AN ACTIVE PROXIMITY WARNING SYSTEM FOR SURFACE AND UNDERGROUND MINING APPLICATIONS

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ABSTRACT

NIOSH has developed an active proximity warning system called HASARD (Hazardous Area Signaling and Ranging Device) for warning workers as they approach known dangerous areas around heavy mining equipment and other dangerous work zones. HASARD is composed of a transmitter and a receiver. The transmitter generates a 60-kHz magnetic field using one or more wire loop antennas. Each antenna is adjusted to establish a magnetic field pattern for each hazardous area. The receiver, worn by the worker, is a magnetic field strength meter. The received signal is compared against preset levels which are calibrated to identify levels of danger. The receiver outputs can include visual, audible, and vibratory indicators and it can also be made to disable machine functions. HASARD was field tested on a Joy 12 continuous miner, a Komatsu 210 M Haulpak, and on a highwall launch vehicle. Slight modifications were made for each application. HASARD provided warnings as designed and proved to be rugged enough to withstand the harshest of production environments.

INTRODUCTION

Researchers at the Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH) have been investigating proximity warning systems [Schiffbauer, 1999] that can be used to warn and protect persons working close to heavy machinery in surface and underground mining operations. Their efforts are based on statistical data which has identified the need for the investigation. The Mine Safety and Health Administration (MSHA) collects data for surface and underground mining operations. The MSHA database shows that there has been a high number of surface and underground personnel that have been killed or permanently disabled as a result of working near machinery and powered haulage. In surface mining operations, an average of 13 mine workers are killed each year by being run over or pinned by mobile mining equipment. In underground mining, twenty-four fatalities were associated with continuous mining machines during the six-year period between 1992 to 1997. In most cases the miners are well aware of the dangers, but at times they become preoccupied with operating their equipment, and they fail to notice when they or their co-workers stray into or are exposed to potentially hazardous situations. Part of the problem is that the workers attention can be divided among many tasks such as maintaining production goals, watching out for their own safety or that of their co-workers, processing visual, touch, and auditory information. The operator may find himself in a rush or mentally overloaded making him less able to process the information and to make safe decisions [Cornelius, et al, 1998]. When these situations occur, the machine operators and their co-workers can be injured or killed.

HASARD DESCRIPTION

NIOSH developed the HASARD system to reduce the risks of working near heavy mining equipment. HASARD is an active proximity warning system. The active feature is a very important part of the system and is somewhat unique since most proximity warning systems [Jurgen, 1998] are of the passive type. Passive types of proximity warning systems are triggered by all objects they detect within their range which is not always desirable. This is especially true in underground continuous miner (CM) coal operations. There, operators and helpers work in proximity to CM's as well as the walls (ribs) of the mine. A passive system would be triggered every time it detected a wall or a person. In surface mining operations large haul trucks frequently run over large pieces of earth, rock, and other debris. If the system triggered with every large piece of material it detected, it would become a nuisance to the driver of the truck, causing him/her to tend to ignore the system. HASARD, being an active type system can minimize or eliminate nuisance alarms.

HASARD requires a transmitter on one object and a receiver on another object. In this way, objects to be avoided are positively identified and can be avoided, and objects that don't matter can be ignored. In the underground mining example with a transmitter on the CM and the receiver on the person, the system could keep the person from being crushed, but would let the operator use the rib to steer. With a receiver on a large haul truck, and a transmitter on a small truck, the large truck operator would know that a small truck was in the vicinity, which could effectively prevent an accident. A transmitter and receiver combination could be put on a wide range of objects such as people, edges of roads, poles, etc.

As mentioned above, HASARD consists of two parts, (i.e., a transmitter and a receiver). Accessories have been added to the system to provide remote alarms, data logging, and shut-down features. The transmitter consists of a low-frequency (60 kHz) source with two independently adjustable power output channels. The transmitter creates a current through a properly tuned loop antenna, producing a magnetic field about the loop. Figure 1 shows how a magnetic field is produced around a conductor. The loop acts like any low-frequency transformer. The magnetic field generated is held constant due to its constant current design. By measuring the resultant magnetic field with a calibrated 3-axis receiver, the distance between the transmitter loop antenna and the receiver can be determined. The 3-axis receiver compensates for fluctuations in the detected magnetic field due to changes in orientation that could otherwise be interpreted as changes in distance. These properties are the essence of the HASARD system. The receiver can be made to provide some action when ever a magnetic field signal of a certain level is detected. From the HASARD perspective, as a person enters a dangerous zone some signal or action can be triggered.

