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"*Enhancing Mine Emergency Response*"

Brenkley D.* Bennett S.C. Jones B.*****

* Consultant, Health and Safety Division, IMC Group
Bretby, Burton-on-Trent, Staffordshire, UK

** Director of Health and Safety Division, IMC Group
Bretby, Burton-on-Trent, Staffordshire, UK

*** Chief Operating Officer, Mines Rescue Service Limited
Mansfield, Nottinghamshire, UK

Abstract

After an underground fire or explosion there is an imperative requirement to achieve escape or find refuge within the operating life of a self-rescuer and to offer immediate wayfinding assistance to the workforce. Conditions of poor visibility, together with possible disorientation, can impede rates of egress and lead to inappropriate escape responses. This paper touches upon a number of aspects of mine emergency response, reviewing self-escape issues and examining the nature and role of specific support technologies with particular note being made of life-support and low visibility wayfinding technologies. A new wayfinding technology, developed by IMC with the support of the UK Health and Safety Executive, is reported.

Introduction and Self-Escape Issues

There will always be a requirement to have rescue teams available to respond to a mine emergency. However it is argued that the greatest impact on survivability is the effectiveness of the self-escape response of the workforce in the critical minutes after an incident. Correspondingly, legislation concerned with escape and rescue from mines addresses self-escape as a high priority and emergency preparedness is a critical element of the safety management system of any mining operation [Gibson 1996, Smith 1996].

Escape strategies need to address a wide range of operational situations and scenarios, including mines with deep, distant workings, where gradients and high heat stress conditions can greatly impede evacuation. This situation is observed increasingly as mines become more capital and energy intensive, are driven deeper and operate with long travelling distances to the production areas.

Fire remains a major hazard, and in devising evacuation strategies the oxygen cost and limitations of life-support technology must be carefully examined. The legislation in a number of countries, particularly where ventilation standards are high, permit mine managers' risk assessments to be based on the use of filter type self-rescuers. This contrasts with an international trend of adopting person worn oxygen self-contained self-rescuers (SCSRs), which provide complete isolation from contaminated mine air. However the use of chemical oxygen or compressed oxygen rescuers is associated with a small or negative safety margin in terms of available wearing time and realistic training is difficult to provide. Studies of SCSR performance under actual escape conditions confirm that the effective duration of SCSRs can be notably less than the reference rating referred to in legislation. The number and capacity of SCSRs a miner may need in order to make an escape from the deepest points of a mine is still a subject of ongoing research [Kovac, 1998].

There remains a significant working lifetime probability that the workforce will have to evacuate the mine under emergency circumstances. In a survey of 7 US mines, Vaught et al [1996] identified that an average of 21% of miners had, at some time, donned a self-contained self-rescuer or filter self-rescuer in an emergency. In the South African mining industry some 609 SCSRs were activated in 39 incidents over the period 1987-1994 [Kriel et al, 1995]. For maximum effectiveness, SCSRs must be considered within an integrated escape and rescue strategy comprising components of escape routes, guidance systems, refuge bays, hazard identification and communication systems [Smith and du Plessis, 1998]. Phillips et al [1997] consider the three key elements of this strategy to comprise body worn SCSRs, the provision of permanent or semi-mobile refuge bays and some form of guidance system for use in low or zero visibility conditions. Post-incident investigations have referred to the need for improved wayfinding following fire, explosion and windblast

[McKensey 1996]. Experience of post-explosion situations has demonstrated that, whilst SCSRs and refuge bays are critical elements of any rescue strategy, conditions can be so adverse that emergency communications and the ability to orientate oneself maybe of equal importance. [SIMRAC 1995, Kriel et al 1995b, Thyer and Weyman 1997]. Kielblock and Van Rensburg [1987] suggest that maximum face to refuge bay distances should not exceed 1500 metres in high seam room and pillar workings and that this distance may need to be halved in low seam longwall operations. These distances assume good visibility. Under conditions of low or zero visibility, speed of travel is materially impaired and may be less than 25 per cent of that possible when visibility is normal. [Kriel et al 1995b]. These findings raise questions regarding how workers wearing SCSRs of limited duration can be guided to a SCSR changeover point, refuge bay or other place of safety under conditions of nil visibility. However, prior to discussing issues of orientation and wayfinding in more detail, it is useful to briefly review refuges and havens as key elements of escape strategy.

