NEW TECHNOLOGY FOR REAL-TIME IN-STOPE SAFETY MANAGEMENT

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1. **Abstract**

South African underground hard rock mines are typically managed using measurements made daily, weekly or even monthly of key parameters like face advance, readiness to blast, blast success, temperature or dust levels. Safety and health can be greatly improved if a real-time measurement system can inform decision making.

To enable this vision of widespread sensing, communication and decision support, CSIR has developed an open standard architecture for communication of sensor data, and a reference implementation using that standard. The standard is called AziSA, which means “to inform” in isiZulu. AziSA provides an architecture that allows for connection of any type of sensor and that is particularly suited to wireless sensing.

On the safety side, the CSIR is developing a suite of sensors specifically around the risk of rockfalls. Sensors such as an electronic replacement for the barring tool, or a thermal sensor that can detect loose rock, can already be used to identify potential hazards in the hangingwall. When these sensors are combined with location and time information in a single database, it becomes possible to build maps of risk and to extrapolate risk into un-mined areas. It is also easy to confirm that routine safety procedures like barring are actually taking place.

In the future, we propose that entry inspections will be made using remote techniques that will not place an individual miner at risk. While miners will still be required to bar or place support, they will do so with a clear idea of which portions of the hangingwall are safe, and which present risk.

On the health side, if a network such as AziSA is deployed in the stope, it becomes much easier to monitor the condition of individual miners. The work strain experienced by miners can be monitored through heart-rate sensors, and their core body temperature can be monitored using various novel techniques discussed in the paper. Additional sensors can be added to quantify worker exposure to hazards such as noise or dust.

Individual sensors allow for people who are at an unacceptably high risk of developing heat disorders to be treated timeously, and they also allow for team management based on objective measures. Over a longer period, position sensing and environment monitors, or personal dosimetry, provide a powerful management tool to prevent workers from being overexposed to hazards, and to confirm that management instructions are being followed.

Cost-effective sensing in the stope is a major challenge, but one that can be overcome through technology like that used in AziSA. Sensing provides opportunities both to

make immediate interventions when workers are exposed to unacceptable risk, and to manage the long-term exposure of workers to hazard.

2. Introduction

Much of the measurement that drives decision making in a typically South African hard-rock narrow-stope mine is acquired relatively infrequently, sometimes as seldom as monthly for survey information. In addition, much of the data is communicated verbally, and can almost be expected to be inaccurate, as accurate data is often not favourable for the deliverer of that data. For example, the answer to ‘did you blast today?’ is always ‘Ja meneer’ (‘yes sir’).

Safety is a key area where measurement can assist in driving behaviour. While culture will always be central to good safety, measurement may be able to drive a more safety-centred culture, by creating an environment where compliance is easily monitored, and by showing workers the direct consequences of non-compliance in the form of a risk map.

3. Background: AziSA

3.1 AziSA

AziSA, from the isiZulu word ‘to inform’ is an architecture and a set of protocols that prescribe how data should be transmitted between sensors and a central database. The protocol and architecture are designed specifically to enable in-stope sensing, and the initial applications use the Zigbee wireless network architecture for the in-stope segment of the system. Applications of AziSA are generically called ‘Smart Mine’ applications [15].

3.1.1 Philosophy

AziSA implements a Data-Information-Knowledge-Wisdom (DIKW) hierarchy [1]. The hierarchy describes how measurements can become the basis for decisions:

- At the lowest level in the hierarchy is data. Ackoff and others [1, 2] define data as simply symbols, or what we call measurements. However, measurements have no value without some descriptive information as to when they were made and where they were made
- Information is formed by data in relationships. The data acquires meaning through its relationships with other data.
- Knowledge is the appropriate collection of information. It implies an application of data and information and is formed through the process of understanding patterns.
- At the top of the hierarchy is wisdom. Wisdom is evaluated understanding. While the first three categories relate to the past, it is wisdom that deals with the future.