Figure 2 shows a top view of the HASARD system as applied to a CM. The HASARD transmitter puts a signal into a loop of wire (the antenna) that is positioned around the periphery of the machine. A HASARD receiver is being held by a miner. As shown, the magnetic field generated by the loop conforms to the shape of the loop. The zone indicated is defined by a certain level of magnetic signal generated by the transmit loop antenna. The receiver contains circuitry for two threshold detectors which are calibrated to trip at signal levels which are relative to specific distances from the transmit loop antenna. These threshold detectors are calibrated to identify the zones around the CM. The receiver (figure 3) includes a vibrating motor. The motor is triggered by the output of one of the threshold detectors when a signal of a certain amplitude is received, which causes the entire receiver to vibrate alerting the wearer. The vibrating motor was chosen as the alert indicator, since a buzzer probably would not be heard by a miner because of the noisy nature of underground mining. A visual indicator was not used since the receiver would most likely be worn on a belt or in a pocket. Figure 4 shows how the HASARD system is typically used with a CM. Included in the receiver design is a short-range UHF transmitter that can convey the receivers status to a remote data collection point. The data conveyed includes radio status, as well as safe, caution, and risk signals.

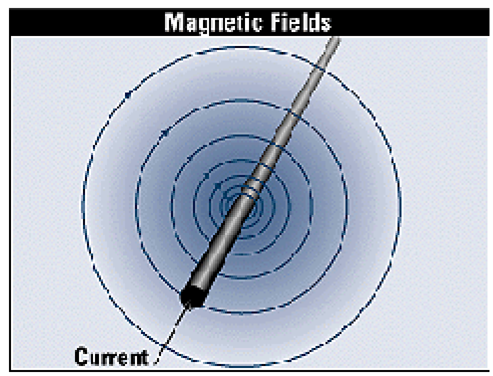

Figure 1. Magnetic fields.

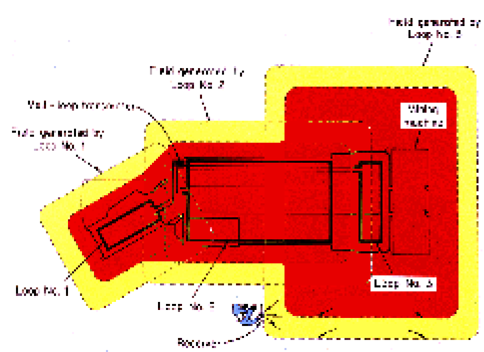

Figure 2. Top view of HASARD on CM.

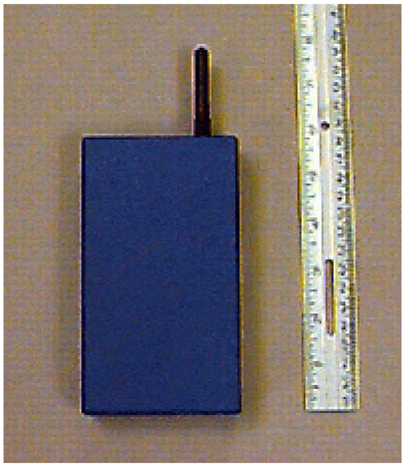

Figure 3. HASARD receiver.

A CM-mounted data receiver and light display intercepts the data from the receiver on the worker, and provides a remote visual indicator of the workers position with regard to zones around the machine. The combination is called a Data Link Receiver with Machine Mounted Indicator Lights (DLRL) (figure 5). The DLRL consists of four explosion-proof enclosures with Lexan caps. One enclosure houses an antenna and receiver, and the other house a red, yellow or green, light bar. The green light bar indicates the worker is in a safe area and the radio link from the worker to the DLRL is functioning. No lights indicate that the radio link has failed. Normally, when the green light goes out, a yellow or red light is illuminated. The yellow light indicates the worker is in an area where his safety will be compromised. The red light indicates the worker is in peril.

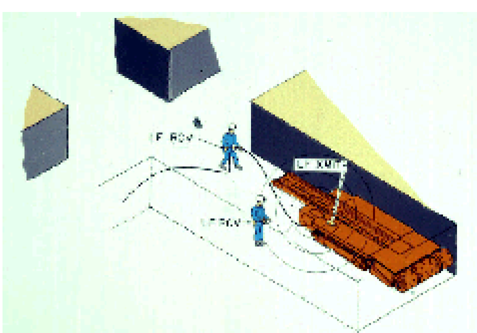

Figure 4. HASARD installation on CM.

