

# Thermal imaging cameras and their use in the mining industry

R.S. Conti and L.L. Chasko

Fire prevention engineer and physical science tech, respectively, NIOSH, Disaster-Prevention and Response Branch, Pittsburgh, Pennsylvania

## Abstract

*To deal with an unexpected event such as fire, prevention and preparedness are important elements in an underground mine's strategic plan. The purpose is to prevent a fire before it initiates and to be prepared to deal with it when it does occur. This paper highlights a technology that may be used by the mining workforce to minimize such occurrences. It discusses thermal imaging cameras and their many applications to detect equipment failures or hot spots before they develop into a fire. It also evaluates the feasibility of using thermal imaging cameras for emergency responders to assist them during exploration, rescue and fire fighting efforts. These thermal imaging systems allow rescue personnel to see in darkness and through dense smoke, thus making it easier to locate heated areas and missing or trapped personnel.*

## Introduction

Fire is a major concern for those who work underground. A mine fire can occur at any time, resulting in the partial or total evacuation of mine personnel and/or fatalities. The remote nature of underground mining requires workers at all positions within the organization to maintain higher skill levels in emergency response compared to workers in many other industries. Prevention and preparedness is a full-time venture and requires commitment by the entire workforce. Mine Safety and Health Administration (MSHA) statistics<sup>1</sup> indicate that 137 fires (fires reported to MSHA) occurred in underground coal and metal/nonmetal mines from 1991 to 2000 in the United States. These fires resulted in two fatalities and 34 injuries. A significant number of unreported fires are also believed to have occurred. More than 24% of the 76 underground coal mine fires during the last decade were caused by friction. Friction is followed by "other" causes, mobile equipment, welding/cutting operations and electrical fires. Of the 61 metal/nonmetal mine fires, 46% were caused by mobile equipment, followed by "other" causes, cutting/welding operations and electrical fires.

Historically, mine fires have caused fatalities, injuries and economic losses totaling hundreds of millions of dollars. A fire that occurred during coal production on Nov. 25, 1998, at the Cyprus Plateau Mining Corp.'s Willow Creek underground mine near Price, Utah, caused 45 miners to be evacuated. The mine was sealed, and inert gas was injected into the fire area. The mine reopened, and 20 months later, on July 31, 2000, two miners lost their lives and eight miners sustained injuries due to a fire and explosion. Mine personnel decided to seal the mine to contain the fire. This was accomplished in a few hours. The mine has recently reopened.

<sup>1</sup>Mine fire statistics were obtained from files maintained at MSHA's Denver Safety and Health Technology Center, Injury and Employment Information Branch, Denver, Colorado.

A more recent fire occurred on Feb. 8, 2001, at the Homestake gold mine, Lead, South Dakota. Thirty-seven miners were evacuated. Rescue teams discovered the fire in an old timber stope (inactive area) between the 1,067- and 1,112-m levels. Water was used to flood the affected area.

One of the goals of the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory (PRL), is to enhance the safety of mine workers by preventing disasters caused by fires and explosions. A series of mine rescue training and mine emergency response drills (MERD) and in-mine smoke training was developed, conducted and evaluated by state and company teams and by NIOSH personnel. These exercises conducted at Lake Lynn Laboratory (LLL) and operating mines resulted in improved technology and training for mine rescue teams, fire brigades, first responders and miners in general (Conti, 2000). During the simulations, mine rescue team members donned self-contained breathing apparatuses (SCBA) and traversed mine passageways filled with nontoxic smoke. Advanced training efforts include combating liquid fuel fires in the surface quarry area and extinguishing a conveyor belt fire in the fire gallery. This paper discusses the thermal imaging camera, a technology that can be used by mine operators for the detection of equipment failures or hot spots before they develop into a fire and by emergency responders during exploration, fire fighting and recovery operations. Several thermal imaging cameras, varying in price from less than \$20,000 to more than \$40,000, were randomly selected and evaluated.

## Thermal imaging cameras

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 sig-



**Figure 1** — A rescue team member wearing the Cairns IRIS.

nificant additional information to the user that would otherwise not be possible to obtain, e.g., fire scene assessments and seeing through smoke. This technology increases the responder's understanding of the environment (fire location, problem areas such as ceiling collapse, firefighters' progress in effective extinguishment and firefighter safety), thus enhancing safety and the ability to accomplish the task. The first civilian life saved with thermal imaging technology occurred during a 1988 fire in New York City.

