A study is currently underway to evaluate the feasibility of using prototype pinwheels to identify primary and secondary escapeways. The pinwheels are constructed from durable and highly reflective Scotchlite or Holographic prism materials. The four colors used, shown in figure 3, are green (Scotchlite), silver, yellow and red (Holographic prism). One side of the pinwheel facing the airflow is painted black. During the six-month evaluation in an eastern coal mine, data will be collected on dust buildup, reflectance to camp lamps and general views from the miners on preferred color, etc.

Figure 3. Prototype pinwheels to identify escapeways.

When smoke is encountered underground, visibility is reduced, anxiety levels increase and decision making skills can become clouded. It is extremely important that the miners from each section stay together and retain the necessary tools to aid them in a successful evacuation. A few mines have evacuation or escape kits on each section. An ideal kit would contain the following items: rope, lightsticks, chalk, SCSR's, first aid kit, brattice curtain, a mine map, handheld gas sensor and, depending on the mine communication system, an extra radio or pager phone. The rope is used for the crew to attach themselves to and keep everyone together, especially when traveling through smoky passageways. Various colored and intensity chemical lightsticks would be available to mark passageways, so if the crew did become disoriented and lost they would know that they had passed this way before. They can also be used as a light source to negotiate travel through smoke or the high intensity lightstick can be used when administering first aid. Chalk maybe used to mark the ribs, stoppings, etc. (names, direction, date and time). Each miner would carry extra SCSR's. A handheld gas sensor can alert the crew of hazardous gases. A pager phone or radio may be used to effectively communicate to the surface or rescue team where the crew is located or underground conditions. An updated map is essential to travel out of the section and mine to safety. Some kits also contain materials to barricade and should only be used as a last resort when all escape routes are blocked. Some mines are considering portable lasers to travel through smoke.

SEEING THROUGH THE SMOKE

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 not be possible to obtain, for example, fire scene assessments and seeing through smoke. This technology increases the responder's understanding of the environment (fire location, problem areas like ceiling collapse, firefighters' progress in effective extinguishment, and firefighter safety), thus enhancing safety and the ability to accomplish the task.

The thermal imaging camera was developed in the early 1970's. Over the last decade, the thermal imaging camera has become an invaluable tool for emergency responders and fire assessment. It is very different than the common night vision device that either amplifies available light or senses reflected near IR energy. Thermal imaging cameras utilize infrared detectors that incorporate special materials that provide an electronic signal proportional to the amount of detected radiant energy. The latest technology being used is a non-contact sensor called a "micro-bolometer." The bolometer is a device that actually changes temperature proportional to the amount of radiant energy focused on the element. This change in temperature generates an electrical signal which when processed produces the infrared image that is seen in the viewfinder. The camera differentiates objects by their thermal temperature characteristics, and it can see through smoke, darkness and invisible flames produced by burning hydrogen or alcohol. However, it cannot see through solid objects, such as concrete and masonry, nor can it see someone directly behind the flames. Shiny surfaces (bodies of water, glass, stainless steel) reflect IR just as they reflect visible light.

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. Firefighters can use the Cairns IRIS to see through dense smoke and darkness in structural fires allowing a faster and more effective "size-up" of the situation. 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 to14-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 (Conti et al.1998). 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 training simulations indicated 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 (TIC) can travel smoke-filled entries much more rapidly than other team members (Conti et al.1999). One recommendation would be to have a retractable line attached to the person using the TIC. This way, the rescue team can still go about exploring and mapping, while the member with the TIC, still attached to the team, can examine the thermal image more closely and report to the team. 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, color images, and storage capabilities. The spectral range is 3.6 to 5.0-microns and it 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 thermal image can be downloaded to a computer for analysis or interfaced directly to a monitor for debriefing members at the fresh air base or command center so that key personnel can view thermal images of the event. IR cameras may also be used for preventative measures, such as to fire boss underground areas prone to fires, for example, belt drives, power centers and areas susceptible to spontaneous combustion. They also could be used to monitor welding and cutting operations.

A Flir System called FireFLIR, is used in conjunction with SCBA's (other TIC's can also be used this way) 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 color. Advanced optics and display offer natural depth perception and orientation. It is also designed to easily view both IR and normal visual modes without moving the TIC. The FireFLIR is quickly and easily handed off to other team members. Rescue teams that had an opportunity to evaluate the various thermal imaging cameras during training simulations preferred this TIC, due to it's light weight, viewing and carrying capabilities and ease in transfer to other team members.