In the context of a measurement system, data is raw measurements, stamped with time and date. Information is created by gathering data in a relational database, allowing connections to be identified. The process of generating knowledge out of information is still a frontier for computer science research because it is difficult for computer systems to reason about patterns. Finally, wisdom remains the domain of the human: even when knowledge can be deduced automatically from information and knowledge, decisions about the future are still made by humans.

3.1.2 Architecture

Details of the AziSA architecture are available in [13]. In summary, the architecture consists of four layers, distinguished by their decision making ability:

- Class 4 devices are just sensors. They can send data sensed locally, and can also receive instructions to raise an alarm, where the alarm conditions are determined elsewhere in the system.
- Class 3 devices are sensors with the ability to raise an alarm based on their own sensor input only. For example, a methane sensor would be a class 3: as well as communicating the level of methane in an area to the network, it is also capable of raising a local alarm if the methane level goes above a set trigger level.
- Class 2 devices can make decisions based on sensor data from anywhere in the network. In general, class 2 devices are connected to a mesh-network of class 3's and 4's, and perform the role of gateway to the larger AziSA network.
- The class 1 has access to all the data in the network, and makes the data available to registered client applications. The class 1 can also determine that an alarm condition exists based on any data in the system, and can raise alarms in specific areas.
- Above the class 1 in the hierarchy is the application specific programme that registers to receive specific class 1 data as it comes in, and analyzes and presents it for operator decision-making.

While the AziSA specification does not require it, typically the class 3s and 4s are deployed in a Zigbee wireless mesh network in the stope [9]. Wireless is used because it is very difficult to maintain a wired network in the harsh stope environment. The vision is for sensors to be sufficiently cheap that they can be deployed once, will run for their design life and are then not recovered (Figure 1).

The class 2 sits at the location of closest power, typically the scraper winch, and communicates wirelessly with the class 3s and 4s. It then typically uses powerline carrier (PLC) along its own power cable, to communicate with the nearest available mine data communication infrastructure (Figure 1).

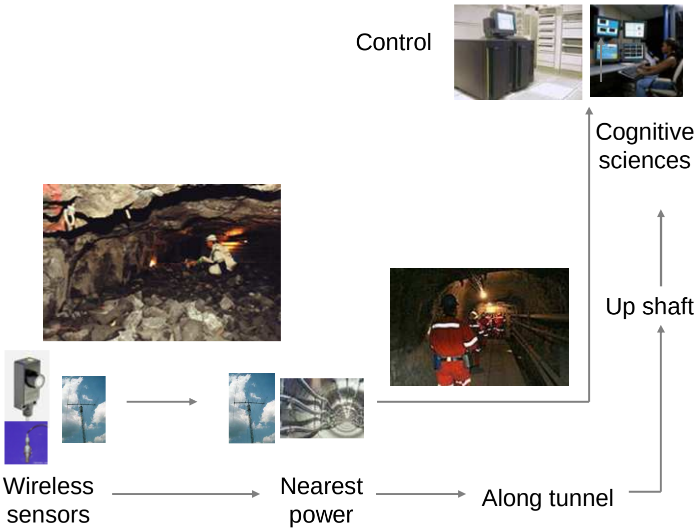

Figure 1. A typical AziSA installation. Class 3s and 4s sit in the stope and communicate wirelessly to the power at the nearest winch. From there, data travels along power line carrier to the mine's IT infrastructure, then up the shaft to a database and to the control room.

3.1.3 Location

As discussed above in 3.1.1, measurements cannot be considered as data unless they are associated with time and place, so the AziSA system supports the attachment of time and position stamps to all data. In order to determine position, ultrasonic beacons have been developed [6] (Figure 2). The beacons would be located at known positions in the stope, for example at survey pegs.