Technologies to Enhance Emergency Response
- Refuge Stations/Safe Havens

When wearing a self rescuer of any type, the ultimate distance covered may well be a function of the physiology of the wearer rather than the performance of the self rescuer. In those mines where there are long distances to a place of safety, long duration self rescuers are considered to be essential. There is an increasing trend that the Emergency Escape Plan should not be based solely on the use of self rescuers and that consideration should be given to the introduction of refuge stations where the workforce shelters in a sealed, fireproof structure, or safe havens where evacuating staff can rest and change self-rescuers. Anecdotal evidence of a recent fire event, where 100 men sheltered safely in underground refuges for 7 hours prior to being rescued confirms the value of the safe haven approach, where the scheme is well planned and implemented.

Refuge stations have been part of the underground mining scene for many years, particularly in Canadian and South African mines. In some countries, however, the provision of such facilities is a relatively new concept. There are two main types in use, with varying designs and sizes.

Permanent Refuges

Sealed unit or permanent site refuge stations are normally large in size, of substantial construction and serve as a focal point for individuals travelling from a broad area of the mine, often serving a dual purpose as a lunch room. Such units are more appropriately installed in larger mines but are not particularly suitable for rapidly moving working areas of mines, which is the situation in most coal mines. The designs of such refuge stations have been well documented, particularly in those countries where their use has been reinforced by minimum legislated requirements and guidelines (e.g. Ontario Mines Rescue Refuge Station Guidelines, MAPAO Committee, Sept. 1990).

The use of refuges in coal mines is becoming more common. The ideal site is one having a borehole to the surface through which air, water and food can be passed to the mineworkers inside. This is typical of South African coal mine refuges. An alternative approach is a dual source of compressed air, although not all mines have compressed air supplies underground and consideration of compressor siting is required to ensure their integrity in an emergency situation. Consequently, assessment is being made of the possible use of independently powered air supply modules, discussed below, which provide a chemical oxygen source and are equipped with CO_2 scrubbing technologies. In general, refuges for metalliferous and other mines must be designed to have adequate bulkhead fire resistance, whilst the designs for coal mines must also consider explosion overpressures. Oberholzer [1997] has reviewed biological and structural impacts and considers a 140 kPa overpressure withstand capability to be adequate for structures sited away from the face.

Temporary or Transportable Units

The design of temporary havens for underground coal mines requires considerable expertise. The havens have to be practical, to suit rapidly moving working places, yet they must retain the basic elements necessary to sustain life for significant periods of time following a fire or explosion. Based on visibility criteria, Smith and du Plessis [1998] state that refuge bays should not be further than 750m from the workplace. This would mean, in South African terms, that refuge bays would need to be constructed at intervals between 36 and 185 shifts. Given the impracticality of erecting permanent refuge bays at these intervals, intermediate staging points and breathing stations are being evaluated.

In some countries, temporary shelters are sited as relay points to assist workers in reaching their permanent safe haven or first aid centre. The nearest shelters are often maintained within 50-100 metres of the working face and are equipped with compressed air lines and communications. The structures are of vinyl tarpaulin construction with fasteners for sealing the doorway. This form of temporary shelter was largely pioneered in Japan. This concept is being introduced into UK coal mines in the form of semi-sealed installations, such as canopies or pressurised "tent-like" refuges, which are erected using a compressed air supply [Forster 1997]. Three safe haven designs are being examined in the UK [Evans and Forster 1999].