A second device designed for the system, called a Data Link Receiver with Data Logger (DLRD) (figure 6) also intercepts the data from the receiver on the worker. It was primarily designed to act as a research tool for our investigations. It provides a remote visual indication of the status signals, and it archives that data in a data logger along with a time stamp. This device was created so that an observer could remotely see the worker's status as he goes about his daily routine. The data logger is initiated at the beginning of the work shift, and is unloaded at the end of the shift. The DLRD provides a continuous recording of the workers position relative to the zones. A typical scenario for the DLRD's use is shown in figure 7.

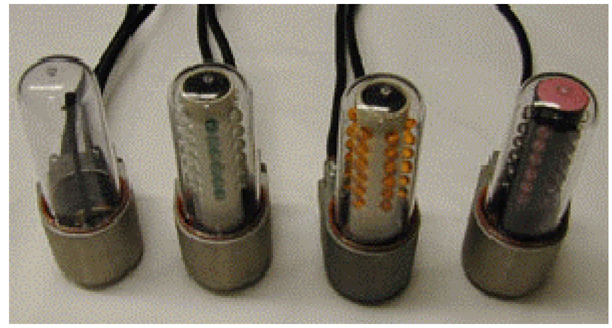

Figure 5. Data link receiver with machine mounted indicator lights.

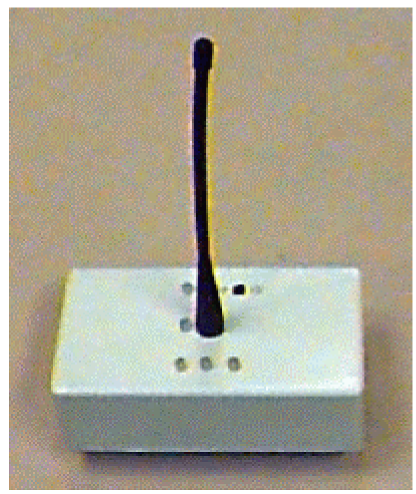

Figure 6. Data link receiver with data logger.

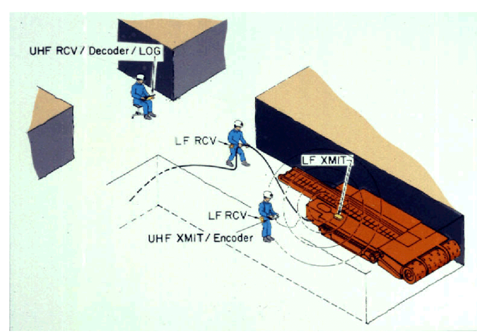

Figure 7. Typical installation of data link receiver with data logger.

DESIGN AND INTEGRATION ISSUES

The HASARD system was originally designed to work in an underground coal mine. It was designed in compliance with the Title 30 Mineral Resources Code of Federal Regulations (30 CFR) Part 18, Section 18.82 as required by the Mine Safety and Health Administration (MSHA) and the Pennsylvania Department of Environmental Protection, Bureau of Deep Mine Safety (DEP). HASARD was assigned an Experimental Permit by MSHA and DEP. HASARD is an intrinsically safe prototype system which was designed to be attached and removed from machinery as it evolved. HASARD is battery operated so that it would not have to be attached to the CM's power system, minimizing the time required to install and remove it. Ultimately, HASARD would be permanently attached to a CM's power system. The output power of the HASARD transmitter was limited to 3 watts at 60 kHz as a result of conforming to the MSHA and DEP approval criteria. Although the power is very low, an effective magnetic envelope can still be produced.

High frequency magnetic fields can be influenced by large metal objects. Since the system is being applied to large metal machinery, a lower frequency was chosen to minimize interference. The large metal machinery can also pose another problem for magnetic fields. Usually large machinery is electrically driven and can generate a tremendous amount of electrical noise. If the electrical noise is in the same frequency band as the frequency of the magnetic signal, the receiver may not be able to distinguish the signal from the noise. To account for this possibility, field tests were performed around the machines to determine their electrical noise characteristics. It was found that most of the noise tapers off above 30 kHz. Another potential source of interference to HASARD are communication devices that operate in the same band of frequencies. One communication device identified in mines that comes close in frequency is trolley phones, which typically operate at 88 kHz. Tests showed that HASARD worked well near large metal machines, with electrically noisy drive systems and 88 kHz trolley phones.