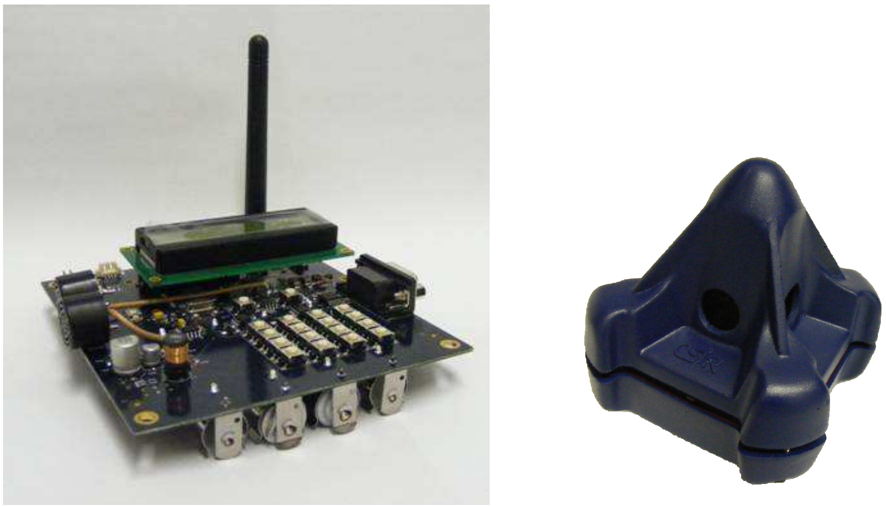

Figure 2. The prototype of an ultrasonic beacon for positioning sensors or mobile sensors underground, together with its housing. The beacon would normally be deployed on the hangingwall.

Each beacon transmits an ultrasonic pulse and a radio pulse at the same time. Any receiver in the stope can determine its distance from each beacon by comparing the difference in arrival times. With three or more beacons, position in two dimensions can be determined. Tests indicate that the system is accurate to tens of centimetres in a typical stope environment.

Typically, when a static sensor is being commissioned, a position receiver that uses the beacon infrastructure would be used to determine the sensor position and then program that sensor with its position. Sensors would not require their own position receiver hardware, saving on cost and on battery life. For mobile sensors, such as sensors carried by individual miners, position would be monitored constantly. It is likely that mobile sensors will be considerably more capable and costly than static sensors so position receiver cost is less of an issue. They will also return to surface every shift, allowing for easy battery recharging.

3.1.3 Risk management

The weather map (Figure 3) is a useful analogy for the processes envisaged for real-time in-stope safety management and the DIKW hierarchy. Weather forecasts are based on a very large number of individual measurements, or data, and a lot of computer modelling of relationships and patterns that together generate information and knowledge. While the underlying process is complicated and involves huge amounts of data, the product is readily understandable, and is typically presented in the form of an estimate of risk. A person who looks at the map is quickly able apply wisdom to determining the risk of particular events such as rain, and make decisions on the basis of that risk. A user of the map need not be concerned over the measurements or computer models, but can simply use the result.