There are now several refuge bay air supply and purification system technology suppliers. These systems can provide an independent oxygen supply and carbon dioxide scrubbing for limited periods of time for groups of 10-20 people or more. Commercial systems include the Canadian Refuge-One Mobile Safety Base or "Tommyknocker", the South African MARS (Mobile Air Rescue Station) and the Survivair-E Life Support System [Venter et al 1997]. These systems are undoubtedly useful but can be compromised by the build up of carbon monoxide due to air leakage into the refuge. It can be technically difficult to create adequate positive pressure inside the bay and hence research is being directed at incorporating carbon monoxide scrubbing [Smith and du Plessis 1998]. The development and introduction of refuges or safe havens is also only useful if individuals know where the havens are located, particularly in low or zero visibility conditions. This is considered in the following section.

Technologies to Enhance Emergency Response
- Guidance Systems for Low Visibility Conditions

Current practice in many mines is to mark escape routes with reflective signs and symbols. However these signs have a number of limitations:

a. The signs need to be kept clean, in good condition, and up to date.

b. Frequently, mine personnel pay little attention to reflective route way markings.

c. Reflective markings are of limited value in low visibility conditions.

In response to these limitations, development of orientation and guidance systems in mines has progressed along two lines [Gouws and Phillips 1995, Weyman and Thyer 1997]:

1. Passive lifeline technologies.
2. Active electronic audio-visual guidance systems.

Whichever approach is considered it should, as far as possible, achieve the following:

- Significantly increase speed of egress.
- Be useful in conditions of extremely low visibility.
- Not present ambiguous directional information.
- Provide visual, audible and tactile cues.
- Be low cost with minimal maintenance requirements.
- Accommodate differences in mine layout, working practices, culture and language.
- Offer high integrity and preferably fail-safe operation.
- Not rely on background lighting being present.

Passive Guidance Systems

Experienced mineworkers can use appropriate structures such as conveyors, cables and rails as a lifeline in conditions of nil visibility. An alternative approach is to use dedicated lifelines which lead along travelling roadways and return escapeways, often directly to refuge bays. Having located the lifeline, the individuals must continue along the line in the appropriate direction towards safety. In an attempt to provide unambiguous direction of travel, lifelines have been designed to provide unidirectional travel or tactile directional cues. According to Weyman and Thyer [1997], there are at least five different types of lifeline in use.

The utility of installed lifelines has been tested under simulated conditions [Kriel et al 1995b]. The results showed that on average, subjects wearing SCSRs and operating in nil visibility, move at approximately 75 per cent of normal walking speed when aided by a lifeline; the corresponding figure was less than 40 per cent when using only the existing structures in the section. On balance, purpose-designed lifelines present a low cost and effective means of guidance where they can be installed.

Active Guidance Systems

In an effort to provide a more effective and general purpose means of guidance, active electronic guidance systems have been developed, which employ visible and audible signals to guide personnel. Within these systems, series of roof or rib-mounted beacons are used to emit an audible and visual signal in a cyclical routine, commencing at the working face and terminating at the refuge bay or at the store of long duration SCSRs. The cost of these systems dictates that the beacons be spaced as far apart as is judged expedient, typically at 50 metre intervals or closer where directional ambiguity is present such as at junctions. This spacing leads to only partial effectiveness of the visual signal since in dense smoke conditions the visible range may be only several metres. To respond to this limitation, the systems have a synchronised stepped tone output which provides aural direction indication and location cues for the next beacon.