Designing transmit antennas for HASARD was particularly challenging because the antennas had to be protected from general abuse such as running into walls, roofs, and other mining equipment. The antennas would also be exposed to falling coal, shale and rock. In order to provide strength and protection heavy metal shrouds were specially constructed to protect the antennas. Installing the antennas on the top of large metal structures attenuates the signal, decreasing its range. Installing the antennas inside metal shrouds further reduces the range of the signals. In spite of those constraints, HASARD was capable of producing enough of a magnetic envelope to effectively mark the dangerous zone.

The HASARD receiver, although relatively simple, is the most complex part of the system. This is primarily due to the nature of the transmit antenna. The loop antenna magnetic field is predominant in one axis. A single receiver would receive the maximum field as long as it was oriented in the same plane as the transmit antenna. The received signal is therefore dependent on the orientation as well as the distance from the antenna. To compensate, the receiver contains three loop antennas, with three separate amplifiers. The antennas are positioned orthogonally in order to pick up the maximum possible signal for any orientation. The received AC signals are converted into DC voltages which are then summed together. The resultant DC voltage is calibrated to relate to the distance the worker is from the machine. A multi-level threshold detector provides a trigger for a built-in vibrating motor and encoder. The vibrating motor lets the worker know that he has entered a hazardous zone. The encoder is used to convey data to an ultra high frequency (UHF) 418 mHz transmitter that provides remote acknowledgment of the workers position relative to identified zones. The loop antennas used in the receiver employ small ferrite rods which concentrate the magnetic signal, effectively reducing the physical size requirements of the loops. This helps to keep the size of the receiver practical.

Although HASARD was primarily designed for use at coal mines, its use could be extended to include applications in metal/non-metal mines. The transmitter signal will be minimally affected by strata. But, large metal machinery will affect the transmitter signal in the same way as it does in a coal mine. Radio frequencies used for communications could be an issue but typically metal/non-metal mines use leaky feeder systems that employ frequencies of 150 mHz or 450 mHz. These frequencies are far removed from any of those used by HASARD so there should not be any interference issues.

LABORATORY TESTING

HASARD was tested at a PRL surface test facility and also in the PRL Safety Research Coal Mine (SRCM). Most tests centered on a Joy 14 CM (Mention of specific products or manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health) in the surface test facility. Some tests were performed on a shuttle car. Other tests were performed on a Jeffrey 102 CM in the SRCM. The testing characterized how magnetic fields were affected by large metal structures. Many different antenna configurations and shapes were built and evaluated. A simple set of antenna design methods were developed that could be easily adapted to most machine types. All antennas were constructed from MSHA-approved three-conductor, No. 14 AWG type, SO cable. The loops consisted of one to three or more turns of SO cable. The number of turns was dictated by the required size of the magnetic field. The magnetic field produced by the antenna is generally referred to as the magnetic moment (*m)* [Fink, 1975]. *m* is the product of the current (I), the number of turns in the loop (N) and the area (A) of a current carrying loop. There is however,

$$m = INA \qquad (1)$$

a practical limit on the number of turns of wire in the loop. As the number of turns of wire increases, a point will be reached where the power begins to decrease due to long cable lengths and increased inductance which limits the size of the magnetic moment.

Antenna protection schemes also required much laboratory testing. An antenna on a CM would be exposed to tremendous abuse. The laboratory prototype antenna cover consisted of 1/8 inch thick "C" channel with a series of holes in it (figure 8). The holes allowed the magnetic signal to emanate but still provided protection for the cable. Experimentation proved that a repeatable and a predictable magnetic moment could be developed around the machine with the metal cover.

Figure 8. C channel on CM.

HASARD UNDERGROUND FIELD TRIALS

A coal mine near Indiana, PA agreed to provide NIOSH the opportunity to test HASARD in a production environment. A test plan was approved by MSHA and DEP, and each inspected the system after its installation to insure that it met all applicable regulations. The HASARD tests were primarily designed to determine if the system would be able to survive an intensive production operation. This mine was a good choice for extreme conditions due to the type of mining method employed and to the tons-per-man-hour of coal produced (10.97). The mine used a Joy 12 CM with a ripper cutting head. This particular cutting head had a large and relatively smooth surface. The HASARD antenna for the cutting head had to be placed on top of this smooth surface. The coal seam was 12 feet high and it had a 6 to 12 inch shale parting at 4 feet from the floor. The mining technique employed involved cutting the top 8 feet of coal. Next the cut would be bolted. Since the mine didn't have a preparation plant they would go back into the cut and take out only the parting. The parting would be loaded separately and then used throughout the mine for road bed construction. Finally, the bottom 4 feet of coal for the cut would be mined. This unique mining method was very destructive to any object that would be attached to the smooth part of the cutting head because the parting would come off in large sheets that would tend to shear off any attached object.