The Argus Thermal Imaging Camera can also see through smoke and darkness. Its spectral range is 8 to14-microns. It is ergonomically designed for comfort and utility, is handheld, and has an angled viewfinder. Moreover, this 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 (Evolution 4000), shown in figure 4. It features a remote wireless video transmission system, high-definition big screen display and a heat seeker indicator system. The heat seeker displays red attributes on the black-and-white display for immediate identification of the seat of the fire when the temperature reaches 200 °C.

Figure 4. Rescue team member using a thermal imaging camera.

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. In the underground tests, the video signal was transmitted from the exploring mine rescue team to the fresh air base (FAB). The remote receiver, located 200-m away, was in the direct line of sight with the camera. Command center or fresh air base personnel could use this feature to better direct rescue and firefighting efforts.

During advanced training exercises, mine rescue teams and fire brigade members used a TIC during a training application while extinguishing a conveyor-belt fire in the Lake Lynn fire gallery. The rollback smoke was so thick and sooty that as the team members entered the fire gallery they could not see their hands in front of their facepiece. The person using the TIC was able to view the flaming belt, the hot rollback smoke and gases at the roof, and the team members as they entered the gallery. This person was in a better position to direct the firefighting efforts of the team. When two waterhoses were activated in the fog stream, the water spray immediately cooled the area, thus allowing the teams to manage the rollback smoke as they advanced towards the fire to extinguish the flames.

Drager recently introduced the next generation FireOpTIC. This camera features color image display, instant on (30-sec for camera to begin normal operation) and remote wireless video transmission. Its spectral range is 8 to14-microns. The optional Life Sensor Software allows the operator to locate persons who may be near flames without the occurrence of "white-outs" or "black-out borders" on the display caused by viewing open flames. The automatic shutdown feature prevents unnecessary and distracting temperatures (above 104 °C**)** from being read and displayed thus allowing the operator to search for bodies based upon their temperatures

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

To better prepare miners to escape from underground smoke-filled environments, a series of smoke training exercises were developed and evaluated by NIOSH. Objectives of the exercises were to evaluate present escape methods, existing technology, and new technology that could be used for escape purposes, while giving the miners an opportunity to travel through smoke-filled entries at their mine. A non-toxic smoke generator is used to create a smoky atmosphere and the visibility can be varied from several meters to zero. The smoke generator is also an excellent device to evaluate the smoke leakage of mine stoppings and seals or to observe air currents. 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 experiences, special training, etc), anxiety levels, usefulness of the exercise and technology, most visible colors seen in smoke, and underground firefighting experience.

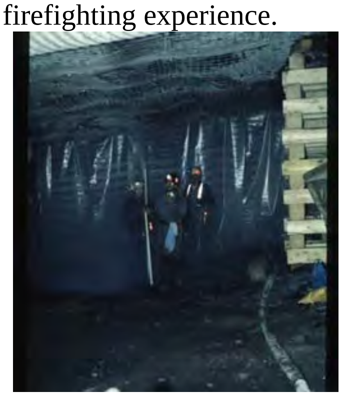

Figure 5. Underground smoke training exercise.

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, shown in figure 5, traversed more than 300-m of mine passageways filled with nontoxic smoke. Visibility ranged from 0.5 to 3-m. Various devices were mounted on the roof in the center of the entry, placed on the floor or secured to the rib and worn by miners. 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, miners felt that the two most beneficial devices for identifying other people in smoky passageways are light vests and lasers. These miners also felt that the lasers and lifelines 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.

An important consideration in any fire safety program is adequate hands-on training for the entire workforce (first, second and sustained responders). Quality training (Conti 2001) enhances the awareness of mine fire hazards and promotes self-confidence. 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 nontoxic smoke. They also felt that it gave them a unique opportunity to evaluate devices that can help them navigate through smoke-filled environments.

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. 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 (Conti 1994; Havener 1975; Nagy et al. 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 well over an hour 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 1994; Conti and Lazzara 1995) 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, 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. 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. 1997; 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 airside.

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 (Conti et al 1997; 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 numerous Open Industry Briefings on Mine Fire Preparedness held at Lake Lynn Laboratory and operating coalmines. 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 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 colored lightshape in both white and black smoke. Some 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 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 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 for improved communications for emergency responders. 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 proven useful 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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