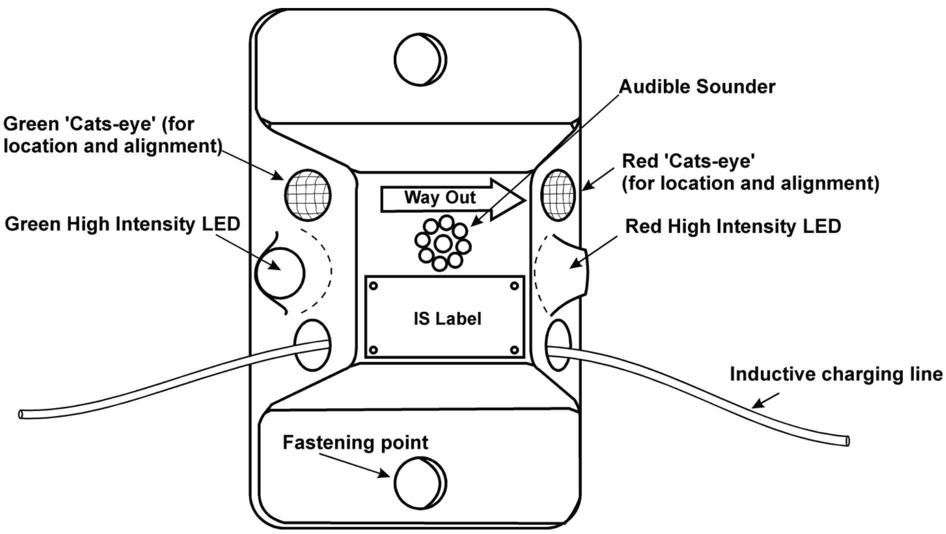
Active systems are typically mains supply operated with a battery back-up supply. The units are fail-safe and are triggered by a loss of power, or by contacts being opened manually or by means of environmental sensors. A number of systems are installed in collieries in Australia and the Republic of South Africa [Dhar 1997]. Evaluation of the South African 'Moses' system has been carried out under simulated escape conditions with nil visibility where it was found that escape time was still of the order of three times that measured under normal vision circumstances [Phillips et al 1997]. One further requirement of a guidance system is that it should show clearly where the refuge bay entrance or similar structure is located. Whatever system is used, it needs to be consistent throughout the mine and made familiar to the workforce on a regular basis.

Further approaches to assist smoke penetration using thermal imaging systems have also been proposed [Conti et al 1998] but the cost of such equipment and the lack of intrinsically safe versions suggest that their deployment in coal mine rescue or emergency evacuation situations may be limited.

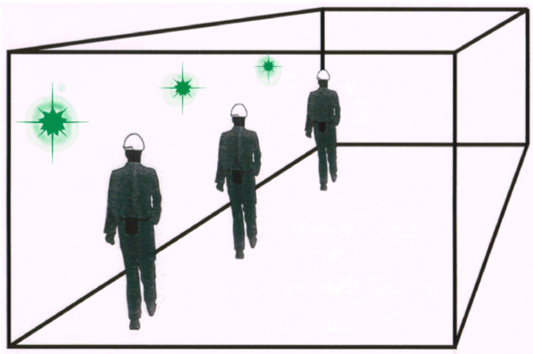
IMC's Egress Beacon System

In conjunction with the UK Health and Safety Executive and Mines Rescue Service, IMC has developed a simple but effective egress beacon system [Brenkley et al 1998]. The technical approach to the problem has involved using a sequence of bi-colour indicators and acoustic senders with a novel approach of using inductive power transfer to each beacon unit. It is feasible that the beacon system can provide a dual early warning function. The system developed by IMC is fail-safe, robust and potentially offers the lowest cost option of any 'active' wayfinding system.

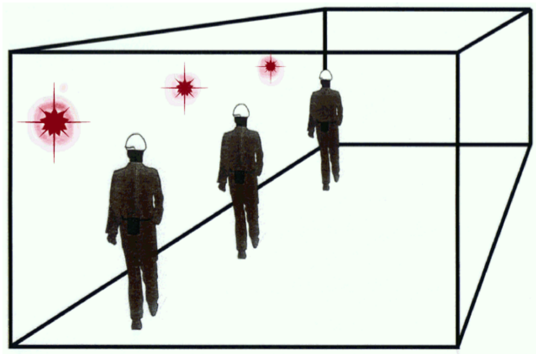
The form of the beacon is shown here in conceptual form, with the key features identified:



In principle, the scheme employs a sequence of beacons each equipped with a pair of oppositely facing red and green high intensity light emitting diodes (LEDs) together with an acoustic sender. The beacons are bolted to the tunnel wall such that when activated, each beacon presents either a red or green light, depending on the direction of travel. Where the subject is moving in the correct direction towards the egress or refuge point, then a sequence of green lights will be seen. Conversely, where the subject is heading away from the egress or refuge point then a sequence of red lights is observed. There is thus no ambiguity over the direction of travel and the system provides a powerful motivation to follow the correct sequence of lights.