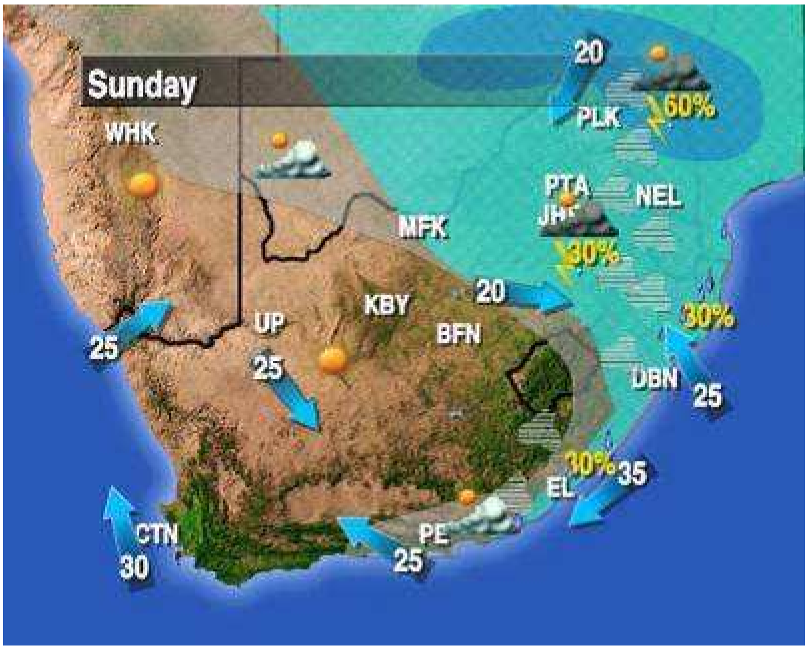

Figure 3. A typical weather map as it appears on South African television.

The vision for in-stope risk management is to combine data from sensors in the stope, as well as historical data and modelled scenarios, to calculate risk contours for various areas in the stope and for different types of risk. The miners who work in that stope can then use the risk contours to plan risk management measures. For example, contours of increased risk of rockfall can lead to placement of more support. An example of such a probabilistic risk assessment methodology with its outputs can be found in [3] (Figure 4).

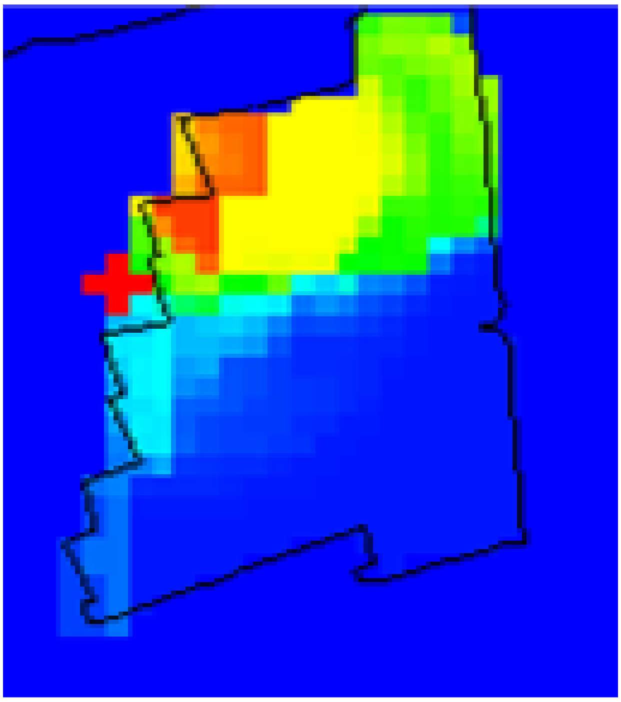

Figure 4. A colour map of risk in a stope, with warmer colours indicating higher risk, together with the location of a seismic event within 24 hours following the creation of the risk map.

4. Case study 1: Thermal Imaging to determine rockfall risk

As part of a major project for the Mine Health and Safety Council (MHSC), the CSIR is investigating the process that results in accidents due to rockfalls [5]. The authors report that the attributes of a typical rockfall are:

- It occurs on the Ventersdorp Contact Reef (VCR);
- At a depth around 2100 m;
- The stoping area suffers 77% of rockfall fatalities;
- Approximately 60% of fatalities occur between 06h30 and 12h30;
- Around 80% of fatal rockfalls occur within 3.5 m from the face; and
- A typical fall area is between 4 and 10m^2.

The time and location of a typical rockfall indicate the importance of the entry procedure: many rockfall fatalities can be traced to inadequate entry examination or barring. The role of thermal imaging in improving this process is discussed here.

4.1 Thermal imaging

It has already been shown [10] that loose hangingwall rocks can be identified using thermal imagery because they are cooled more by ventilation than rocks that are more firmly connected to the surrounding hot rock mass (Figure 5). The CSIR is investigating the incorporation of thermal imagery into a larger AziSA based system for determining the risk of rockfalls, together with other information from closure meters and an acoustic sounding tool. For this paper, only the thermal imaging is considered.