The thermal imaging camera was developed in the early 1970s. During the last decade, the thermal imaging camera has become an invaluable tool for emergency responders and fire assessment. It is very different from the common night-vision devices that amplify available light or sense reflected near-IR energy. Thermal imaging cameras use 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 noncontact sensor called a "microbolometer." 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 that, 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 (e.g., bodies of water, glass and stainless steel) reflect IR just as they reflect visible light.

The former US Bureau of Mines conducted an investigation in the use of finding miners in smoke-filled environments and detection of mine hazards with infrared devices in the 1970s (Stateham, 1976; Stateham and Lombardi, 1976). For the technology used, the results showed that miners could be detected in smoke from burning coal at a distance of 80 m (260 ft). The IR imagers were also used to remotely sense potentially hazardous mining conditions (loose rock, shorted power cables, etc.).

Emergency responders are now using thermal imaging cameras (TIC) for a variety of applications. These cameras can assist rescue teams in searching through collapsed build-

ings after an explosion or earthquake to locate and extricate any victims. Many structural firefighters are using TICs to find trapped people and disoriented firefighters in smoky environments or to locate the source of the fire. On the average, it takes approximately 28 minutes to search the average home by conventional means, which requires firefighters to crawl on their hands and knees feeling for victims. A TIC can reduce the search time to two or three minutes.

Companies are using infrared scanning programs (Knisley, 1993) to uncover abnormal operating conditions for preventive maintenance in electrical/electronic installations. TICs are being used as 24-hour security and surveillance systems to monitor businesses, and they are used by law enforcement to "cruise" high-crime areas and observe suspects covertly at night. Other applications include the detection of fires in highway tunnels (Noda and Ueda, 1994), automobiles equipped with night-vision capabilities (Kaplan, 1999) and hazardous-material applications (Woodworth, 1995), including evaluating drums and cylinders for heating.

Recent improvements in the sensitivity and resolution of uncooled IR imaging detectors provided the major enabling technology for the development of a practical helmet-mounted IR vision system (Miller, 1997). In 1995, Cairns & Brother Inc.<sup>2</sup> 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. Figure 1 shows a rescue team member wearing the Cairns IRIS and preparing to enter a smoke-filled entry. 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 (0.5°F) differences in temperature. The sensor is mounted on the right side of the helmet and is housed in a flame, high-heat and impact resistant thermoplastic housing. At the front of this housing is a specially coated 15-mm germanium lens that filters out everything except the 8 to 14- $\mu$ m wavelength band or long wavelength infrared radiation band. This range allows for better resolution when trying to locate humans with an average skin radiance of 9- $\mu$ m. It also ensures that objects can be detected at longer distances through the smoke. The helmet-mounted IR imaging system weighs 4.8 kg (10.5 lb). A rechargeable nickel-cadmium battery pack provides 30-min of continuous, uninterrupted use at ambient temperatures.

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 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

<sup>2</sup>Mention of any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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° rotating display provides comfortable viewing from any position. It enables the user to see from 0.9-m (3 ft) 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  $\mu\text{m}$ , and it weighs 2 kg (4.5 lb). 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. Figure 2 shows a rescue team after they built a roof support using timbers in near zero visibility in a limestone mine at LLL. The image illustrates that team members are extremely warm after the physically demanding task, while in the background the wood crib can be seen wedged tight to the roof. 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, shown in Fig. 3, is used in conjunction with SCBAs and is easily attached to the underside brim of most standard fire fighting 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 to 14- $\mu\text{m}$ . The device weighs less than 2 kg (4.5 lb), and images can be viewed in black and white or in color. Advanced optics and display offer natural depth perception and orientation. It is also designed to easily view both IR and visual viewing 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 its light weight, viewing and carrying capabilities and ease in handing off to other team members.

The Argus thermal imaging camera can also see through smoke and darkness. Its spectral range is 8 to 14- $\mu\text{m}$ . 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 Fig. 4, that 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.

During experimental tests at LLL, the video signal from the camera, shown in Fig. 5, was successfully transmitted from inside a metal and concrete block fire gallery to an outside remote receiver station. The remote receiver, located 60 m

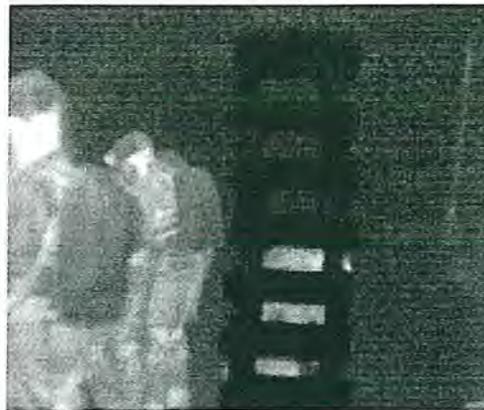


Figure 2 — A thermal image of a rescue team in dense smoke after building a roof support.