Following assigned escape route

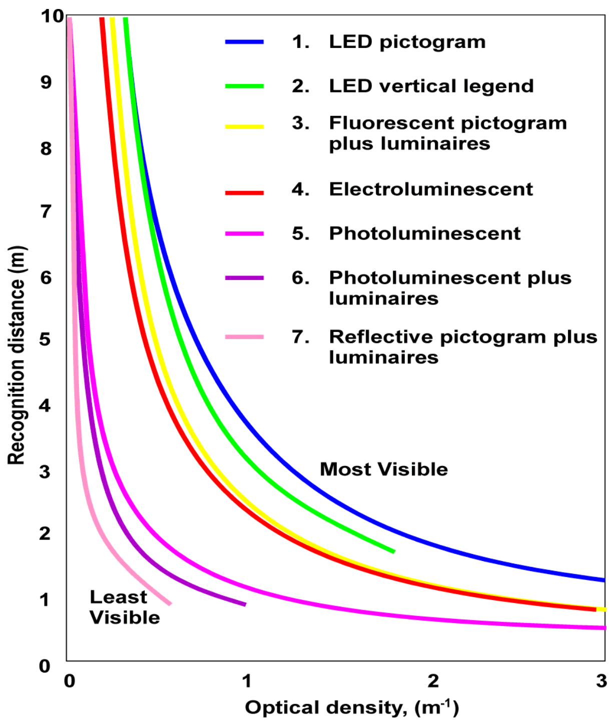


Opposite direction…

For the small percentage of the workforce with severe red-green colour blindness, visual-tactile cues in the form of a raised arrow have been applied to prototype mouldings. The direction assignment of the beacons is determined from the mine's risk assessment. Variations of the beacon have also been developed which incorporate programmable direction assignment, using low frequency inductive signalling techniques. This permits the direction of evacuation/direction to the refuge to be periodically reassigned to match changes in local requirements. The dual red-green light emitting diode arrangement can also be replaced by a single green light emitting diode to reduce beacon cost.

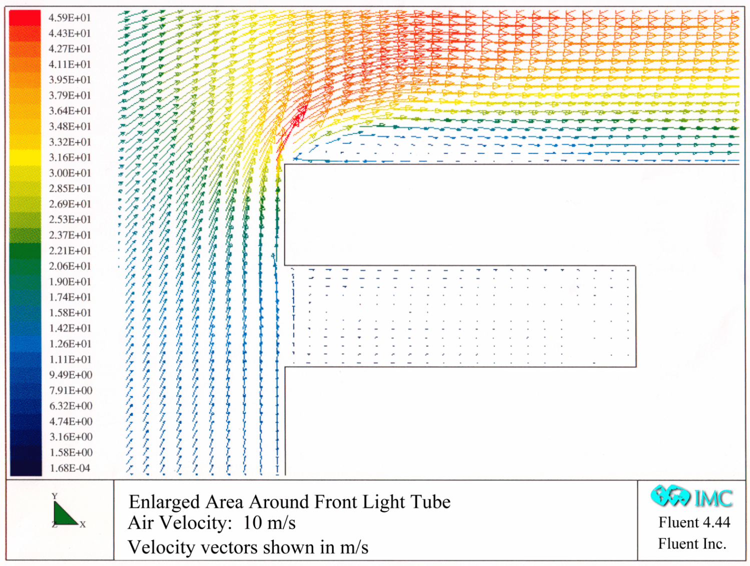
Each beacon is powered by a small internal rechargeable cell with power inductively coupled into each beacon from a charging line carrying a high frequency current. The key to the scheme is that a small but useful amount of power can be bled from the line to trickle charge the cell within each beacon. Important advantages of this approach are that the system is fail-safe, each beacon receives an identical charge current irrespective of where it is located on the line, that each beacon is totally galvanically isolated, and, any electrical failure within a beacon has no effect on the rest of the system. In practical terms, there are also significant cost and reliability benefits from not having to use multipole connectors or glanded compartments.