Figure 9. Antenna on cutting head.

The HASARD transmitter was bolted close to the center of the machine. One loop antenna was spot welded to the cutting head and along the conveyor box down the center of the machine. This antenna consisted of one long cable with two multi-turn lobes, encased in a protective metal channel, each attached to the surface of the cutting head (figure 9). The second antenna was spot welded to the conveyor. It consisted of two multi-turn lobes, one on each side of the conveyor. With this configuration the transmitter was able to generate a magnetic envelope which extended a number of feet around the periphery of the machine. A receiver was arbitrarily calibrated so that at two feet from the machine a "Caution" signal was triggered, and at one foot from the machine a "Risk" signal was triggered. The receiver was worn by a miner operator for a full production shift. His actions were remotely observed both visually and with a DLRD. As the miner moved into and out of the different zones, the indicators on the DLRL and DLRD performed as designed with no major failures. After the tests, the transmitter was removed from the machine but the antennas were left in place for long term exposure to production. These first antennas lasted for about one week of production which consisted of 10 shifts. The remnants of one lobe of the cutting head antenna is shown in figure 10. The antennas on the conveyor were ripped off. More rugged antennas were designed and installed. The new cutting head antenna cover was constructed from 1/4 inch thick angle iron. The conveyor antenna was protected by 1/8 inch thick "C" channel. The cutting head antenna was largely encased in the angle iron with some of the cable being attached along the body of the machine. The antenna on the conveyor was recessed into the "C" channel. Again the system was tested and the antennas were left on the machine. This set of antennas lasted about one month. The conveyor antenna suffered minimal damage. One lobe of the cutting head antenna was ripped away , but the second lobe remained intact. In the final phase of antenna testing, only a new cutting head antenna was evaluated since there was confidence that ½ inch "C" channel would protect the conveyor antenna. The last cutting head antenna cover design consisted of ½ inch thick angle iron (figure 11). A wider weld was used to hold the angle in place more firmly. The cutting head antenna was installed, tested and left in place for over three months. The antenna showed no signs of failure (figure 12).

Figure 10. Remnants of cutting head antenna.

Figure 11. ½ inch angle iron antenna.

Figure 12. Cutting head antenna.

The HASARD field trials showed the system could withstand the abuse of a production environment. The environment in which it was tested was probably a worst case scenario due to the unique mining method employed.

The signal from the transmitter was degraded each time thicker steel was used for the antennas, but the signal was able to penetrate all the protective coverings and provide a large enough magnetic envelope to identify a hazardous zone. The area in front of the cutter head was the hardest to cover with magnetic signal because the antenna was two feet or more from the tip of the picks on the cutter. All other areas around the machine perimeter were easily covered with the signal. A more powerful transmitter and a more finely tuned antenna would certainly achieve a more substantial magnetic envelope beyond the cutter head. Using a higher power transmitter would probably require housing the transmitter and antennas in explosion proof enclosures in order to meet the MSHA and DEP regulations.

HASARD SURFACE FIELD TRIALS

The HASARD system was tested for potential use in surface mining operations. In one case it was evaluated in combination with researchers at the Spokane Research Laboratory (SRL) of NIOSH. SRL researchers were investigating various sensing and warning system technologies [Ruff, 2000] that could be used to detect the presence of on obstacle in the blind spot of a large haul truck. The obstacle to be avoided in the SRL evaluation was a small pickup truck. HASARD was compared with other types of systems including radar, and Radio Frequency Identification Systems (RFID). The SRL study was limited to radio frequency devices. For purposes of comparison, this test classified HASARD as an RFID type of system, although it might have been more appropriately identified as a magnetic sensing system. The testing centered on a 50-ton Komatsu 210 M Haulpak at an SRL surface test facility. While this truck was much smaller than most trucks used in surface mining operations, it provided an adequate platform for the tests.

A more powerful version of the HASARD transmitter was configured for the SRL tests in order to provide more range between the transmitter and receiver. The underground version of HASARD was severely limited in power because of the stringent MSHA and DEP regulations required for electrical equipment. The HASARD transmitter was capable of developing about three watts of signal in an antenna. The surface version of HASARD was designed to develop 50 or more watts. The same receivers used for underground tests were also used in the surface test.