Figure 3 — Rescue team member wearing the FireFLIR thermal imaging camera.

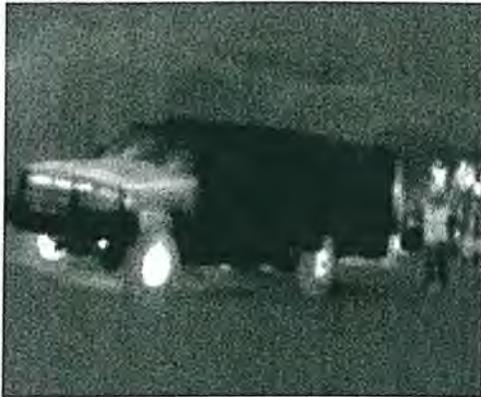


Figure 4 — Rescue team members using the Evolution 4000 TIC.

(200 ft) 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 (650 ft) 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 fire fighting efforts.



**Figure 5** — Thermal image transmitted onto a video monitor.



**Figure 6** — Image of diesel mantrip underground.



**Figure 7** — Miner behind plastic barricade.

During advanced training exercises, mine rescue teams and fire brigade members used a TIC during a training application that involved 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 face piece. 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 fire fighting efforts of the team. When the two water hoses 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.

Dräger 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 to 14- $\mu\text{m}$ . 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 (220°F) from being read and displayed, thus, allowing the operator to search for bodies based upon their temperatures.

### Thermal images

Thermal images were acquired with the Agema TIC at several underground mines. A diesel mantrip is shown in Fig. 6 as it arrives at an underground section. As seen in the image, miners are exiting the rear of the vehicle, and the temperature of the engine and the front brakes were higher as compared to the rear brakes.

Figure 7 was obtained during an underground training simulation for rescue teams in nontoxic smoke. This image shows a miner behind a plastic brattice barricade. Although thermal cameras can't see through solid materials, if the material is thin and the hot object is close to the material, the hot object can be detected, as in this case. If the miner were to move 1 to 2 m (3.3 to 6.6 ft) further away from the barricade, the image would eventually fade away.

The Dräger TIC was also used to evaluate thermal images behind yellow and white brattice curtains. When looking through brattice curtains, a miner was much more easily detected behind the white brattice curtain than the yellow brattice. For example, if the TIC is 1 m (3 ft) away from the white brattice curtain, a faint image of a person 14 m (46 ft) away on the other side could be seen. If the TIC were moved 14 m (46 ft) further away from the curtain, a faint image was only seen when the person was 2 to 3 m (6.5 to 10 ft) behind the brattice curtain. When the white brattice was replaced with the yellow brattice, the person on the other side must touch the curtain for the TIC to recognize a thermal image. This maybe due to the pigment used in fabricating the yellow brattice. The image is a depiction of radiant energy, not temperature. As conditions change, so will the image and definition.

Footprints and handprints on walls or ribs can also be detected if the individual was recently (within several minutes) in the area. However, these thermal images would fade as such prints cooled to the ambient temperature of the floor, wall or rib.

One objective of an underground training simulation was to evaluate a thermal imaging camera during exploration in zero visibility by mine rescue teams. Two dry stacked concrete block stoppings were built, one of which was coated with mortar on the heated side. Kerosene heaters were used to heat the backside of each stopping and simulate a fire. Transfer of heat through concrete block stoppings would be slower compared with the brattice material. The missing miners stood in the center of the “hot” stoppings on the sides opposite the heaters. The team members with the TIC could see the person standing in front of the “hot” stopping, as they appeared darker than the white wall. Wall temperatures of the coated and uncoated stoppings when the missing miners were found were 35° and 44°C (95° and 110°F), respectively.

Using a thermal imaging camera in a limestone mine at LLL with no wire mesh would show absolutely nothing

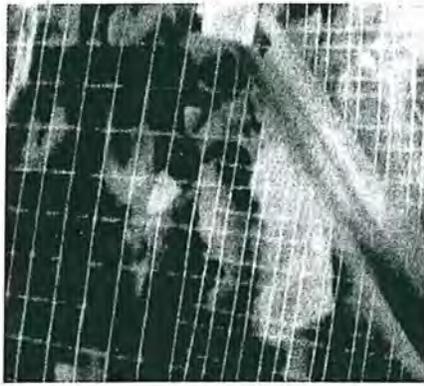


Figure 8 — Coal mine rib

because the temperature of the wall, roof and floor are fairly constant. It would be the same as traveling in the darkness or in a smoke-filled passageway without a heated object present. The opposite is seen in a coal mine. Figure 8 depicts a thermal image of a coal rib. Here, one can perceive some temperature differences of the coal, rock dusts and wire mesh mounted on the rib. If the entry were filled with smoke, a TIC could be employed to negotiate travel out of the mine.