Tests conducted by the UK Building Research Establishment [Webber and Aizlewood 1994, Webber 1997], have shown that high intensity red and green light emitting diodes offer fair transmission through a scattering medium such as suspended smoke or dust particles. The relative visibility in smoke was observed to be higher than that of conventional signs (below). The high visibility of green and red light colours through smoke has been confirmed by Conti et al [1998].

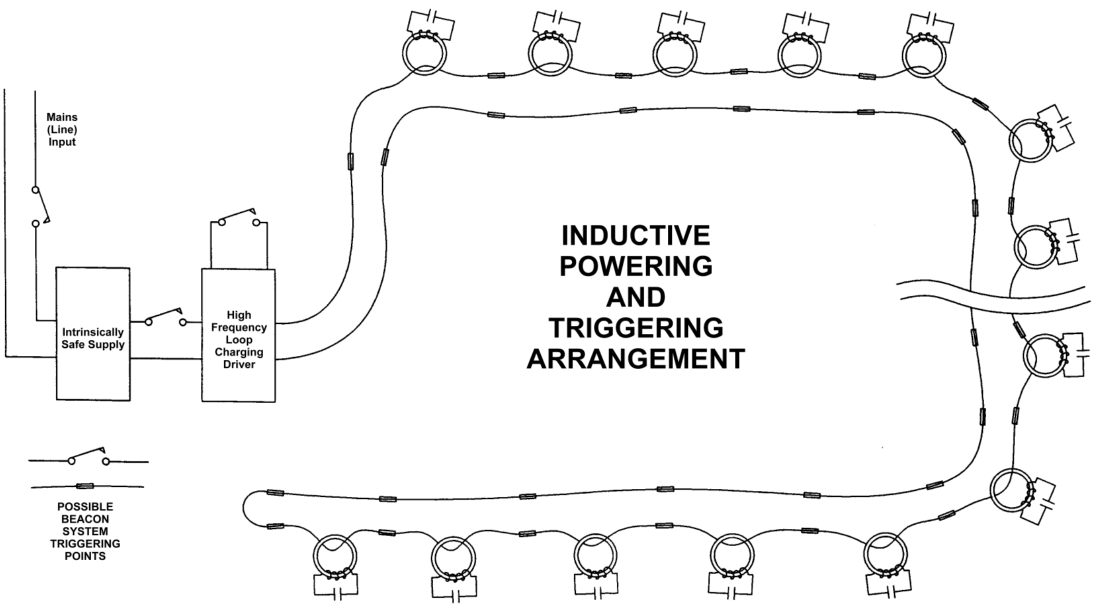


To further assist in conditions of extremely low visibility, each beacon is equipped with an acoustic resonator to provide a pulsed high frequency tone. This allows the approximate location of the next beacon to be determined even though it may not be visible.

Each beacon unit has relatively few components both to reduce cost and improve reliability. The system has been designed such that any interruption of the power supply or charging loop, whether by damage or being disconnected manually, or by an environmental monitor alarm output, will cause the beacons to automatically switch on (below). The system is thus fail-safe when subject to power loss. This also allows routine functional testing and maintenance of the network to be carried out relatively straightforwardly, since any beacons not working when the network is activated are self-revealing. In order to prevent dust build up on the optics, novel self-cleaning optical window designs have been developed. These have been shown, by the use of testing and CFD modelling, to substantially reduce dust deposition for the envisaged range of ventilation Reynolds numbers. A typical CFD plot for the optical window is shown, with stagnation in the tubular optical window resulting in only a small degree of dust entry and settlement.