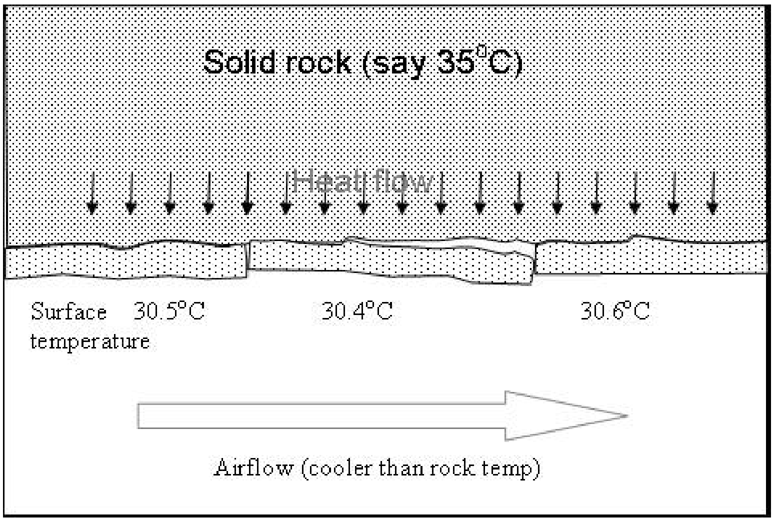

Figure 5. An illustration of the concept of heat flow from the warmer solid rock, with the more detached rock being more insulated and cooler. Thermal imaging (right) shows loose rock underground (left). From [10].

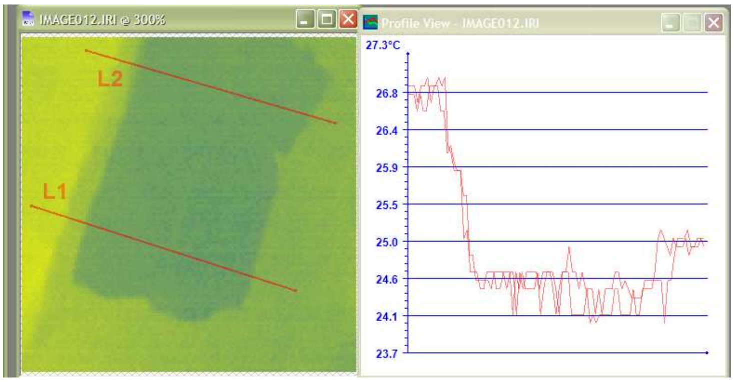

Figure 6. A loose section of hanging in the gully (with dimensions of .8m by .3m and an estimate mass of 65 Kg) on a Klerksdorp mine. With relatively newly exposed ground the temperature differential is more that 2.5 °C as shown in the temperature profiles along L1 and L2.

4.2 Identifying and quantifying risk

The most obvious use of thermal imagery is as a tool to assist a miner who is conducting an entry examination, which are most commonly both visual inspection and sounding of the hangingwall. As shown in Figure 6, a potentially unstable area could be as small as .5m^2 and may easily be missed. Should the hangingwall be examined carefully with a thermal imager, such smaller but still high risk areas can be recognised and marked for closer inspection by sounding, and for subsequent barring. The preliminary identification of high risk areas therefore allows the miner to prioritise areas for attention, and prevents unstable areas from being ignored.

Entry inspection procedures are well established, and if they are properly executed they should provide a safe environment in terms of rockfalls. Thermal imaging complements and enhances the current practices by allowing the miner to quickly scan a large area; his attention is being draw to potentially dangers hanging, with the benefit of not missing it during the inspection process; and prompting him to be extra careful during the sounding and barring process. The area of potential instability, or size of the rockfall, may also assist the miner in deciding whether to bar or support.