An interesting observation was made during smoke training at an operating mine. The nontoxic smoke generator used to create a smoky atmosphere is an excellent tool to evaluate smoke leakage of mine stoppings and seals. The pressure differential between the two entries allowed the smoke to leak through or around the stopping if not properly sealed. If the smoke or air leakage were warmer than the ambient temperature of the stopping, a TIC could be used to detect the leak.

Another interesting note is that the TIC can also be used to view the thermal effects of underground air conditioning systems. During a visit at a metal/nonmetal deep gold mine, the TIC was successfully used to view the warm humid mine ventilation airflow currents as they passed through a water-spray system. The warm air currents were immediately seen being cooled by the array of water-spray jets.

### Preventive measures

These cameras may also be used as an aid to fire bosses for preventive maintenance in areas typically prone to fire. For example, the images shown in Fig. 9 depict a conveyor belt structure and a moving belt. The rollers are shown in their normal mode of operation, indicating that they are hot as compared to the rest of the conveyor belt structure. If one of the rollers were beginning to fail, it could easily be detected before it could become a fire hazard. Seen in the upper left quadrant of the image is the mine water supply line, which appears dark black because it contains cold water. Figure 10 illustrates a thermal image of a belt drive, again showing the normal operating temperatures of the motor and surrounding structure. Someone trained in the use of these cameras could very easily identify problem areas.

An interesting thermal image is shown in Fig. 11. It illustrates a misalignment of an overhead conveyor belt and the belt rubbing on the structure as shown by the hot streak on the side of the belt. As the belt moves away from the point of contact, the hot streak is seen dissipating. The image shown in Fig. 12 illustrates an overhead belt structure with wire mesh attached to the underside. The operation of the belt roller deteriorated the steel mesh, but still seen is the remnant of hot steel from the mesh in contact with the moving belt roller.

Figure 13 represents an electrical power cable hung from



Figure 9 — Conveyor belt structure.



Figure 10 — Belt drive motor.

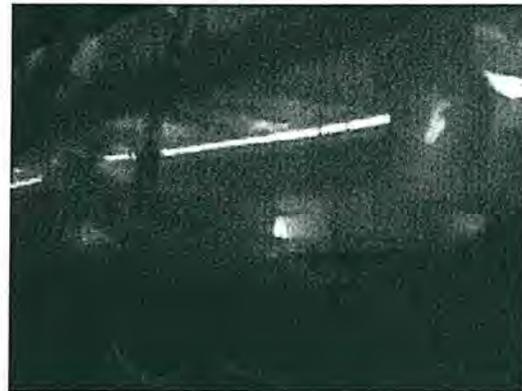


Figure 11 — Conveyor belt rubbing.

the roof near the underground power center. Clearly seen from this thermal image is a fault that is starting to develop near the left side of the image.

Field tests using a thermal imaging camera were also conducted to evaluate the migration and heat dissipation of hot residues (molten metal) from underground cutting/welding operations. Figure 14 delineates a typical electrical welding operation on a conveyor-belt structure. It should be noted that whenever using a TIC, the welding arc should be shielded from the camera to protect the focal plane array sensor from damage. Preliminary observations show that during welding operations where the residue is contained by a curtain, the hot particles fall to the floor (Fig. 15) bouncing off the structure in various directions. The particles can remain hot for several



Figure 12 — Belt roller in contact with wire mesh.

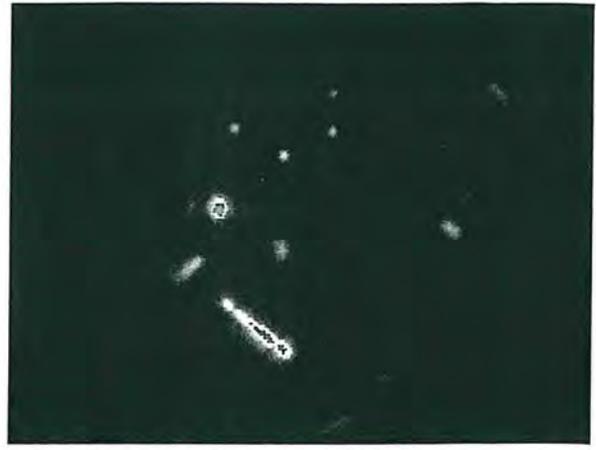


Figure 15 — Hot residue from welding.