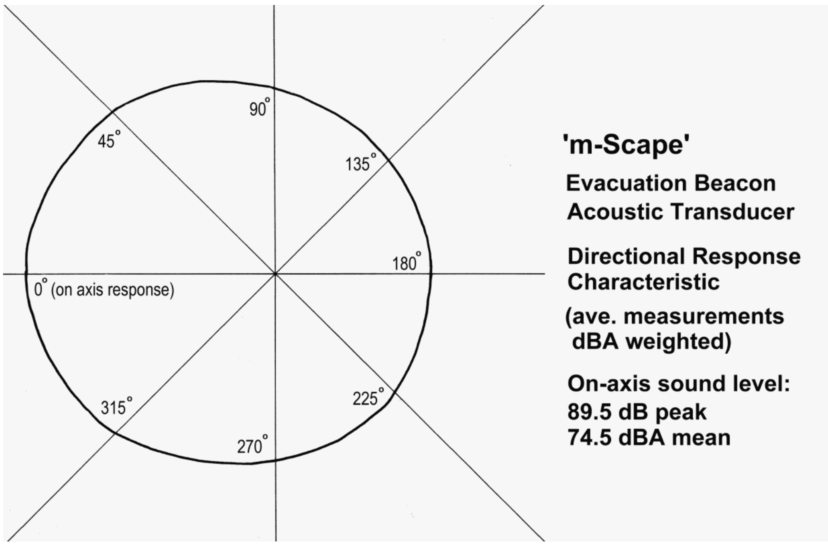
Conceptual scheme for beacon charging and triggering:



Sound Localisation of Beacon

In extreme visibility conditions, the optical penetration of any visual beacon system will reduce to the order of a few metres and sound localisation must be used to help identify the beacon direction. In the scheme proposed by IMC, a decision was made, on the grounds of cost and complexity, to dispense with the requirement for synchronised clocks between adjacent beacons. In this case the beacon acoustic arrangement must be designed such that a single sound transducer is able to provide free field localisation Auditory localisation depends on several perceptual processes, the most common cues being inter-aural amplitude differences and inter-aural time delay [Elfner and House 1987, Searle 1982].

Tests confirmed that a single sound transducer within each beacon could provide useful directional information if the high frequency directional characteristics of the transducer and the human ear were exploited. The tone frequency was selected to be around 3 kHz and various acoustic transducers were investigated for directional characteristics. Piezo-electric sounders were rejected due to their impact spark hazard. Small mylar cone transducers were selected which exhibited a high Q resonance at circa 3.0kHz, permitting a relatively high peak acoustic output from a modest drive power. The directional characteristics of the transducer were also shown to be acceptable, with an off-axis reduction of 6-7 dB(A), 18-20 dB(A) and 27 dB(A) for ±45°, ±90°and 180° respectively. A peak output level of 90 dB was observed at one metre, with an A-weighted mean of 74.5 dB(A) (reference level 2. 10^{-5} Pa). The resonators have also been successfully subjected to modest windblast overpressure testing (<5kPa peak) at IMC's Swadlincote ignition test facility.



To exploit the directional characteristics of the transducer it is necessary that the acoustic transducer be mounted in the beacon enclosure such that it faces the same direction as the green light emitting diode. In this case, as the beacon is approached there is a progressive increase in sound intensity which drops off significantly as the beacon is passed and the next beacon is sought. Discharge tests confirmed that the beacons offer a useful operational life of approximately seven hours. This period is sufficiently long to offer assistance to both escapees and rescuers, who enter later and must be able to retrace their steps. A full beacon system has been evaluated for over 18 months in an underground gallery of the UK Mines Rescue Service at Houghton-le-Spring, County Durham. Station brigadesmen have conducted a number of tests where the galleries have been filled with smoke. In the majority of these tests, trainees were not briefed on the operation of the system but were simply told to follow the sequence of green indicators. The first-hand feedback and response from the 'escapees' is that the system is regarded as having considerable value and utility.