4.3 Determining quality of processes

Greater value can be gained by incorporating the thermal imager into an AziSA system. By adding location capability using ultrasonic beacons or other navigation methods, it becomes possible to match measurements to location. Measurements can now be saved and compared to measurements close by on previous days and to measurements from other tools:

- Trends may be recognised, and extrapolated into the future, immediately marking particular areas for special care in coming days; and
- Results from the thermal imager can be compared against other sensors such as acoustic sounding or closure, to build up a clearer picture of the risk at various points in the stope.

If measurements are recorded, it also becomes possible to determine how well a particular area of hangingwall was examined. The quality of entry inspections could then be audited. It is hoped that the combination of improved risk maps and improved audit will encourage better quality entry examinations and improved safety.

4.4 Proposed future application

It is unlikely that barring will automated in the near future, but it is proposed that a small robot could be sent in to the stope to do the entry examination remotely. Such a robot could be remote controlled, or ultimately become autonomous. In either case performance of the process can be monitored.

Robots are already being applied in dangerous situations such as in the search for survivors after the World Trade Center disaster in 2001 [3, 14]. There are still a number of challenges particularly in developing a robot that can manoeuvre and survive in a hard rock mine, and in providing a robot with a manipulator that can bar. But it is reasonable to expect that with the rapid progress in robotic technology, the day is not far off when a mobile platform such as the iRobot PackBot in Figure 7 could travel into a stope and conduct an entry inspection using a combination of remote sensing tools, and potentially then mark off dangerous areas with spray paint.

Figure 7. The iRobot PackBot [8]

5. Case study 2: temperature and heart rate monitoring

There has been research undertaken in South Africa on the stresses that miners are exposed to, particularly heat stress, since the 1930's. In the 1960's, 27.5 °C wet bulb was discovered to be the upper limit of environmental temperature underground for unacclimatised men performing physical work [15]. Later, a very similar limit (28 °C wet-bulb) was found to be applicable to cognitive ability: miners cease to think clearly at temperatures above the limit [12].

However, the limit was set following extensive testing on a cohort of fit young men. With time, the demographics of the South African mining population are changing, as the average age of miners increases, women join the workforce in greater numbers, and the diseases such as AIDS and TB become more prevalent. All these factors (age, fitness, gender, disease) affect the body's ability to work, and its response to heat and other environmental stressors.

The Physiological Strain Index is one technique that can assist in monitoring and managing heat stress, and allow the effect of other stressors to be quantified. The methods described here could equally be applied to other measures of work stress.

5.1 Physiological Strain Index

In order to quantify the effect of work on the human body, Moran and his co-workers [10] proposed the Physiological Strain Index or PSI. The index is calculated as a combination of heart rate and core body temperature, and ranges from 0 to 10. A level of 5 is regarded as moderate, while levels greater than 7 are regarded as potentially dangerous.

In Figure 8, heart rate and body temperature are graphed for a miner during a shift at an underground hard rock mine. Annotated on the graph are the activities performed at various times. The resting heart rate is between 60 and 80 beats per minute, with a corresponding temperature of 37° C. As the miner undertakes different physical tasks, the immediate response in heart rate is obvious, followed by a slower increase in core body temperature.