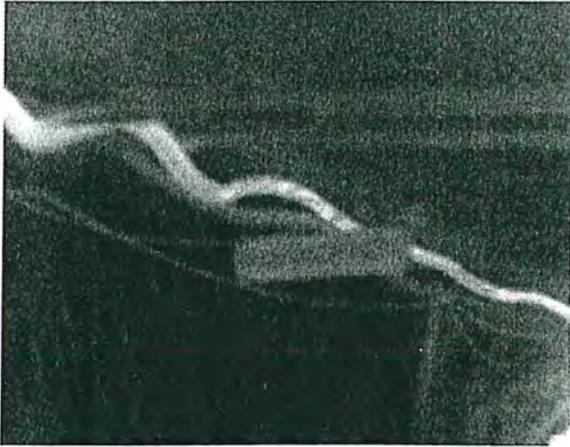


Figure 13 — Electrical power cable.



Figure 16 — Cutting operation.



Figure 14 — Welding operation.



Figure 17 — Residue from cutting operation.

minutes. However, the spent welding rod can remain hot for more than 20 minutes. It was also observed that, during the welding operation, as the welder changes positions and moves around the welding area, the hot residue can be buried under the rock dust and the rock dust can serve as a thermal insulator. Additional experiments would be required to measure the spot temperatures of the residue and determine how temperatures decrease over time.

A thermal image of an oxygen-acetylene cutting operation is shown in Fig. 16. During the cutting operation, the hot

particles are seen hitting the floor. As part of the standard operating procedure at this mine, a miner can be seen pouring water over the hot residue after completing the cutting operation in Fig. 17. As the water is being applied, steam is being produced and the hot water can be seen flowing on the floor. Even after being cooled with water, the molten metal remains hot for well over 15 to 20 minutes.

Thermal imaging cameras have potential to be used after these types of operations or when fire bossing other areas prone to fire. An IR or thermal imaging camera could be

incorporated into the operating procedure of a welding/cutting permit (Conti et al., 2000) to ensure that all hot residue is cooled down to ambient temperatures before leaving the area.

Spontaneous combustion of coal is due to the oxidation of coal surfaces, a heat-producing reaction. The self-heating of coal can occur in aboveground stockpiles, open-pit storage bins and in underground areas. Early detection is critical in the prevention and control of fires caused by spontaneous combustion. The photo in Fig. 18 illustrates a typical aboveground stockpile and storage area. In Fig. 19, the heated area of the outcrop can be seen with a TIC. The image was acquired during daylight hours. In some areas of the pile, visible smoke was clearly seen rising from the smoldering coal. The point is that a TIC may be used to determine where the heatings are occurring, and they can be controlled before visible smoke or flames are observed.

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 are properly trained and that practice-training sessions are conducted frequently, so they can readily interpret the images. For example, during an underground mine rescue training simulation, an inexperienced team member using a TIC, misinterpreted a heated object behind a yellow brattice curtain as three of the missing miners from the problem.

Current thermal imaging cameras require too much power and produce too much energy to qualify as intrinsically safe products. Products that are intrinsically safe will not generate enough heat or electrical energy to serve as the ignition source for an explosion. Currently, there are no standards or regulations for intrinsic safety of TICs. However, technology is rapidly improving and lower power thermal imaging cameras at lower costs are on the way.

## Summary

Prevention and preparedness are essential elements of any underground mine's strategic plan in dealing with an unexpected event, like a fire. Time is a critical factor, and any delay may mean serious injury and the loss of the mine. Therefore, it is important that a heating or fire be detected in the incipient stage.

The thermal imaging camera has merit for mine rescue exploration and recovery in smoke-filled passageways. However, the training 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.

Fire bosses and other mine personnel could use thermal imaging cameras for preshifting of areas prone to fires, like conveyor beltlines and power centers and for detecting spontaneous combustion. They may aid miners during welding/cutting operations by ensuring them that the hot residue is cooled enough or extinguished before moving onto another task.

Although this technology is expensive and the cost may prohibit many mine operators from procuring a device for preventive maintenance, everyone should have access to thermal imaging cameras when lives are at stake. Perhaps communities can pull their resources together so that a TIC is available for all emergency responders (fire departments, etc.) to use during a catastrophic event.



Figure 18 — Photo of coal pile and outcrop area.



Figure 19 — Thermal image of heated area in Fig. 18.

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