Observations and Current Status of Beacon Development

A number of observations can be drawn from the research and trials of the egress beacon system:

1. The concept of using high intensity red and green light emitting diodes to provide wayfinding assistance has been shown to be feasible.
2. For maximum penetration through smoke, point sources rather than planar light sources are required. Under 'heavy smoke' conditions, high luminous intensity light emitting diodes have a range of around five

metres. The visible range rapidly reduces with increasing smoke obscuration. In 'light smoke' conditions the beacons are visible beyond 15 metres or more.

3. Anticipated improvements in light emitting diode technology will permit luminous intensity to be increased by a factor of 2-3. This will increase range under heavy smoke conditions to around 8 to 10 metres or more.
4. The use of an acoustic sounder is an important aspect of providing additional directional cues in extremely low visibility conditions. Whilst a sequenced set of pulses or increasing pitch tones between adjacent beacons provides the conventional means of localisation, it is considered feasible to use a simpler approach relying on the directivity of a subject-facing acoustic sounder.
5. Intrinsically safe inductive power transfer is feasible and it is estimated that approximately 50 beacons could be attached to an IS charging line. The power delivered to each beacon battery is small, circa 5 mW maximum.
6. To address the problems of dust deposition around the beacon optics, a novel optical window design has been developed which has been shown to work well under prevailing underground ventilation conditions.
7. Compared with alternative wayfinding technologies the proposed scheme has several advantages:
   - The low cost of the beacons allows them to be more closely spaced.
   - The cost of cabling is substantially reduced.
   - Each unit is galvanically isolated and individual beacon failures have no effect on the system.

The system has been developed to a stage where it is ready for a submission of intrinsic safety. Other applications for a non IS version of the system have been identified in civil engineering tunnels.

Conclusions and Recommendations

There is an emerging recognition, world-wide, that major incidents have profound and lasting repercussions on all stakeholders involved with mining operations. This is shifting the emphasis of safety management to a proactive, risk-based approach, where effective emergency preparedness measures and emergency support provisions are key elements of reducing workplace and business risks. The organisation, systems and technologies for rescue and emergency support are reviewed by the authors in a recent IEA report [Jones, Brenkley, Burrell and Bennett, 1999].

The founding principles of any emergency escape plan must be to seek to evacuate the mine with minimum complication and delay. However for a number of reasons this may not be possible and alternative survival strategies based on the use of safe havens (refuge bays) and self-rescuers are required. The use of safe havens can enhance the viability of self-rescuers, either by providing a location to change a person-worn short duration self-contained self-rescuer for a longer duration unit, or alternatively by providing a separate, sealed life support system. Potentially, the safe haven concept, if developed effectively, has a vital role in establishing a robust emergency survival strategy for use in large hot mines or where there are significant gradients impeding passage out of the mine.

In planning escapeways, attention has to be given to achievable escape speeds and the significant reduction expected from loss of visibility after a mine fire or explosion. In this case, nominal escape speeds of approximately 3 kilometres per hour in good visibility, may be reduced drastically. The issue of post-incident orientation and wayfinding in low or nil visibility conditions is receiving increasing attention world-wide. Mine operators and Mines Inspectorate need to be provided with best available knowledge on measured impacts and how visibility issues may be best addressed in the evacuation planning process. Both active audio-visual and passive life-line systems can offer substantial assistance under heavy smoke conditions and further reduce the risks from working in long, isolated drivages. Generic active and passive wayfinding systems have been reviewed and these offer considerable value in helping locate refuge bays in poor visibility conditions. The IMC Egress Beacon system described within the paper provides a new flexible, low cost approach to providing such wayfinding assistance. The active guidance system, which is fail-safe and utilises both visual and audible cues, offers the prospect of an intrinsically safe system with wide potential application.

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