Figure 13. Roof antenna.

The system configuration for underground applications of HASARD consisted of putting the transmitter and antennas on the CM and placing the receiver on the person. For the surface tests, the transmitter was placed on a small truck, and the receiver was placed on the large haul truck. The experiment consisted of placing a rectangular loop antenna (approximately 49 by 53 inches) on the roof of the small truck (figure 13). The antenna was composed of seven turns of 14-gauge wire encased in PVC pipe. The receiver (figure 14) incorporated a simple LED bar graph display that indicated the signal strength from 1 to 10, with 10 indicating the strongest signal. The receiver was used to map the detection area. The results of the tests showed that a very uniform detection zone of about 30 feet could be provided at each corner of the large haul truck. In retrospect, if the transmitter and antenna were placed on the haul truck and the receiver was placed on the small truck, the range of operation would have increased substantially due to the fact that a larger antenna generates a bigger magnetic envelope. The selected test configuration proved that HASARD could be used as an effective warning system for surface mining operations.

The HASARD system was only tested between a large haul truck and a small pick up truck. To include protection for people working in blind areas around the machine, it would make sense to have the transmitter and associated antenna installed on the large truck and have a receiver on the person. The primary advantage for this configuration would be increased system range.

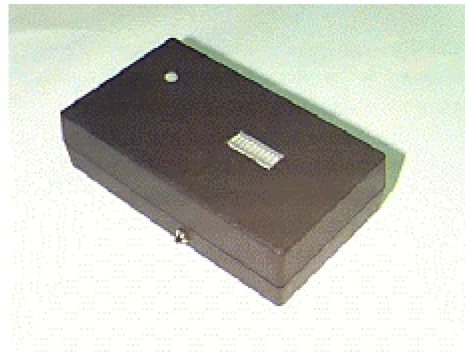

Figure 14. Receiver with LED bar graph.

Using a higher powered transmitter for HASARD raised some safety concerns should it be employed in an area where explosives were used or stored. No known MSHA regulation could be found to determine a safe operating distance from a HAZARD transmitter/antenna to an explosive material. The Institute of Makers of Explosives [Safety Guide, 1981] provided recommendations for frequencies above 535 kHz, and powers above 4,000 watts. At that frequency and power a suggested separation distance from an antenna to a blasting cap was 750 feet. A second known recommendation was provided in a mining research contract report [Franklin Research Center, 1985]. The report suggests that a minimum distance of 10 feet should be maintained from antennas and signals of the type used in HASARD, from any blasting cap or wiring attached to a blasting cap.

A second surface mining application of HASARD was on a highwall mining system. This system consisted of a continuous mining machine, a multiple-car haulage system, and a large launch vehicle (figure 15). The problem addressed by HASARD was on the launch vehicle. The vehicle included a long and wide conveyor belt that ran through the center of the machine and located just below worker foot level (figure 16). In most cases the conveyor belt area was covered by a stacked conveyor section, but there were times when that was not so. There was a fear that an operator may trip and fall on to the belt, and be transported off the machine. To address the potential problem, a HASARD transmit loop antenna was placed below the belt and along the length of the launch vehicle. The loop antenna established a danger zone over the whole length of the belt. Workers on the launch vehicle were required to wear a receiver. The system was designed so that if anyone got close to or fell on the conveyor belt, a radio remote switch would be activated via the workers receiver and the belt would be shut off. The system was placed on the machine in early 2000 and is still in operation on the machine. Plans include adding the system to the remainder of the companies launch vehicles.

Figure 15. Launch vehicle.

Figure 16. Conveyor belt.

CONCLUSIONS

NIOSH has created an innovative safety device called HASARD that has the potential to not only warn workers around dangerous machine areas but can also shut down the machine should it pose a danger to the worker. The system has been installed in a very harsh production environment. In that environment the antenna and its protective cover has proven itself to be capable of surviving even when exposed to tremendous forces. HASARD has been tested and compared to other warning systems and has demonstrated its ability to provide a uniform and reliable marker in blind spots around heavy trucks. HASARD has also demonstrated that it can be applied to heavy equipment where a uniform marker and machine shutdown capability is needed to keep workers out of harms way.

NIOSH has demonstrated that HASARD is a rugged and reliable tool that can be adapted to alert workers when they approach hazardous work areas and can also provide remote machine shutdown should the worker be in imminent danger.

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