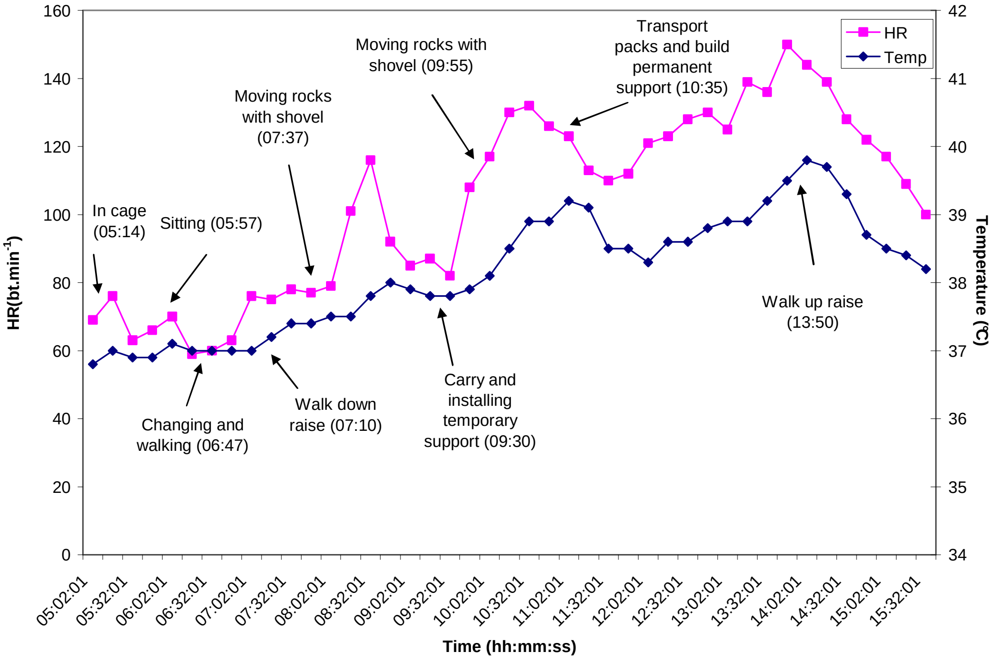

Figure 8. Heart rate and temperature for a miner before and during an underground shift.

In Figure 8, heart rate was measured using a Polar heart rate monitor, strapped around the chest. Core body temperature was measured using a CorTemp ingestible core body temperature sensor from HQInc [13]. The sensor (Figure 9, left) is a single use capsule about 2 cm in length that is swallowed by the subject. It transmits temperature wirelessly to a data logger worn by the subject (Figure 9, right). The data logger also logs the signal from the Polar heart rate sensor worn by the subject.

Figure 9. The CorTemp ingestible core body temperature sensor (left) and its data recorder (right).

In Figure 10, the measurements from Figure 8 are converted into PSI. It is now apparent that the subject's PSI is steadily increasing during the shift, due to the work being done and because the subject's body is not allowed sufficient time to recover following extensive physical effort. The long recovery time following exercise may be because of high ambient temperatures, or due to low levels of physical fitness.

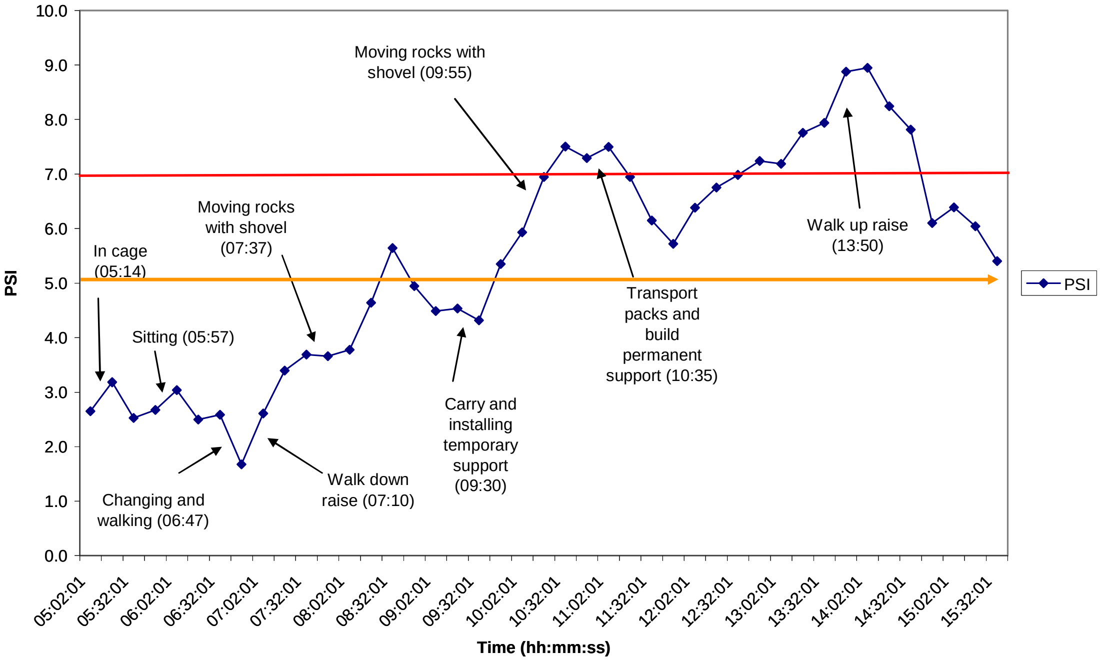

Figure 10. PSI calculated from the measurements plotted in Figure 8

5.2 Identifying and quantifying safety risk

The most immediate benefit of measuring PSI is to alert the miner or team leader to the potential danger of heat stroke in a member of a team. The core temperature alone would provide a measure for the onset of heat exhaustion and subsequent heat stroke, and could be used as an alarm to initiate standard procedures that are already in place. The advantage of subjective measures of heat exhaustion is the elimination of mis-diagnosis.

5.3 Determining quality of processes

High PSI can be an indication of an environment which is too hot, of physical activity that is too strenuous, or of individual susceptibility to heat stroke. If PSI instrumentation such as that presented here is incorporated into an AziSA system in a working place, it then becomes possible for a team leader to monitor the state of the whole team, which should differentiate between individuals who are susceptible, and high effort or hot workplace. Additional sensors would confirm workplace temperature.

The team leader is now in a position to manage the situation: manage the individual, manage the workload or manage the environment. At a higher level, operators in the control room will be able to see PSI across the mine, and use that knowledge to manage their heat stress programmes and ventilation. For example, PSI measured together with location may reveal areas where miners spend time that should be cooler to lower PSI, such as waiting places or stations.

If PSI and workplace temperature data are being logged by an AziSA system, histories will be built up for individuals. It is then possible to identify changes in individual responses to temperature with time. Long term changes may imply that individuals are no longer adapted to hot environments and may have to be moved to cooler occupations. Short term changes imply that the individual may be ill or unable to manage heat stress for other reasons. In either case, having objective data makes management simpler and reduces the opportunities for conflict caused by subjective management decision making.

5.4 Proposed research

At present, the ingestible pill is a barrier to the widespread take-up of PSI. As it is single use, it is a major cost, and there are also communication problems to be overcome in getting miners to ingest the pill. Research is therefore focussing on using other measurements as proxy for core body temperature, or even using just heart rate as an indication of physiological strain.

At present, there is a move towards measuring functional work capacity. While functional work capacity indicates whether individuals can undertake particular activities, there is a question over how well it measures response to typical underground activities. Research can be undertaken using PSI as a tool to determine functional work capacity in the actual underground environment.

PSI can also be included in a suite of measures to research the broader issue of work stress. For example, do high noise levels increase worker stress? Research is proposed to examine the consequences of several simultaneous stresses and their effect on worker physiology and therefore productivity.

6. Conclusion

The quest for zero harm requires tools at three levels:

- At the lowest level, risks need to be identified, so that appropriate measures can be taken to mitigate them.
- At a higher level, processes need to be in place to ensure that risk identification is taking place.
- At the top level, there need to be systems that ensure mine-wide compliance, and that also allow connections to be made for particular risks across different work places.

None of these three tools requires technology, but technology can greatly facilitate the identification of risks at individual, workplace and mine level and can enable real-time monitoring of safety critical parameters and subsequent processes in a manner that is not possible without it.

None of the technology can replace the requirement for a culture of safety among workers. But it can provide a framework that can facilitate such a culture.

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